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INSTRUMENTED HOME ENERGY RATING AND COMMISSIONING TECHNICAL REPORTS

Residential Commissioning: A Review of Related Literature

Practical Diagnostics for Evaluating Residential Commissioning Metrics

Potential Benefits of Commissioning California Homes

TECHNICAL REPORT

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Energy Systems Integration

What follows is an attachment to the final report for the Instrumented Home Energy Rating and Commissioning project, Contract Number 500-98-033, conducted by the Energy Performance of Buildings Group, Environmental Energy Technologies Division of the Lawrence Berkeley National Laboratory. The report is entitled Instrumented Home Energy Rating and Commissioning Technical Reports. This project contributes to the PIER Building End-Use Energy Efficiency program.

This attachment, "Instrumented Home Energy Rating and Commissioning Technical Reports" (Attachment A-1), provides supplemental information to the project's final report and includes the following three reports:

- *Residential Commissioning: A Review of Related Literature*
- *Practical Diagnostics for Evaluating Residential Commissioning Metrics*
- *Potential Benefits of Commissioning California Homes*

More information on residential commissioning, including a downloadable Microsoft Word version of the literature review, is available at http://epb1.lbl.gov/EPB/commissioning/index.html.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

Abstract

This "Technical Reports" attachment is a set of documents produced by the Instrumented Home Energy Rating and Commissioning project, funded by the California Energy Commission's Public Interest Energy Research (PIER) Program.

Currently, houses do not perform optimally or even as many codes and forecasts predict, largely because they are field assembled and there is no consistent process to identify deficiencies or to correct them. Solving this problem requires field performance evaluations using appropriate and agreed upon procedures in the form of a new process called residential commissioning.

This attachment, "Instrumented Home Energy Rating and Commissioning Technical Reports" (Attachment A-1), provides supplemental information to the project's final report and includes the following three reports:

Residential Commissioning: A Review of Related Literature
This report discusses the status of commercial building commissioning and compares it with residential commissioning. Based on an extensive review of 469 readily available documents, it summarizes existing metrics, diagnostics, and norms for all building types that are relevant for evaluating, tuning, and retrofitting various aspects of new and existing houses.

Practical Diagnostics for Evaluating Residential Commissioning Metrics
This report identifies and describes 24 practical diagnostics that are ready now to evaluate residential commissioning metrics.

Potential Benefits of Commissioning California Homes
This report focuses on the energy and operating cost benefits related to commissioning houses in California. It also qualitatively discusses related non-energy benefits.

Keywords: Buildings, HVAC, energy, metrics, diagnostics, commissioning, retrofits, benefits, Commissioning Report

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Residential Commissioning: A Review of Related Literature

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EXECUTIVE SUMMARY

Currently, houses do not perform optimally or even as many codes and forecasts predict, largely because they are field assembled and there is no consistent process to identify problems or to correct them. The emerging process of residential commissioning can rectify this situation by providing performance assurances.

Residential commissioning is defined within this report as a performance assurance process in the form of agreed upon metrics, diagnostics, and norms that might be carried out between the time installation and construction are complete and when the buyer occupies the new house. It also includes many activities such as rating, auditing, super-commissioning, or recommissioning. 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 California houses, as well as the indoor environmental performance of all houses in the State.

The literature review reported here is the first step in a larger 30 month-long project that will lay the groundwork for a residential commissioning industry in California focused on end-use energy and non-energy issues. The intent of the review is to facilitate access to existing literature related to residential commissioning. Emphasis is placed on reviewing documents published over the past 20 years, which represents the period of time over which building commissioning and closely related issues have been actively reported.

This report discusses the status of commercial building commissioning and compares it with residential commissioning. Based on an extensive review of 469 readily available documents, it summarizes existing metrics, diagnostics, and norms for all building types that are relevant for evaluating, tuning, and retrofitting various aspects of new and existing houses. The relevant areas of concern for California houses are: Building Envelope, Cooling Equipment and Heat Pumps, Air Distribution Systems, Indoor Air Quality, Combustion Appliances, Controls, and Other Electrical Appliances.

There is a substantial amount of useful information in the literature about metrics, diagnostics, and norms that are relevant to residential commissioning. However, there are also some significant gaps. This report concludes by highlighting gaps in existing knowledge that require further research and development.

Areas in particular need of work include: metrics, diagnostics, and norms for thermal mass and moisture-damage susceptibility; diagnostics for steady-state capacity and efficiency, as well as refrigerant charge level, for cooling equipment and heat pumps; diagnostics and norms for ventilation effectiveness and efficiency; diagnostics to evaluate the potential for backdrafting and combustion gas spillage; and metrics, diagnostics, and norms for controls and other electrical appliances.

Only 33 of the 469 papers specifically addressed a house as a system of interacting components, although many mentioned that this is an important issue. It appears that more research is necessary to assess and describe the performance of a house as a system.

INTRODUCTION

Currently, houses do not perform optimally or even as many codes and forecasts predict. For example, Jump et al. (1996 [223][♣]) found variations of a factor of two in distribution system efficiency. Walker et al. (1998 [448]) found similar magnitudes of variation for distribution systems. The latter study also found changes of 50% in envelope leakage for houses with the same design, builder, and subcontractors within the same subdivision. A substantive reason for these problems is that most buildings are field assembled from a large number of components and there is no consistent process to identify problems or to correct them.

To ensure components and systems interact together as intended and to yield the energy and non-energy performance that building designers, trades, owners, and occupants find acceptable, performance must be judged using appropriate and agreed upon metrics, diagnostics, and norms. Many of these elements already exist in a fragmented environment. Some are already used to commission commercial buildings. Most can be integrated into residential commissioning to provide performance assurances.

The work reported here is the first step in a larger 30 month-long project that will lay the groundwork for a residential commissioning industry in California focused on end-use energy and non-energy issues. The overall goal of this project is twofold: it will demonstrate the value that performing building commissioning services would have in both new and existing residences; it will also develop and document residential building commissioning procedures. The project will address the house as a system of interacting components and will attempt to redress the problem that treating them separately has led to sub-optimization of performance. Developing metrics, diagnostics, and norms to quantify energy and indoor environmental performance within this framework will contribute to the improvement of the energy cost/value of electricity for the State. It will also contribute to the quality, comfort, and safety of homes for the citizens of California.

One technical objective of this project is to collect and analyze data on the methods and techniques of residential commissioning, as well as on its costs and benefits. The results of this work will provide new insights on how to address the problems of energy and indoor environmental performance in new and existing houses. These results will also foster the discussion of how to integrate aspects of commissioning with other building industry processes so that more value can be obtained from a single site visit. Another objective is to provide standardized, robust, cost-effective, and accurate tools and techniques for verifying house performance, by adapting existing ones or developing new ones. The ultimate objective of this project is to increase the number of houses that undergo building commissioning, which will optimize their energy and indoor environmental performance.

As the first step toward meeting these goals and objectives, this report discusses the status of commercial building commissioning and compares it with residential commissioning. Based on an extensive review of readily available literature, it summarizes existing metrics, diagnostics, and norms for all building types that are relevant for evaluating and tuning various aspects of new and existing houses. Gaps in

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[♣] The bracketed value refers to the reference number in Appendix B (Alphabetized List of References).

existing knowledge that require further research and development are highlighted. Each of the 469 documents that were collected and reviewed is listed in the annotated bibliography attached as Appendix A. All these documents are also listed in alphabetic order in Appendix B.

In the next step of the project, a set of metrics, diagnostics, and norms for residential commissioning will be developed based on data from the literature review and on analyses performed using simulation tools. This selected set of commissioning elements will subsequently be tested in the field to demonstrate the accuracy, usability, relative importance, and value of each element for both new and existing California houses. Finally, guidelines for the building industry will be developed to document the commissioning procedures. Research findings will also be transferred through workshops with and presentations to the building industry.

BACKGROUND

This section provides an overview of the emerging process of commissioning in commercial and residential buildings. It describes what commissioning is, why it is done, its principal elements, how its process is structured, what needs to be commissioned, some of its costs and benefits, and who does it today. It should be noted that the elements of this discussion pertaining to residential commissioning are largely preliminary, because such a practice does not yet exist. It is one of the goals of this project to formulate and clarify these residential commissioning issues.

What is Commissioning?

Commissioning has its roots in shipbuilding where the term was first used to describe the process that ensures a ship is sea worthy and ready for service. While there are many definitions for commissioning, one simple one is “a set of procedures, responsibilities, and methods to advance a system from static installation to full working order in accordance with design intent” (Yoder and Kaplan 1992 [465]). The variations in definitions relate to the scope of commissioning, and the activities related to commissioning. 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 (recommissioning).

Commissioning is common practice today in industrial plant operations, where control systems are regularly "commissioned". The principles behind commissioning are also similar to those of "total quality management" (TQM). In TQM, one attempts to establish metrics that can be tracked and evaluated to determine whether the quality of the desired activity or system meets expectations.

While many in the building industry may think of commercial buildings when the subject of commissioning is raised, it is still uncommon to commission these buildings at any stage of their life cycle. Based on the definition above, only a few percent of commercial buildings are commissioned. Some of the primary issues that are now driving the building industry to pursue commissioning of commercial buildings are:

- Demand-side management evaluations of energy-efficiency measures in commercial buildings have shown that many of these measures do not perform optimally or even as well as intended, typically because commissioning was never done or it was done haphazardly (Piette et al. 1995 [329]). Commissioning that follows formalized methods can establish and track operations and provide intended energy performance from startup throughout the life cycle of the building.
- Architects and engineers pay little attention beyond initial start up to ensuring that building systems meet intended energy efficiency, comfort, indoor air quality, and operations and maintenance (O&M) targets. The lack of involvement results in a knowledge gap: designers often do not understand how the systems they design actually function. This can lead to persistent design errors and deficiencies in subsequent designs. Commissioning can help alleviate this problem by educating building designers, so their designs and building technologies can be improved.
- Commercial buildings are becoming more complex and dynamic. Energy Management Control Systems, dynamic daylighting, direct-digital controls, variable frequency drives, and thermal-energy storage systems are just a few of the technologies contributing to this issue. Most of these technologies interact, which confuses building operators and demands that commissioning be used to optimize their mutual performance.

Residential buildings have many of the same problems and motivators, although their systems tend to be less complex. However, houses are becoming more complex. This is especially problematic, because few houses are now built or retrofitted using formal design procedures. As a result, residential commissioning is an even more nascent practice that means little to most people at this time.

In its narrowest sense, residential commissioning could be defined as the performance assurance process that might be carried out between the time installation and construction are complete and when the buyer occupies the new house. This process would assure the buyer that all required equipment is installed correctly, the final product is assembled correctly, and the house performs as intended. To this end, the California Title 24 energy code already provides elements of commissioning in the form of metrics, some diagnostic methods, and norms for evaluating the energy performance of new houses. The extensive literature associated with building commissioning also describes many such elements.

For the purposes of this project, we use a broader definition of residential commissioning, which includes many activities such as rating, auditing, super-commissioning, or recommissioning. 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 California houses, as well as the indoor environmental performance of all houses in the State.

Principal Commissioning Elements

Every commissioning process includes three principal elements: metrics, diagnostics, and norms. The following defines these elements and offers examples to aid understanding:

- *Metrics*: For whole buildings, there are two broad performance objectives of interest: Energy Performance and Indoor Environmental Performance (e.g. IAQ and comfort). Each objective can be represented by various performance metrics, which are simply defined as a quantification of the performance of the relevant components or systems.

  To understand what a metric is, consider a manufacturer that produces a pen. One relevant metric in this case might be how long a line the pen can produce until it runs out of ink. Three other examples, but in terms of building performance, are duct leakage, which is a metric that represents the airtightness of a duct system; specific leakage area, which is a metric that represents the airtightness of the building envelope; and house depressurization, which is a metric that represents the backdrafting potential for combustion appliances. These latter three metrics each has implications in terms of energy and indoor environmental performance. However, the importance of a particular metric to each performance objective may be weighted differently, and therefore each must be able to stand on its own.

  To assure whole-building performance, it is also necessary to consider the relationships between metrics for components and systems, due to interactions between systems and components (Koles et al. 1996 [241]). For example, it is necessary to quantify duct leakage, specific leakage area, and house depressurization to understand the impact that duct leakage flows can have on combustion safety in tight houses.

- *Norms*: A metric itself does not indicate good or bad performance. However, when quantified, each metric forms the basis for developing the norms against which component or system performance is compared. As with the metrics, the norms will vary depending on the objective of the commissioning. They will also depend on the stage of the house in its life-cycle.

  To understand what a norm is, again consider the pen. A norm in this case might be the length of a line of ink produced by a reference pen, it might be an average of the length of lines drawn by several pens, or it simply might be the general length of line that the user wants it to produce. For the metrics related to building performance, consider that various building standards specify requirements for maximum duct leakage, for minimum or maximum specific leakage area, and for maximum house depressurization levels. An example is the Title 24 norm that duct leakage be 6% or less of the nominal total airflow through the air handler.

- *Diagnostics*: Diagnostics are usually defined as relatively quick short-term field procedures involving measurements and perhaps analyses to evaluate performance metrics for a system or component under functional test or actual building site conditions. 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. Such 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.

To understand what a diagnostic is, consider once again the pen. The diagnostic to quantify the line length metric might be using a tape measure to determine how long a line the pen was able to produce. Once the line length metric is quantified with this diagnostic measurement, its value can be compared with the norm to determine whether the pen's performance is acceptable or not. From the building performance examples above, consider duct leakage. A possible diagnostic is to use airflow measuring equipment that creates and measures pressure differences, which can then be used in subsequent computerized analyses to calculate the duct leakage.

The same metrics and diagnostics can be used in new and existing houses, although some diagnostics may not be appropriate early in the construction process. However, the norms for existing houses will have to be adjusted to account for 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 Title 24 specifications for energy consumption. The retrofitting required to meet Title 24 insulation levels in this example would be prohibitively expensive.

The Commissioning Process

Even for commercial buildings, there is no universal or even dominant approach for commissioning. ASHRAE (1996 [30]) offers HVAC commissioning guidelines that are probably the most widely utilized in the United States. However, the focus of these guidelines is too narrow for the many projects that involve activities such as whole building commissioning.

Three other commonly referenced documents relevant to commercial building commissioning include:

- "Building Commissioning Guidelines" (PECI 1992 [316]),
- "Procedural Standards for Buildings Systems Commissioning" (NEBB 1999 [300]), and
- "HVAC Systems - Testing, Adjusting, and Balancing" (SMACNA 1993 [407]).

While the details of the commissioning procedures vary among various guidelines and procedures, most descriptions of commissioning for commercial buildings include the following three general steps:

1. *Develop Commissioning Plan*: The Commissioning Authority develops a plan that includes items such as the project schedule, construction contractor responsibilities, outstanding information requirements, component and system test procedures, monitoring requirements (if any), and building operator training.
2. *Execute Commissioning Tests*: The testing activities typically begin with pre-commissioning or inspection tests to verify that the equipment and controls are installed as specified. More sophisticated functional performance tests follow these inspections. These acceptance tests are intended to assess whether the installed system is adequate, the controls are properly calibrated and have correct control sequences, and that proper actions occur in response to predefined stimuli.

3. *Operations and Maintenance Summary and Training*: The Commissioning Authority reviews the training procedures and O&M manuals to ensure that proper attention is given to key issues. This step may also include periodic inspections and tests of the type described above.

Most of this discussion about commissioning commercial buildings is concerned with new construction. Many of the same principles and methods are equally relevant to commissioning of a retrofit or tuning up an existing building. In the case of an existing commercial building, the procedures can be modified to focus on identifying major O&M problems, or there may be an extensive "recommissioning", which generally refers to a systematic review of building systems to ensure they perform as desired. A good resource guide for commissioning existing commercial buildings is provided by DOE (1998 [119]). For these buildings, the basic process is again to outline how you think the building systems should be performing, conduct a series of tests and measurements to examine actual performance, and reconcile differences between expectations and reality.

Houses tend to be less unique from one another than is the case for commercial buildings. Also, few houses have operations and maintenance staff. As a result, developing a unique commissioning plan and O&M manual for each house may be unwarranted. In addition, it is anticipated that commissioning can sometimes provide better performance than is called for in the design. Therefore, the residential commissioning process as envisioned in this project is slightly different. It has three main phases that can probably be encompassed by generic guidelines geared to specific commissioning issues or system and component types:

1. *Audit and Diagnostic*: In the first phase of commissioning, the metrics for the house are surveyed using instrumented and non-instrumented techniques. The results of this survey are then compared with the norms for the house. For new construction, the norms will be those of the Title 24 compliance material or of the equivalent local building codes. For an existing house, the norms may be based on design intent (if any was ever documented) or on what a particular component should be able to do compared to other similar houses.

2. *Tuning and Tweaking*: The performance of many components and systems may not meet the norms, but it will 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 without repair or retrofit.

3. *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 should be further investigated. Even when components are performing to their norms, newer technology may make replacement worth considering.

What Needs to Be Commissioned?

The most critical items to commission in commercial buildings are the dynamic systems, especially the Energy Management Control Systems (EMCS), and other HVAC equipment. Lighting controls are equally as important to commission. Some Commissioning Authorities and building owners include many additional systems in commissioning. These can include static systems such as the building envelope, as well as non-energy systems such as life safety and plumbing equipment.

There are also many components and subsystems of a house that need to be examined in the course of residential commissioning. For houses, the seven key performance areas of current concern in California are as follows: Building Envelope, Cooling Equipment and Heat Pumps, Air Distribution Systems, Indoor Air Quality, Combustion Appliances, Controls, and Other Electrical Appliances.

- *Building Envelope*: The building envelope is more important to the performance of a house than it is to that of a commercial building, because unlike commercial buildings, the envelope loads instead of internal loads dominate the house heat transfer mechanisms. Assumed thermal loads, equipment sizing, structural durability, and occupant comfort for houses are based on having the building envelope perform as intended, including windows, air tightness, and insulation levels. In new houses, installation failures, especially in insulation and air sealing, can cause problems. In existing houses, subsequent loss of durability can also decrease performance. Poor material selection and installation (e.g. insulation settling, air barrier damage from UV exposure) can result in performance reductions over time.

- *Cooling Equipment and Heat Pumps*: Even in new houses, cooling systems rarely perform as intended (Sherman et al. 1987 [401]). Refrigerant charge levels, airflow across coils, and other operating conditions often do not meet manufacturers specifications used in the system design. As a result, the capacity and efficiency of the equipment is degraded. Heat pumps share many of the same problems associated with cooling systems, but have some unique features. Use of electric resistance ("strip") heaters can significantly increase energy consumption. Heat pump (and desuperheater based) water heaters require careful integration into the whole-building to be successful.

- *Air Distribution Systems*: 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 [223]). Duct leakage, duct insulation compression, and other poor installation practices can reduce duct efficiency by 30% from even a moderate level of design performance. 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, some houses use whole-house ventilation as well, which is sometimes directly linked to the space conditioning system. The delivery effectiveness and room by room distribution efficiency of both the thermal and ventilation distribution systems thus depends on the proper flow of air through the air moving equipment. Poor operation of the air distribution systems can cause comfort problems, structural moisture problems, and poor indoor environmental quality, as well as wasted energy.

- *Indoor Air Quality*: Related to the performance of thermal and ventilation distribution systems is a host of indoor air quality issues that apart from the airflows themselves include the generation, transport, and removal of pollutants. Examples of pollutants in houses include gaseous ones such as carbon monoxide and nitrogen oxides; biological ones such as molds, fungi, and mites; and particulates such as dust.

- *Combustion Appliances*: In addition to fuel-related issues for these kinds of appliances, poor operation of vented and non-vented appliances can reduce their efficiency and indirectly affect electricity usage. Fueled appliances must vent as intended. Poor installation of either the combustion equipment or air moving equipment can also reduce efficiency and lead to backdrafting and combustion gas spillage or other hazards. 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.

- *Controls*: In commercial commissioning, control problems are the key item of concern. While not as important in residential houses, controls can still play an important role, especially when the systems become complex (e.g. multistage systems, integrated heat-pump/ventilation systems) Even common heating setback / cooling setup thermostats need to be properly commissioned. Making sure that these controls are doing what was intended or is appropriate is often crucial to achieving good energy performance.

- *Other Electrical Appliances*: Apart from the HVAC system, there are many other electrical appliances in the house. Some of them (e.g. stoves, water heaters, refrigerators, clothes dryers) can be quite large consumers of electricity. Improper configuration of some appliances (e.g. clogged dryer vent) can cause poor performance. Most of these appliances require only simple commissioning.

Although only some of these facets of commissioning may need to be examined in each instance, it is important to recognize that they are not mutually exclusive and many of them interact. Therefore, the commissioning procedure must not only identify the energy and non-energy benefits associated with improving the performance of each component, but it must also indicate how these individual savings interact in the complete building system.

Costs and Benefits of Commissioning

The most common question after "what is commissioning?" is "what are its costs and benefits?". There are two ways to answer this question. Ideally, we would develop an answer by examining existing case studies of commissioning that describe how much was spent and quantitative assessments of the benefits. Unfortunately, these case studies are somewhat limited, especially those that quantify the benefits, even for commercial buildings.

An alternative method of answering the question is to examine hidden costs involved in *not* commissioning. The type of benefits one receives from commissioning includes items such as improved energy efficiency, better operations and maintenance, fewer change orders, and improved air quality. Heinz and McCray (1996 [210]) presented an

excellent discussion of how a university engineering staff improved the commissioning process as they moved from their first to their second, third, and fourth building project. They suggest that the costs to commission a building are far less than the hidden costs that occur in cases where buildings are not commissioned.

Over the last few years, significant energy savings have been demonstrated by correcting problems in existing commercial buildings. For example, research at Texas A&M (Claridge et al. 1998 [76]) has found that in almost all older commercial buildings, and even in many new buildings, use of the building is quite different from the original plan. Consequently, they developed a process of "continuous commissioning" that tunes the systems of the building for optimal comfort and peak efficiency based on the current use. Implementing that process has saved an average of over 20% of the total energy cost (over 30% of the heating and cooling cost) in more than 80 buildings in which it has been applied. Simple payback times under two years were achieved in nearly all of the 80 buildings.

Piette and Nordman (1996 [327]) carried out a study on the energy savings achievable with utility-funded commissioning of energy-efficiency measures in new buildings. On average, they found that commissioning costs of about \$0.20/ft^2 were marginally cost effective based on energy savings alone. These low costs were based on limiting the scope of the commissioning effort to only the energy-efficiency measures. Whole-building commissioning of all major energy-using systems would likely be even more cost effective.

For houses, one example of the energy savings potential of correcting problems during commissioning is sealing leaky ducts. Field tests and existing simulation tools have shown that about 15% (new construction) to 20% (existing houses) of the energy consumed to heat or cool a California house could be saved in this manner. Taking the conservative estimate of 15% savings, this is equivalent to about 7 x 10^{15} J (or 7 Trillion Btu) if applied to all California housing. Associated reductions in peak demand are higher than these seasonal average values, and are typically about 25%. The 15% savings in cooling costs correspond to about \$42 per year of the \$700 average annual residential electricity bill in California. These savings estimates are based on field data measured by LBNL and other researchers, as well as on data from the CEC (1995 [65]), Energy Information Administration (1999 [137]), California Department of Finance (CA State 1999 [63]), and F.W. Dodge (1996 [112]).

In general, improvements in indoor air quality and other non-energy benefits may be even more important than the energy saving benefits from commissioning. For example, the health, safety, and productivity of building occupants can be improved by ensuring there is proper airflow in the building (Sterling and Collett 1994 [413]). In office buildings, energy costs are around \$1 to \$2 per ft^2 per year, while salaries of employees are two orders of magnitude greater. From a simple economic standpoint, clearly the ultimate concern should be the health and productivity of the occupants, both in these offices and in their homes. Showing quantified occupant productivity gains due to a well commissioned building compared to a building that is not commissioned is extremely difficult. However, many case studies have shown that the types of problems found during commissioning result in sub-optimal or unhealthy conditions for occupants when left uncorrected.

Who Should do the Commissioning?

In addition to the important questions of "what is it?" and "how much does it cost?", a common question is "who is qualified and who should do it?" The most common method for commissioning commercial buildings today is to hire an independent third party (Commissioning Authority) to lead the commissioning effort. The independence allows the Commissioning Authority to maintain neutrality and avoid conflicts of interest, which is difficult if the design team also does the commissioning.

In spite of the benefits of independence, many design engineers argue that they are the best qualified to conduct the commissioning. One reason is that they are closest to the design. A second is that they understand the functional intent. A third reason is that they believe they should be involved in defining and performing test sequences. A problem with this arrangement is that the design team is less interested in uncovering design problems that an independent party might more fully explore.

Even when the Commissioning Authority is an independent third party, the job can be complicated by design problems. For example, the Commissioning Authority is supposed to ensure that the installed system functions in an optimal fashion, but is in a quandary when problems with the original design are found during that process. Commissioning Authorities are not usually responsible for the design. Therefore, to facilitate feedback to the designers on how building systems actually perform, the Commissioning Authority should be engaged early in the process.

Other problems can arise in commissioning when the Authority does not become involved until late during the design or early in construction. An example is that the collection of information (such as design specifications and drawings) required to perform commissioning is more difficult later in the process. Another example is that late scheduling of tests into a typically rushed and inflexible construction and start-up schedule is more difficult and therefore more expensive.

Many of these principles apply to houses as well, even though they are not typically "designed". Likely parties who will be involved in residential commissioning include the State through statewide energy codes, home energy raters, home inspectors, auditors, and weatherization contractors. Other parties involved may include utilities, realtors, financial and insurance institutions, and environmental groups. If independent parties are required in this process, then the contractors will not carry out commissioning themselves, but they would receive feedback from the others who do carry out the commissioning. Alternatively, the contractors might also do commissioning, if a certification and audit process is developed to ensure commissioning quality.

LITERATURE REVIEW APPROACH

This report is meant to be a stand-alone document to facilitate access to existing literature related to residential commissioning. Until now, there has been no single document that summarizes the readily available literature related to this issue.

Many literature sources were accessed, including:

- American Council for an Energy-Efficient Economy (ACEEE) conference proceedings.

- Air Infiltration and Ventilation Centre (AIVC) technical notes and conference proceedings.
- American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) IAQ conference proceedings; ASHRAE International Journal of HVAC&R Research; ASHRAE Journal, Standards, and Transactions; and ASHRAE Thermal Performance of the Exterior Envelopes of Buildings conference proceedings.
- ASTM Standards and special publications.
- California Energy Commission (CEC) standards and statistics documents.
- Canadian General Standards Board (CGSB) standards.
- Home Energy magazine.
- Indoor Air conference proceedings.
- Lawrence Berkeley National Laboratory reports.
- National Association of State Energy Officials (NASEO) home energy rating guidelines.
- Portland Energy Conservation Institute (PECI) commissioning conference proceedings and guidelines.
- U.S. Department of Energy (DOE) commissioning documents and home energy rating guidelines, as well as the DOE International Performance Measurement & Verification Protocol.

Apart from these sources, a search of the Internet was carried out to locate relevant documents and websites.

In searching for documents, we developed and used a set of keywords to locate information relevant to commissioning. Specifically, the search focused on metrics, diagnostics, and norms for components and systems that can be inspected to verify conformity with a specification, that can be "tweaked" or tuned during a residential commissioning process, or that can be modified later to improve the energy and indoor environmental performance of a house. Based on these principles, an outline of relevant issues was developed to guide the search and to help categorize reviewed documents. That outline is attached as Appendix C.

Emphasis was placed on locating documents published over the past 20 years, which represents the period of time over which building commissioning and closely-related issues have been actively reported.

SUMMARY OF RELEVANT METRICS, DIAGNOSTICS, AND NORMS

To commission the components and subsystems in California houses, we have preliminarily identified the following metrics, diagnostics, and norms as being relevant. This list is not static and is subject to modification as further information becomes available. Not included in the list below are standard measurement techniques, such as those for determining house geometry or for measuring temperature and pressure. The

summary in each category is brief and does not include many references. The annotated references in Appendix A provide more detail.

Building Envelope

- *Metrics*: The literature reports several metrics of interest for commissioning the building envelope. A common one is the thermal conductance of individual windows and opaque elements, which is often denoted by the assembly R- or U-value. In its simplest form, the conductance metric is the insulation level and location. The insulation level can be defined in terms of its type, thickness, and/or density. Other related qualitative metrics include the presence of anomalies such as missing insulation, insulation settling in a wall, or uneven distribution over a ceiling. Christian and Kosny (1995 [73]) have refined the conductance metric for wall sections using terms such as center-of-cavity (not including framing or additional elements such as doors or windows), clear-wall (including framing but no additional elements such as doors or windows), and whole-wall conductance (including framing, doors, and windows). Window radiative behavior can be described by metrics such as emittance, solar heat gain coefficient, daylight transmittance, and UV transmittance. Subbarao et al. (1985 [418]) have attempted to combine the thermal conductance and radiative behavior by characterizing the long-term thermal performance of the entire building using two short-term parameters: building heat loss coefficient for conductance and equivalent clear aperture area for solar radiation. Saunders et al. (1994 [363]) defined a similar metric (building load coefficient), but included infiltration as well.

  The airtightness of the building envelope elements, both at the component level and together as a system are often described in the literature. They can be characterized by terms such as airflow or air change rate at a standard pressure differential (e.g. CFM50, CFM25, ACH50), or by effective leakage area (e.g. ELA4). In some cases, the intermediate parameters of equations used to calculate these metrics are used instead. They include terms such as the flow coefficient and pressure exponent. The airtightness metrics are sometimes normalized by floor area and/or building height to allow comparison between buildings. Normalized terms include specific leakage area, normalized leakage area, and leakage class. In rare cases, economic factors are included with the airtightness metrics (e.g. $/CFM50). Another simple metric of interest with respect to airtightness is air barrier type and location. Many of these metrics can also be applied to describe the airtightness of interzone elements such as interior partition walls and doors, when that airtightness is of interest.

  There are virtually no metrics described in the literature to characterize thermal mass in relation to the building envelope. One is the time constant of the building (Sonderegger et al. 1981 [409]), which represents how quickly internal temperatures within a building assembly respond to an external change in temperature or heat flux. Two others are capacity and availability. Capacity represents the maximum amount of thermal energy that can be stored or released due to a uniform change in temperature of the building assembly. Uniform temperatures are not achieved instantaneously, which leads to thermal gradients within a building assembly. This means that only part of the assembly is thermally charged or discharged initially.

Availability represents the fraction of the capacity that remains available to store or release heat at any given time.

In terms of moisture-damage susceptibility, there are also few metrics and they are not commonly referred to in the literature we reviewed. Simple qualitative metrics include visible wetness or degradation of interior or exterior finishes and structural components. Degradation can include staining, streaking, mold or fungal growth, and wood rot. More complex and quantitative terms used by researchers involved with this issue include vapor partial pressure, condensation potential, mass of condensed water, surface water activity, water intrusion rate, diffusion path length, drying potential, and moisture content.

- *Diagnostics*: Standard techniques for evaluating the performance of the building envelope are often described in the literature. The simplest technique is visible inspection during construction, which can include thickness measurements and sample extractions of the insulation to assess its density. This technique can also be used for some ceilings and floors after construction. However, more complex techniques are generally required after construction to avoid dismantling envelope components such as walls. These techniques include infrared thermography combined with blower door pressurization to evaluate leak location and insulation homogeneity. Aerial thermography has also been used to rank roof insulation levels of buildings (Burch 1980 [61]) in broad surveys. Other techniques for assessing assembly conduction heat transfer include the use of non-contact spot radiometers, contact heat flow transducers, portable calorimeters, and guarded hot boxes. The latter two devices are better suited to laboratory use. An adaptation of the guarded hot box called the Envelope Thermal Test Unit (ETTU) has been developed for use in the field by Sonderegger et al. (1981 [409]). Three-dimensional simulation of building envelope elements has also been used to evaluate thermal conductance (Christian and Kosny 1995 [73]).

  Janssen and Rasmussen (1985 [219]) developed a complex technique for determining the thermal conductance of the entire envelope. It relies upon temperature decay and rise during one- to two-hour-long furnace off and on periods respectively and the elimination of infiltration effects. Those effects are removed using infiltration diagnostics during the temperature decay and rise periods and using subsequent calculations. Sandberg and Jahnsson (1995 [361]) describe a similar technique that does not involve furnace cycling. Instead, it characterizes the total heat loss rate of a house as it is normally operated by its occupants. Actual indoor-outdoor temperature differences and energy consumption are measured. Average heat loss per unit temperature difference is calculated from these data. Saunders et al. (1994 [363]) also describe a related technique that is based on coheating. That technique involves maintaining constant indoor air temperatures using electric heaters and continuously measuring the input power for the heaters. Unlike Sandberg and Jahnsson, Saunders et al. remove infiltration effects. As a result, their technique separates out thermal conductance and is more useful for describing heat transfer characteristics at times other than just during the test.

  Standard techniques for determining airtightness such as blower door pressurization are frequently described. Alternative techniques such as AC pressurization and pulse

pressurization also exist, but are impractical for residential commissioning. The literature also describes techniques that use balancing fans (two blower doors operated simultaneously) or leakage variations to determine interzone and series leakage, such as between living spaces and the attic or between adjoining dwellings. In terms of air barrier location, blower doors can also be used to establish the boundaries of the pressure envelope (Fitzgerald et al. 1994 [153], Cummings 1998 [94]). Many of these techniques are already automated using computer-controlled fan speed and pressure sensing. Some of the literature focuses on issues surrounding test accuracy, such as single point versus multipoint tests. To identify leak locations, techniques other than using infrared thermography are available. They include the use of a blower door and smoke, tracer gases, draft sensation, anemometry, or in some cases acoustic transmitters and sensors (ASTM 1995 [38]).

To determine the emittance of windows, a prototype portable spectrometer is available (Griffith 1999 [181]). Well-developed simulation software is also available to characterize window performance, once the properties of the windows are known.

No diagnostic methods were found to quantify envelope thermal mass, except for the ETTU device developed by Sonderegger et al. (1981 [409]). That device has been used to evaluate the time constant metric for walls. A similar technique has been developed by Roulet et al. (1985 [356]).

Diagnostics for assessing moisture-damage susceptibility are less well developed. In particular, most diagnostics that were found can only evaluate the presence of moisture, rather then the susceptibility to moisture-damage. Thermography has been suggested as a way of assessing wet insulation (Knehans and Styer 1983 [238]). Moisture content of building assemblies can be measured using resistive- or impedance-type electrical devices or by determining weight changes due to drying extracted samples of insulation (NAHB 1997 [293]). Impermeable or absorbent materials can be placed over envelope sections and then, after a fixed period of time, can be visually inspected for wetness or weighed to determine absorbed moisture (Lichtman et al. 1999 [252]). To evaluate moisture-damage susceptibility, checklists can be used in visible inspections of likely defects that may lead to future damage. Computer simulations can be used to assess the condensation potential of windows.

We are quite familiar with all these technologies and no development in this area is anticipated. Because some envelope diagnostics are impractical in a commissioning environment, visual inspections will often play a key role.

- *Norms*: Most of the norms relevant to building envelopes are contained in Title 24 and ASHRAE Standards. Some are also contained in home energy rating guidelines. These norms include specifications for R- or U-values for opaque assemblies and for windows, solar heat gain coefficients, interior thermal mass, and whole-building airtightness.

  There are a few references in the literature in addition to these documents that provide norms for opaque assembly conductance and for whole-building airtightness. In particular, there are large sets of data describing the airtightness of houses. Some of these datasets have been correlated with building type, wall construction, and climate.

Other than the thermal mass capacity estimates for slabs and whole buildings in Title 24, no norms related to the thermal mass of the envelope itself were found.

No norms other than inspection checklists for envelope defects and a few data from moisture conductance surveys were found that are related to moisture-damage susceptibility.

Cooling Equipment and Heat Pumps

- *Metrics*: Steady-state performance characteristics for air conditioners (and to some extent for heat pumps) are often referred to in the literature in terms of capacity and efficiency. Capacity is usually referred to in terms of the name plate rating or the ARI rating, but is sometimes called the "installed" capacity. A related metric is the required capacity that is determined using load calculations and that is used to size equipment. These capacities can represent the system as a whole or its components (e.g. evaporator, condensing unit). Common metrics associated with the efficiency issues are the energy-efficiency ratio (EER) and seasonal energy-efficiency ratio (SEER). A less common one is the integrated part load value (IPLV). For heat pumps in cooling mode, the term coefficient of performance (COP) is also a common metric. To account for equipment, installation, and operation deficiencies, Neal (1998 [298]) has proposed the use of another metric: field adjusted SEER (SEERFA). One other metric referred to is simply total electricity consumption over a fixed time period.

  Heat pumps also provide a heating function. That performance can be characterized by the heat pump seasonal performance factor (HSPF). Associated with this type of performance are common metrics used for other space heating equipment such as furnaces and boilers. These metrics include steady-state and seasonal combustion efficiency. Regardless of heating equipment type, an important metric is the heat exchange efficiency, which is the ratio of the duct energy input to the total energy input to the equipment (Walker et al. 1998 [453]).

  Because refrigerant has such an important impact on performance for cooling equipment and heat pumps without thermal expansion valves, its level or charge within the system is a metric in itself. Coil volume and refrigerant line length are related metrics, because they affect the amount of refrigerant that a system requires.

- *Diagnostics*: The steady-state capacity and efficiency of an air conditioning unit (or heat pump) can be measured under a single set of environmental conditions occurring at the test time. There are few diagnostic techniques currently described in the literature. Most are based on laboratory tests, which may be too complex and time-consuming for commissioning. Some field tests to estimate performance metrics are available, but they also involve complex measurements. An example is the use of the REGCAP performance simulation software to evaluate performance metrics by interpolating within equipment manufacturer's performance data (Walker et al. 1998 [453]). A second example is the use of electric coheating to determine cooling efficiency (Sonderegger et al. 1980 [411]). A third example is the use of motor current signature analysis to correlate motor startup current waveforms to COP, as well as to refrigerant charge level (Miller et al. 1989 [272]).

Refrigerant charge is known to have a significant impact on equipment performance. Several methods other than the one described above are available to assess the charge level. They include simple methods such as using temperature and humidity measurements, refrigerant gauge pressures, and lookup tables in superheat and subcooling tests, as well as the “approach” tests for Lennox equipment. More elaborate methods include software packages such as "Check-Me" that automate these methods and often can be used to find combined performance. An even more complex method to check charge level is to evacuate the system, weigh the removed charge, and then replace the charge into the system. This latter approach has the problem however that the amount of charge that should be in the system is unknown due to the use of evaporator coils that differ from that intended by the system manufacturer.

Modifications to these extant methods will be needed to make such diagnostics more practical in terms of equipment and time constraints.

- *Norms*: Most of the norms relevant to cooling equipment performance are contained in Title 24 and ASHRAE Standards. They include norms for EER, SEER, COP, HSPF. Title 24 also includes norms for integrated part load value (IPLV) for unitary air conditioners and heat pumps. Some norms, such as SEER, are also described in Energy Star literature. Norms for equipment sizing (in the form of sizing criteria) are contained in ACCA Manual J (Neal 1998 [298]).

  The applicability of manufacturer specifications as a norm is questionable, given that mismatched indoor coils are installed in some cases. Beyond these specifications, there are no norms for refrigerant charge level.

Air Distribution Systems

- *Metrics*: There are numerous metrics related to the thermal performance of residential air distribution systems, most of which have been developed over the past ten years. These metrics include delivery effectiveness and distribution system efficiency, both on a design condition basis and on a seasonal basis. Other related metrics include duct leakage flows (e.g. CFM25, CFM50), duct leakage class, effective duct leakage area (e.g. ELA4, ELA25). These duct leakage metrics can be subdivided into leakage to indoors and outdoors, as well as into return, supply, cabinet, and register boot components. Thermal regain (ASHRAE 1999 [32]), “tons at the register”, which is a measure of enthalpy flow delivered at each register (Walker et al. 1998 [449] [453]), as well as airflow and pressure drop within a duct, are also relevant metrics. Other metrics include power delivered to the duct system, power lost from supply ducts due to conduction and leakage, and fractional conduction loss (Walker et al. 1996 [446]).

  Ventilation-related metrics are similarly numerous, and have been developed over a longer period (about 20 years). Many can be used at component, room, or whole-house levels. They include metrics such as ventilation airflows and air exchange rates, temporal and spatial ventilation effectiveness and efficiency, and indoor-outdoor and interzonal pressure differentials. Some of these metrics can be subdivided. In particular, the temporal distribution of air within a room or entire house can be represented by metrics such as age of air, turn-over time, and effective

ventilation rate. CO_2 levels indoors are sometimes used as a surrogate metric to quantify ventilation adequacy, but may be inappropriate when there are other pollutants of concern within the house. Ohnishi et al. (1998 [308]) has defined three metrics to describe whole-house ventilation performance: supply rate fulfillment, exhaust rate fulfillment, and overall ventilation rate fulfillment. An additional metric useful to discussing infiltration-based ventilation airflow potential is infiltration degree-days (IDD). Parameters used in infiltration or ventilation simulation models also represent metrics that can be used to characterize how a house will perform in terms of ventilation. Such terms include surface pressure coefficients, as well as terrain and shielding parameters, all of which are related to wind effects.

Several metrics represent the performance of heat recovery devices in ventilation processes. These include terms such as sensible, latent, and total energy recovery effectiveness; sensible and total heat recovery efficiency; temperature ratio; ventilation reduction factor; and exhaust-air-contamination ratio.

- *Diagnostics*: The performance of both the cooling and ventilating systems depends on airflow through the air-moving equipment. A flow measurement technique involving a calibrated perforated metal plate is being developed with DOE STTR funding for use in measuring the total flow through air handlers. Other devices and procedures are already in use to carry out this measurement. They include the use of pitot-tube traverses, tracer gas methods, or calibrated fans such as “duct blasters” and static pressure measurements at representative locations in the air moving system. In some cases, extrapolation of flow measurements to operating static pressures is necessary when the flow measuring fans have insufficient capacity. Commercially-available flow balancing stations are also available, but are impractical unless installed permanently in the air distribution system. Other techniques can be used that contain simplifications, such as those in ASHRAE Standard 152P (Andrews 1996 [5], ASHRAE 1999 [32]). The simplifications include using the fan curve (if known) and pressure difference measurements to estimate the airflow instead of directly measuring it.

  Delivery efficiency and room by room distribution system effectiveness cannot be measured directly. Instead, they are calculated using the system flows described above, along with other diagnostic inputs such as duct location, surface area, and thermal resistance (obtained through a combination of observation and simple calculation), duct leakage (described below), and by determining the flow for each branch of the duct system. Airflow measurement using flow hoods (some of which are fan-assisted), vane or hot-wire anemometer samples, or simple inflation of a plastic bag of known volume are standard techniques for determining register flows. Some optimization may be necessary to make them more practical for the specific intended purpose. Andrews et al. (1996 [6]), as well as Siegel and Davis (1998 [403]) have suggested that coheating can be used to measure system efficiency before and after retrofits, but this technique may not be practical for commissioning. Airflows through individual ventilation devices can also be verified using the measurement techniques applied to thermal distribution systems.

  Air leakage for duct systems is a key factor in determining their performance. There are currently several documented diagnostic options. One suggested method relies

only on visual inspection, but this is unlikely to be adequate in many houses due to concealed duct systems. The others include using one or more calibrated fans such as blower doors and "Duct Blasters", as well as static pressure measurements at representative locations in the air moving system. Specific methods include the duct pressurization test ("Duct Blaster" test), the pressure pan test, the house pressure test, the nulling pressure test, and the delta-Q test (relies on differences in blower door flows with and without pressurization of the envelope by the air handler). The first test has the disadvantage that almost all registers need to be sealed to determine duct leakage. In the house pressure test, the return grille also needs to be partially or fully blocked for some parts of the test. Some of these tests also require more equipment and time than others, and all have some potential problems as documented in much of the literature on this subject. This is an active area of research and may require further development to be applied to commissioning.

Apart from simple pressure differential measurements, the literature reports a novel technique for determining pressure drop and assessing flow obstructions in ducts using acoustical methods (deSalis et al. 1996 [105]).

There is a substantial body of literature from the past 20 years related to determining room and whole-building air exchange rates, as well as ventilation effectiveness and efficiency. Most techniques rely upon the use of tracer gases in decay tests, constant concentration tests, or constant injection tests. Some of the techniques also use multiple tracers to determine interzone air exchange rates. All these techniques are problematic for determining ventilation effectiveness and efficiency of mechanical ventilation systems in houses, because they include infiltration effects that these metrics assume can be ignored. Two novel techniques that may help solve this problem rely upon video techniques to analyze either smoke transport or helium-filled zero-buoyancy balloon motion indoors (Ohba and Irie 1999 [307], Berckmans et al. 1993 [50], Pickering et al. 1987 [326]).

- *Norms*: Norms for duct thermal performance, including duct effectiveness and distribution system efficiency, are largely contained in Title 24 and ASHRAE Standard 152P. SMACNA standards, Title 24, and some home energy rating system guidelines (Cummings 1998 [94]) also contain norms for duct leakage. Treidler et al. (1996 [432]) report norms for duct insulation.

  Ventilation and air exchange norms are largely represented by Title 24 and ASHRAE Standard 62, although the latter are currently being revised to provide specific requirements for houses (ASHRAE Standard 62.2). The literature reviewed contains considerable amounts of field data on infiltration, but those data are for older homes and are likely not applicable to newer construction. Limited data are available to serve as norms for residential ventilation effectiveness and efficiency (Sherman 1989 [387], Sherman et al. 1989 [379], Matson and Feustel 1998 [263]).

Indoor Air Quality

- *Metrics*: Indoor air quality (IAQ) is a broad concept that can encompass thermal comfort issues, as well as the behavior of pollutants such as non-biological gaseous

ones (e.g. carbon monoxide, nitrogen oxides, formaldehyde, radon), particulates (e.g. dust), bioaerosols (e.g. molds, fungi, mites), and moisture.

Metrics for thermal comfort include room air temperature, radiant environment temperature, and room air velocity. Spatial asymmetry and cyclic or non-cyclic drift rates of these temperatures are other metrics related to thermal comfort. Another related metric is relative humidity. Metrics that combine several parameters in attempts to quantify occupant satisfaction with the indoor thermal environment include operative temperature (ASHRAE 1992 [23]), the "Overall Liking Score" of Levermore et al. (1999 [250]), standard effective temperature, predicted mean vote, and predicted percent dissatisfied. Pulldown time is another metric associate with thermal comfort (Walker et al. 1998 [453]). It represents the time it takes to reduce the air temperature to an acceptable level after cooling startup, such as when occupants return home on a hot summer afternoon.

For pollutants, generation rates (e.g. emission, desorption), concentration, level, index, and removal rates (e.g. sorption, absorption, deposition) are relevant metrics. Literature on specific metrics for the generation and removal of pollutants is sparse or non-existent, other than to describe pollutant sources in general. Most metrics reported in the literature for pollutants are in the form of a pollutant level or index. Depending on the type of pollutant, these metrics may be in standardized units of PPM, mass per unit volume of air, colony forming or biological units per unit volume, mass of allergen per unit of particulate, particulate mass deposited per unit area, and number of mites per sample sheet. Most of these metrics represent an integrated quantity over a desired period of time. Moisture itself has several well-known metrics that include vapor partial pressure, relative and absolute humidity, humidity ratio, and dew-point temperature. Related metrics are condensation potential for windows and surface water activity (Flannigan 1992 [156]), both of which provide an indication of the availability of moisture for microbial growth. Moschandreas and Sofuoglu (1999 [289]) have suggested an "Indoor Pollution Index" metric that attempts to sum the effects of multiple pollutants to determine their synergistic effect.

- *Diagnostics*: Because the cooling distribution system can induce changes in indoor air quality (both in terms of thermal comfort and pollutant behavior), some diagnostics are needed in this area.

  Some comfort diagnostics involve no measurements and only checklists or occupant satisfaction surveys. The surveys are not simple. They involve analyzing and interpreting human behavior, which can be difficult, as is good survey design to avoid biasing the results. More elaborate schemes monitor room air or radiant environment temperatures using simple portable data loggers as the space conditioning system operates. In some cases, these loggers also contain switches for occupants to record their comfort satisfaction. Temperature sensors can include aspirated shielded thermocouples or thermistors to measure room air temperature, globe thermometers that measure mean radiant temperature (MRT), or more sophisticated Kata probes that measure air motion effects. Vane or hot wire anemometers can also be used to measure air motion. Other related techniques include using a low thermal mass, porous fiberglass screen and infrared thermography to determine room air

temperature distribution (Hassani and Stetz 1994 [207]). Humidity can be measured using a simple sling psychrometer (dry- and wet-bulb thermometer pair), an aspirated psychrometer, an electronic capacitive relative humidity sensor, or a dew-point hygrometer. Some development in the area of comfort diagnostics is anticipated to provide a simple rapid technique for characterizing the performance of each room in a house.

Standard techniques for measuring pollutant levels include grab sampling or passive pollutant sampling. As with the pollutant metrics, the sample technique used largely depends on the pollutant of interest. In some cases, automated samplers such as for carbon monoxide may be used. In other cases, the sampling equipment can be very sophisticated and expensive (e.g. portable gas analyzers for nitrogen oxides), which may reduce the likelihood that the technique would be used during commissioning (except perhaps by an IAQ commissioning specialist). Particulate sampling includes techniques such as vacuum collection and sampling tape or paper, with subsequent microscopic inspection to determine particle size and number. Other simpler assessment methods are available that simply determine total particle mass for the collected sample or that are based on optical transmission through the sample. Most of the techniques for bioaerosols involve field sampling and then subsequent culturing and laboratory analysis. Computer simulations can be used to assess the condensation potential of windows. In terms of diagnostics for pollutant generation or removal, it is likely most techniques will be limited to simple observation during commissioning. LBL is familiar with all these technologies and no development in this area in anticipated.

- *Norms*: Norms for thermal comfort are largely embodied within ASHRAE Standard 55. That standard defines temperature, air motion, and relative humidity limits to represent the range of comfort that 80% or more of occupants in a space will find acceptable, excluding the possible synergistic effects of pollutants other than moisture in the space.

  For pollutants, the literature reports several norms for pollutant levels, depending on the pollutant of interest and the jurisdiction. Most are summarized within an appendix of ASHRAE Standard 62. Nagda et al. (1987 [292]) report norms for many pollutants as well. Other than Energy Star requirements that a building should be free of microbiological sources (EPA/DOE 1999 [140]), no norms for pollutant generation or removal were found in the reviewed literature.

Combustion Appliances

- *Metrics*: As with air conditioners and heat pumps, steady-state performance characteristics for combustion appliances are also often referred to in the literature in terms of capacity and efficiency. The capacity metric is the name plate output rating, but these appliances are often referred to in terms of their burner “input” capacity. A related metric is the required capacity that is determined using load calculations and that is used to size equipment. Common metrics associated with the efficiency issues are the steady-state combustion efficiency, the annual fuel utilization efficiency (AFUE) for space heating equipment, and the Energy Factor (EF) for water heating

equipment. The Energy Factor includes other water heater metrics such as standby losses, recovery efficiency, and the tank volume.

Familiar metrics for installation and operation of combustion appliances include safety issues such as clearance to combustibles, vent sizing, and outdoor air flow rates to support combustion. Performance metrics that describe the ability of an appliance to properly vent its combustion gases or conversely its potential for backdrafting and spillage of these gases into a house are less familiar. They include house depressurization or the draft (pressure differential) in the attached vent. These metrics can apply either to startup (cold flue) conditions or to steady-state operation. For the startup case, a particular metric is the cold-vent establishment pressure (CVEP), which represents the maximum indoor-outdoor pressure differential against which the hot combustion gases from the combustion appliance can establish a proper flow through the vent.

Two other important metrics involved with this issue are the concentrations of carbon monoxide and nitrogen dioxide in the combustion gases. If the appliance backdrafts, exposure to elevated concentrations of carbon monoxide indoors can be lethal to occupants, while exposure to nitrogen dioxide can lead to chronic respiratory problems.

One other relevant metric is heat exchanger leakage, which involves the direct leakage of combustion gases into the space conditioning air flowing through the air-handling unit. This metric is more important for commissioning existing houses than for new houses. However, it may be desirable to check new equipment to detect manufacturing defects.

- *Diagnostics*: Diagnostic methods to assess the fuel-related performance of combustion appliances are well developed. They include temperature and carbon dioxide measurements to assess burner efficiency. Pressure differential measurements are used to adjust operating fuel pressures. Visual inspection is also used to assess flame conditions. Steady-state capacity can be derived using simple methods such as gas meter “clocking”.

  Methods to address backdrafting and combustion gas spillage are less well developed. These methods are principally contained within two documents (CGSB 1995 [67], ASTM 1998 [42]). Several methods with slight differences are used. The house depressurization test involves measuring the indoor-outdoor pressure differentials created by operating various combinations of installed air-handling equipment (for space conditioning and ventilation) and combustion appliances (off and then on). The downdrafting test involves similar conditions, but all combustion appliances are off and there is no measurement. Only simple observation (yes/no) is recorded of whether the appliance backdrafted. The appliance backdrafting test involves similar conditions again and involves determining how long it takes for the appliance to establish a draft after the combustion appliance is turned on. It requires that the combustion vents be cooled by house depressurization before the timing begins. The cold vent establishment pressure test (CVEP) involves similar conditions to the latter test and requires measurement of the indoor-outdoor pressure differential. In addition, it induces these pressure differentials with a blower door to identify the limit

at which an appliance begins to backdraft under operating conditions. The ASTM document describes all these tests; the CGSB document only describes the first.

An additional method is reported in the ASTM document and in part by Fugler (1989 [171]). The ASTM method involves continuous monitoring of vent differential pressures, air temperature at the draft hood rim, carbon monoxide and dioxide concentrations, and appliance operation status over the period of about a week or more under natural conditions. The method reported by Fugler involves only the temperature monitoring. Although both methods provide definitive measurements of performance during the monitoring period, they are impractical for commissioning and do not necessarily identify houses at risk of backdrafting and spillage under all conditions.

All of the backdrafting and spillage tests are problematic, because they are susceptible to signal noise from wind effects, which can easily make the test results meaningless. Further development of these tests is required to make them usable and reliable during commissioning.

Measurement of carbon monoxide and nitrogen dioxide in the combustion gas can use the same diagnostics as for indoor air quality, although equipment may need to be more robust due to the higher temperature associated with sampling these hot gases. Oberholtzer (1993 [304]) provides a chimney inspection protocol that includes draft and carbon monoxide testing, as well as the use of a video camera to inspect the interior of the chimney.

DeWerth and Sobieski (1985 [109]) have described a three-step diagnostic method to detect combustion gas leakage in heat exchangers. It relies upon visual inspection of the heat exchanger, observation of burner flame patterns, and the use of tracer gas. Other less reliable methods exist, such as using smoke, salt spray, or odors as tracers to detect leakage.

- *Norms*: Most of the norms for fuel-related performance of combustion appliances are contained in Title 24, ASHRAE Standards, and building codes. They typically include norms for AFUE. Norms for equipment sizing (in the form of sizing criteria) are contained in ACCA Manual J (Neal 1998 [298]).

  The norms reported in the literature for backdrafting and combustion gas spillage are contained within the same two documents that describe the diagnostics (CGSB 1995 [67], ASTM 1998 [42]). For the depressurization test, the norms are pre-established house depressurization limits that depend on appliance type. For the downdrafting and appliance backdrafting tests, the norms are simple observation of appliance behavior (i.e. whether backdrafting occurs in the first test and how long it takes to establish a draft in the second test). For the CVEP test, the norm is the CVEP. In this case, the CVEP must be greater than the maximum house depressurization achieved using installed equipment.

  In support of the continuous monitoring method under natural conditions, no norms were found in the literature to indicate what constitutes an acceptable frequency and duration of backdrafting with combustion gas spillage.

Other than a specification for the free-air carbon monoxide concentration provided by Conibear et al. (1995 [87]) and some test safety criteria described by ASTM (1998 [42]), none of the literature reviewed provides norms for carbon monoxide or nitrogen dioxide concentrations in the combustion gas stream. The ASTM criteria may not be suitable for normal operation.

No norms for heat exchanger leakage were found in the literature reviewed.

Controls

- *Metrics*: Except for Keithly (1999 [229]), no metrics were found in the literature to describe residential control performance. Even then, Keithly only describes common deficiencies with thermostat installations.

  Some metrics that are relevant to thermostat performance include calibration, setup/setback strategy, and anticipator or temperature swing setting. Other controls in the space conditioning system include those for the burner of a heating system and the thermal expansion device in a cooling system. Specific metrics for the burner include fuel pressure, fuel orifice size, and primary air supply flow. For the thermal expansion devices, relevant metrics are the orifice size, thermal expansion valve (TXV) size, as well as the superheat bulb location and bulb-line contact resistance. Other metrics include heat pump outdoor thermostat and defrost timer settings, blower and burner thermal limit switch settings, blower motor speed, automatic control sequence for duct damper on outdoor air intake, and ventilation switch settings (e.g. humidistats or run and defrost timers).

- *Diagnostics*: Diagnostics in this area are often little more than checking configurations and settings. Apart from diagnostics intended for laboratory use or for energy management control systems (EMCS), the literature reviewed provides no useful information for residential commissioning.

- *Norms*: Other than Title 24 requirements for lighting controls, no norms related to controls were found in the literature. One slightly related document mentions that Energy Star homes must have a programmable thermostat (Werling et al. 1998 [460]).

Other Electrical Appliances

- *Metrics*: Only a few references were located that discuss metrics relevant to the commissioning of residential electrical appliances. For water heaters, one metric is its recovery efficiency. Others include its energy consumption, energy factor, standby energy loss, and how much insulation is located around the tank. For appliances associated with plug loads, such as refrigerators, metrics include energy consumption and interior compartment temperature. An important metric for electric water heaters and these appliances is the electric load, both at startup and while operating.

- *Diagnostics*: Diagnostics in this area are often little more than checking configurations and settings. Other than one reference on monitoring and modeling hot water system energy losses (Stewart et al. 1999 [415]), an ASHRAE Standard (1993 [25]) that provides a laboratory test method for rating water heater

performance, and a few references on electric load monitoring, the literature that was reviewed contained no relevant information on quantitative tests for residential commissioning.

- *Norms*: Norms for water heaters are described in Title 24, by DOE (1995 [116] [117]), and by ASHRAE (1993 [27]). They include requirements that limit energy loss and for tank insulation. Other than a few data from Sherman et al. (1987 [401]), Meier (1993 [268] [269]), Parker and Stedman (1993 [312]) and Parker et al. (1998 [314]), no data were found to serve as performance norms for electrical appliances.

LITERATURE GAPS

There is a substantial amount of useful information in the literature about metrics, diagnostics, and norms that are relevant to residential commissioning. However, there are also some significant gaps. The following discusses those gaps.

- *Building Envelope*: Few metrics or diagnostics for thermal mass and moisture-damage susceptibility were found. Those that are available for thermal mass are complex and time consuming. All need further development work. Other than the thermal mass capacity estimates for slabs and whole buildings in Title 24, no norms related to these two issues were found. These benchmarks will need to be established if either of these two issues are to be addressed by residential commissioning.

- *Cooling Equipment and Heat Pumps*: There are few diagnostic techniques currently described in the literature to determine steady-state capacity and efficiency of an air conditioning unit (or heat pump). Those that are available are complex and time consuming. There are several techniques to determine refrigerant charge, but they also often require too much time. All these methods will need to be modified to make them more practical in terms of equipment and time constraints for residential commissioning. Norms for refrigerant charge, other than manufacturer specifications, are lacking and need to be developed. The applicability of those specifications as a norm is questionable, given that mismatched indoor coils are installed in some cases.

- *Air Distribution Systems*: Several diagnostic methods exist now to evaluate duct leakage. However, this is an active area of research and most methods require some further development to be useful in residential commissioning.

  Determining ventilation effectiveness and efficiency of mechanical ventilation systems in houses is problematic, as there is no appropriate diagnostic method available. Further development of such diagnostics is necessary, as is the development of corresponding norms, if these issues are to be considered during residential commissioning.

- *Indoor Air Quality*: Many diagnostic methods exist already to characterize thermal comfort. However, some development in this area is required to provide a simple rapid technique for characterizing the performance of each room in a house.

  Although there are several norms for pollutant concentration, virtually none were located for pollutant generation or removal. If these latter two issues are to be

considered in residential commissioning, then norms based most likely on visual observation will need to be developed.

- *Combustion Appliances*: Several methods for assessing the potential for backdrafting and combustion gas spillage are available in the literature. However, all of the tests are problematic, because they are susceptible to signal noise from wind effects, which can easily make the test results meaningless. It is important that these tests be further developed to make them usable and reliable during commissioning. In addition, norms for carbon monoxide or nitrogen dioxide concentrations in the combustion gas, as well as for heat exchanger leakage need to be developed.

- *Controls*: Metrics, diagnostics, and norms in this area are almost completely lacking. Extensive development work will be necessary so that issues associated with control performance can be addressed during residential commissioning.

- *Other Electrical Appliances*: There are few metrics, diagnostics, and norms in the literature we reviewed. If these appliances are to be dealt with during residential commissioning, then we need to locate and review more relevant literature. Considerable work relating to appliance performance has already been carried out or is underway at LBL, particularly with respect to water heaters and plug loads.

Few (33) of the 469 references that we reviewed specifically addressed a house as a system, although many mentioned that this is an important issue. Of these 33 references, nine considered systemic links between either building envelope airtightness or ventilation and air distribution system performance. Eight considered the links between either airtightness or ventilation and envelope insulation performance or moisture damage. Four considered the links between ventilation or air distribution system related loads and air-conditioner performance (Sonderegger et al. 1980 [411], Cummings et al. 1990 [98], Proctor 1997 [338], Walker et al. 1999 [447]). Four directly considered the links between airtightness, ventilation, and combustion safety (CGSB 1995 [67], ASTM 1998 [42], Lstiburek 1998 [256], Grimsrud et al. 1999 [184]). Other references considered various links between the building envelope, HVAC system, indoor air quality, and controls, but usually only one link. It appears that more research is necessary to assess and describe the performance of a house as a system of interacting components.

OTHER ISSUES

In the course of the literature review, several non-technical documents were found on the subjects of general instrumentation, commissioning processes, HVAC installation, and economics. All these documents pertain to commercial buildings, but some of this information can be adapted to residential commissioning.

Most of the papers on instrumentation dealt with diagnostics involving short-term monitoring, which might be useful depending on the time available for commissioning or the issue to be resolved. Sometimes, such monitoring is the only way to detect or diagnose a performance problem.

Of the documents discussing commissioning processes, one described ten metrics that could be used to evaluate the effectiveness of commissioning (Tseng et al. 1994 [435]). These involved issues such as the number and severity of defects remaining after

commissioning and the quality of maintenance training. Most of the other documents described specific processes to commission commercial buildings, the rationale for them, or ways to improve them.

The papers that relate directly to HVAC installation all list steps to follow or details to verify during commissioning after installation. Meckler (1991 [267]) also lists steps to follow during the design and occupancy phases of a building life cycle.

Several references specifically discuss economic issues involving building commissioning. Some describe economic metrics, which include the average or net present value for the cost of tuning or tweaking (duct sealing) and the associated energy savings, as well as simple-payback times. Some also present diagnostic methods, all of which involve the use of computer simulation to determine costs and savings associated with implementing energy efficiency measures. No literature was found that describes diagnostic methods to assess the value of non-energy costs and benefits. Some references also describe norms for use in economic analyses, such as equipment use and cost data and state-wide energy consumption data.

APPENDIX A: ANNOTATED BIBLIOGRAPHY*

1. BUILDING ENVELOPE

1.1 Opaque Building Assemblies

Metric

ASSEMBLY THERMAL CONDUCTANCE

1. Christian and Kosny 1995 [73] described the thermal performance of walls in terms of the center-of-cavity R-value, clear-wall R-value, and whole-wall R-value.
2. Christian and Kosny 1997 [74] discussed the importance of five elements (R-value, thermal mass, air tightness, moisture tolerance, and sustainability) to evaluate whole-wall performance.
3. Christian and Kosny 1999 [72] defined and compared clear-wall and whole-wall R-values.
4. Condon et al. 1980 [85] used a wall's thermal resistance to relate the heat flux through a wall to the temperature difference across the wall.
5. Desjarlais et al. 1998 [108] defined the R-value of a window assembly.
6. Forest et al. 1991 [165] measured thermal resistance of porous insulation.
7. Isaacs and Trethowen 1985 [218] defined a "cumulative" method of determining thermal resistance from a series of heat-flux and temperature-difference measurements.
8. Lambert and Robison [244] measured whole-house thermal loss in terms of a K factor (slope of line regressed to chart of measured space heat average energy use vs. inside-to-outside temperature difference).
9. Modera et al. 1986 [283] found through computer simulations that the dynamically measured thermal conductance of a wall was mostly likely to be inaccurate in the cases of (a) well-insulated walls; (b) large indoor and outdoor temperature fluctuations; (c) small average indoor-outdoor temperature differences; and (d) thermally massive walls.
10. Saunders et al. 1994 [363] defined "building load coefficient" (BLC), an area-integrated envelope thermal heat transfer coefficient (U*A) incorporating both conduction and infiltration effects.
11. Sherman et al. 1983 [380] described a wall's dynamic thermal performance by a small number of "Simplified Thermal Parameters," including a steady-state conductance, a time constant, and some storage terms.
12. Sonderegger et al. 1981 [409] described the thermal performance of an heterogeneous wall in terms of its conductance, its time constant, and two or three pairs of correction terms that express the wall's heterogeneity.
13. Subbarao et al. 1985 [418] reported on the early stages of a project to characterize the long-term thermal performance of a building using only two short-term-measurable parameters (building heat loss coefficient and equivalent clear aperture area).

INSULATION LEVEL AND LOCATION

1. BII 1998 [53] discussed insulation performance metrics including R-value, installation depth, and infiltration rate.
2. Grot and Chang 1983 [195] defined nine classes of envelope thermal anomalies (e.g., uninsulated exterior-wall cavity regions, improperly-insulated ceiling areas, air leakage around door or windows) that thermographic inspection of buildings can find.

Diagnostic

ASSEMBLY THERMAL CONDUCTANCE

1. Burch 1980 [61] used infrared thermography to rank roofs of residential and commercial buildings according to their thermal resistances, and found that it worked best under low-wind conditions.

* Each bracketed paper reference number in Appendix A (Annotated Bibliography) is hyperlinked to the paper's bibliographic reference in Appendix B (Alphabetized List of References). For example, [283] is a link to the bibliographic reference for paper 283 (Modera et al. 1986).

2. Christian and Kosny 1999 [71] described Oak Ridge National Laboratory's web-based whole-wall R-value calculator.
3. Christian and Kosny 1995 [73] described a method/procedure for the estimation of whole-wall R-values considering both "clear wall" and envelope interface details. Generated an R-value database by 3-D heat-conduction simulation of 18 systems.
4. Christian and Kosny 1999 [72] described an Internet-based calculation tool that computes whole-wall values of thermal resistance for 40 different wall systems.
5. CMHC 1998 [79] described the physics and mechanisms of heat transfer in buildings. Also discussed general insulation strategies.
6. Condon et al. 1980 [85] discussed steady-state measurement of wall thermal resistance with (a) heat flux sensors and (b) a guarded hot box. Also discussed the use of transient heat transfer analysis with the envelope thermal testing unit (a portable guarded hot box) to determine a wall's complex conductance (a.k.a. admittance).
7. Creech and Tiller 1993 [92] described the "cookie cutter" technique to remove and weigh attic insulation samples to check insulation density and R-value.
8. Crowell 1992 [93] discussed visual signs of poor insulation installation quality.
9. Cvetkovic 1982 [99] successfully tested a compensated heat-flux meter (i.e., one with a heating element used to compensate for the flux reduction induced by the presence of the meter).
10. Fang et al. 1985 [141] measured the thermal resistance of the exterior envelopes of six test houses using (a) a portable calorimeter and (b) a heat-flux transducer. Laboratory tests showed that calorimeter and transducer results were within 9% of those yielded by a guarded hot box.
11. Fang and Grot 1985 [142] measured the thermal resistance of office-building envelopes using (a) heat-flux transducers (four-inch-diameter wafer-type sensors with embedded thermopiles) and (b) a portable calorimeter.
12. Flanders 1992 [154] discussed the effect of changing the data time period for the two proposed tests for ASTM C1155-90 to measure R-values of building envelope components.
13. Flanders et al. 1995 [155] discussed test protocols and results of two in-situ long-term tests (multiple-day long, with values calculated based on incremental 24 hour blocks of data) to determine R-values of building envelope components. Tests are two proposed for ASTM C1155-90: summation technique and sum of least squares. Found that the R-value agreement between the two techniques varied by material, but was within 3% for metal panels, 13% for metal panel/block walls, and 1% for masonry walls and attic insulation.
14. Grot et al. 1985 [194] discussed four tools (non-contact spot radiometer, contact heat flow transducer, portable calorimeter, and envelope thermal testing unit [guarded hot plate]) that can be used to measure the thermal resistance of building components.
15. Harrje et al. 1985 [205] described the use of fan pressurization and infrared thermography to detect convective loops in buildings.
16. Isaacs and Trethowen 1985 [218] measured the thermal resistances of roofs, walls, and floors with thermocouples and heat-flux sensors.
17. Janssen and Rasmussen 1985 [219] used computer simulations of the thermal performance of a house to analyze the errors associated with a transient procedure used to measure overall "building thermal resistance" (BTR). Also programmed the algorithm into a microprocessor-based meter and measured the BTR of three homes.
18. Lugano 1998 [257] discussed key air sealing and insulation locations by house type (colonial, contemporary, ranch, and finished half-attics).
19. Modera et al. 1984 [285] outlined two techniques for thermal testing of walls: one active and one passive. The active method uses heat generation to produce the necessary delta T across the wall, whereas the passive method uses weather conditions.
20. Modera et al. 1986 [283] found through computer simulations that the dynamically measured thermal conductance of a wall was mostly likely to be inaccurate in the cases of (a) well-insulated walls; (b) large indoor and outdoor temperature fluctuations; (c) small average indoor-outdoor temperature differences; and (d) thermally massive walls.
21. Persily et al. 1988 [323] described the use of calorimeters and heat flux transducers to measure envelope thermal resistance.

22. Roeder 1992 [352] discussed the American Society for Non-Destructive Testing's (ASNT) guidelines for the voluntary qualification and certification of thermographers.

23. Roulet et al. 1985 [356] described both steady-state and dynamic methods for computing the thermal conductance and time constants of building assemblies. Presented a criterion for determining how close a dynamically computed thermal conductance is to its true value. Tested both steady-state and dynamic methods on various building elements (windows, light sandwich panels, and heavy elements).

24. Sandberg and Jahnsson 1995 [361] presented a simplified method (periodic electricity meter readings + indoor-outdoor air temperature measurements) for measuring the thermal loss factor (area-integrated conductance) of the envelope of an electrically-heated detached house with low thermal mass.

25. Saunders et al. 1994 [363] described the measured performance rating (MPR) method, an overnight coheating procedure that predicts building load coefficient (BLC), thermal time constant for the building mass, heating system efficiency, and annual fuel consumption of single-family detached home.

26. Sherman et al. 1982 [400] described wall thermal performance and temperature results using the envelope thermal test unit (ETTU).

27. Sherman et al. 1983 [380] described the Envelope Thermal Test Unit, a device (surface heater + surface-temperature sensor + heat-flux meter) that characterizes a wall's dynamic thermal performance by controlling and measuring heat flux.

28. Sonderegger et al. 1981 [409] discussed the Envelope Thermal Test Unit (ETTU), a tool developed to dynamically measure component U-values in the field. Also described in Condon et al. 1980 [85], Sherman et al. 1982 [401], and Sherman et al. 1983 [382].

29. Wishner 1996 [463] discussed a program to determine whether sufficient attic insulation is installed, based on the "cookie cutter" method; included a graph showing apparent thermal conductivity related to bulk density of four insulation materials.

INSULATION LEVEL AND LOCATION

1. ASTM 1990 [34] described the ASTM 1060-90 standard practice for using thermography to qualitatively inspect insulation installations in frame buildings.

2. Christian and Kosny 1997 [74] described how to determine whole-wall R-values using a guarded hot box and computer simulations.

3. Grot and Chang 1983 [195] discussed the use of thermography to detect defects in cavity-wall insulation.

4. Harrje 1981 [203] described a technique (blower-door depressurization + infrared thermography) for detecting envelope leakage sites and insulation defects.

5. Harrje et al. 1979 [204] described an IR thermography method for determining insulation irregularities.

6. NAHB 1997 [293] measured air-dried density of wall insulation samples that had been extracted with a "cookie cutter". Also inspected wall insulation for defects using the NAHB Research Center Certified Insulation Contractor checklist (detailed in an appendix), and recorded time to install wall insulations.

7. NAHB 1997 [294] provided quality checklists for installation of wall insulation, including fiberglass batts, spray cellulose, blow-in blankets, and foam-in-place. Included 7 to 13 possible defects for each type of insulation.

8. Persily et al. 1988 [323] described the use of thermography to qualitatively analyze the performance of building envelope insulation.

9. Proskiw 1995 [340] discussed the use of thermography to detect envelope anomalies.

10. Snell 1993[408] explained how to choose an infrared thermography system for building-energy audits.

11. Treado and Burch 1983 [430] evaluated the effectiveness of aerial infrared thermography in detection of roofing insulation defects, finding it to be useful in comparing adjacent houses (same external climate). Factors to take into account when conducting tests are included.

12. Zmeureanu et al. 1998 [469] used infrared thermography to detect envelope insulation voids in nine row houses.

Norm

ASSEMBLY THERMAL CONDUCTANCE

1. ASHRAE 1993 [27] specified how envelope tradeoff factors can be used in the prescriptive compliance path of ASHRAE Standard 90.2-1993: added heating or cooling loads imposed by a given envelope component can be offset by load savings from other envelope components.
2. ASHRAE 1995 [28] specified, based on local degree-days, overall thermal performance requirements for replacement building envelope components.
3. CEC 1999 [66] presented the Title 24 California building code that specifies R- and U-values for residential and non-residential roofs, walls, and floors.
4. Christian and Kosny 1999 [71] presented clear- and whole-wall R-values calculated using a web-based calculator, and provided examples of the effect of installation quality on insulation performance.
5. Christian and Kosny 1997 [74] presented whole-wall R-values for 18 wall configurations, determined using a guarded hotbox and computer simulation procedure.
6. Conover 1992 [88] discussed laboratory test results of convective heat loss through loose fill fiberglass insulation, in relationship to temperature differentials for attics.
7. Creech and Tiller 1993 [92] discussed results from a study of attic insulation R-values using the "cookie cutter" method; 95% of the houses had loose-fill fiberglass insulation, the rest had loose-fill rock wool or fiberglass batts; 25% had R-values less than claimed and 50% had R-values greater than claimed.
8. Greenberg 1994 [178] reported floor insulation techniques and their effect on insulation quality, based on work by Oak Ridge National Laboratory.
9. Isaacs and Trethowen 1985 [218] reprinted roof & wall R-value standards from NZS 4218P (New Zealand, 1977).
10. Katz 1997 [226] discussed visual inspections of insulation installation in 100 homes. With a minimum code requirement of R-30 attic insulation, 23% of the homes had attic insulation levels below R-30; floor R-values were compromised by poor-to-mediocre installation.
11. McBride 1992 [264] listed ASHRAE 90.2P's (ASHRAE 1993 [27]) prescriptive requirements for ceiling, wall, slab, floor, door, and fenestration thermal conductances in single- and multi-family houses.
12. Modera et al. 1984 [285] gave data for the U-values of various wall types.
13. National Association of State Energy Officials (NASEO) 1999 [295] gave HERS reference-home R- and U-values.
14. Penn 1993 [319] noted Minnesota's building code revision that includes a requirement that "all insulation materials must achieve their stated performance of 75˚F and no less than stated performance at winter design conditions".
15. Rainer 1995 [341] compared field findings to default framing factors and proposed ways to index and rate wall systems.
16. Schalch and Fryer 1992 [364] discussed the Energy Crafted Home's performance-based requirements for shell insulation levels.
17. Uniacke 1996 [444] discussed framing and insulation quality goals to obtain quality construction.
18. Werling et al. 1998 [460] gave Energy-Star required performance levels for envelope R- and U-values.

INSULATION LEVEL AND LOCATION

1. BII 1998 [53] described the proper installation of building-envelope insulation, with attention to insulation type, installation depth, and location.
2. ConSol 1999 [89] specified criteria for a quality thermal envelope, and detailed procedures (with checklist) for proper installation of wall, ceiling, and floor insulation. Included procedures for proper caulking and sealing.

ENERGY EFFICIENT FRAME DESIGN

1. ConSol 1999 [89] specified procedures for energy efficient building frame design, with attention to insulation and HVAC system issues.

1.2 Windows and Skylights

Metric

1. Dubrous and Wilson 1992 [127] described energy rating (ER) numbers, a window thermal performance metric that indicates whether a

window arrangement increases or decreases a building's thermal load.

Diagnostic

Assembly Thermal Conductance

1. Arasteh et al. [8] described an infrared thermography laboratory that measures window temperature and is used to validate computer models of window heat transfer (more detailed version of [9]).
2. Arasteh et al. [9] described an infrared thermography laboratory that measures window temperature and is used to validate computer models of window heat transfer (less detailed version of [8]).
3. Desjarlais et al. 1998 [108] used a large guarded hot-box to measure window heat transfer in accordance with ASTM Standard C 236-89.
4. Dubrous and Wilson 1992 [127] presented a procedure and data tables for calculating the Energy Rating (ER) of a building's windows based on building location, type, orientation, and ratio of window area to floor area.
5. Energy Design Update 1986 [136] discussed inaccuracies in prediction of window heat transfer (i.e., frame effects).
6. Finlayson et al. 1995 [150] described the WINDOW5 software package for analysis of fenestration heat transfer.
7. McCabe 1987 [265] described calorimeter measurement of window heat transfer.
8. Roulet et al. 1985 [356] described both steady-state and dynamic methods for computing the thermal conductance of building assemblies. Presented a criterion for determining how close a dynamically computed thermal conductance is to its true value. Tested both steady-state and dynamic methods on various building elements (windows, light sandwich panels, and heavy elements).

Radiative Behavior

1. Finlayson et al. 1995 [150] described the WINDOW5 software package for analysis of fenestration heat transfer.
2. Griffith 1999 [181] discussed a hand-held detector that uses an infrared light-emitting diode and a phototransistor to indicate whether a window is clear, regular low-e, or spectrally-selective low-e.
3. Griffith et al. 1998 [182] found that either a portable spectrometer or an inexpensive IR diode and a phototransistor could be used to identify the emittance of low-e window coatings.
4. Tinker and Al-Buijan 1998 [425] used the MoWitt/Passys test cell approach to measure the on-site solar control performance of glazing systems, and compared these results to those predicted by the ESP-r simulation model.

Norm

Assembly Thermal Conductance

1. ASHRAE 1993 [27] specified how envelope tradeoff factors can be used in the prescriptive compliance path of ASHRAE Standard 90.2-1993: added heating or cooling loads imposed by a given envelope component can be offset by load savings from other envelope components.
2. BII 1998 [53] briefly specified procedures for proper window installation, including labeling, certification, thermal conductance, orientation, and shading.
3. CEC 1999 [66] presented the Title 24 California building code specification for window U-values for residential and non-residential buildings (also refers to National Fenestration Council's NFRC-100-91 (1991) and NRFC 100 (1997)).
4. McBride 1992 [264] listed ASHRAE 90.2P (ASHRAE 1993 [27]) prescriptive requirements for ceiling, wall, slab, floor, door, and fenestration thermal conductances in single- and multi-family houses.
5. Shapiro and James 1997 [367] presented air tightness measurements and heat loss calculations (WINDOW 4.1) for different types of existing windows.

Radiative Behavior

1. CEC 1999 [66] presented the Title 24 California building code table for default values of solar heat gain coefficient.

Window Installation

1. BII 1998 [53] briefly specified procedures for proper window installation, including labeling, certification, thermal conductance, orientation, and shading.

2. ConSol 1999 [89] specified criteria for a quality window, and procedures for proper window installation.

1.3 Thermal Mass

Metric

1. Condon et al. 1980 [85] described a wall's dynamic thermal performance in terms of its admittance, which depends on its thermal conductance and thermal mass.
2. Roulet et al. 1985 [356] described both steady-state and dynamic methods for computing the thermal conductance and time constants of building assemblies. Presented a criterion for determining how close a dynamically computed thermal conductance is to its true value. Tested both steady-state and dynamic methods on various building elements (windows, light sandwich panels, and heavy elements).
3. Saunders et al. 1994 [363] described the measured performance rating (MPR) method, an overnight co-heating procedure that predicts building load coefficient (BLC), thermal time constant for the building mass, heating system efficiency, and annual fuel consumption of a single-family detached home.
4. Sherman et al. 1983 [380] described a wall's dynamic thermal performance by a small number of "Simplified Thermal Parameters," including a steady-state conductance, a time constant, and some storage terms.
5. Sonderegger et al. 1981 [409] defined a time constant based on thickness and thermal diffusivity that describes the dynamic thermal performance of a wall.
6. Subbarao et al. 1985 [419] used Fourier analysis to describe the thermal capacity of a building in terms of its thermal admittance, which relates the sinusoidal temperature response to the sinusoidal addition of heat to interior air.

Diagnostic

1. Christian and Kosny 1995 [73] outlined a procedure for measuring the energy-savings benefits yielded by wall systems with significant thermal mass.
2. Subbarao et al. 1985 [419] measured the thermal capacitance of a room-sized test cell, and discussed why a sinusoidal driving function is superior to a step function in the measurement of building capacitance.

Norm

1. CEC 1999 [66] presented the California Title 24 code that specifies minimum interior thermal mass for some residential prescriptive compliance packages (component-based list of energy-efficient features).

1.4 Airtightness

Metric

ENVELOPE AND INTERZONE LEAKAGE

1. ASTM 1992 [35] defined leakage terms, including air changes per hour (ACH) and effective leakage area (ELA) using fan pressurization.
2. ASTM 1995 [39] described the standard specification and performance of an air retarder for low-rise framed building walls, gaged by the rate of air leakage through the envelope (cfm/ft^2) at a pressure difference of 0.3 in. w.g.
3. ASTM 1997 [41] defined leakage terms, including air changes per hour (ACH) and effective leakage area (ELA) using an orifice blower door.
4. Bahnfleth et al. 1999 [43] listed four metrics for envelope leakage (flow coefficients, Q_{50}, ELA_4, and ACH at some reference pressure), and defined whole-building pressure differential for tall buildings.
5. CMHC 1998 [79] described the physics and mechanisms of airflow in buildings. Also discussed how to do air sealing.
6. CMHC 1998 [80] discussed a test procedure to measure the air leakage rate and structural performance of air barrier systems in wood frame walls.
7. Cummings 1998 [94] compared leakage flow metrics evaluated at a single pressure difference (single-point Q_{env}) to those evaluated at several pressure differences (multi-point Q_{env}).
8. Cummings and Withers 1997 [96] defined CFM_{50}, ACH_{50}, and uncontrolled airflow (UAF).
9. Cummings and Withers 1998 [95] defined ACH_{50}, CFM_{25}, $CFM_{25,out}$, $CFM_{25,tot}$, and CFM_{50}.

10. Forest et al. 1991 [165] discussed metrics for evaluating moisture and airflow (moisture content, moisture release rates, infiltration rates, relative humidity, ambient conditions, thermal resistance). Also measured airflow resistance of porous insulation.
11. Grimsrud et al. 1979 [189] compared tracer-gas based infiltration measurements and predicted infiltration based on air leakage measurements using fan pressurization and on surface-pressure-difference measurements. Grimsrud et al. 1979 [191] presented a subset of these results.
12. Grimsrud et al. 1981 [188] defined the effective leakage area of a building envelope.
13. Grimsrud et al. 1981 [192] defined ELA_4. Described fan pressurization techniques and the use of specific leakage areas, nomographs, and component leakage guides to be used by practitioners in determining building leakage and infiltration rates.
14. Harrje et al. 1990 [206] described metrics related to three tracer gas measurements (constant tracer gas method, multiple tracer measurement system [MTMS], and perfluorocarbon tracer measurement method [PFT]).
15. Jump and Modera 1993 [222] measured envelope leakage as part of a research project on zoned distribution systems.
16. Keefe 1994 [228] compared ACH vs. CFM as envelope leakage metrics (the latter can be measured without knowing the building volume), and noted that CFM_{50} measurements are made at a pressure low enough to be easily achievable and high enough to resist wind-induced errors. Mentioned $/$CFM_{50}$ as an estimate of the cost or benefit of a leakage change.
17. Koles et al. 1996 [241] discussed airtightness as defined by normalized leakage area (ASHRAE Standard 119-1989).
18. Lambert and Robison [244] used four envelope leakage metrics: (1) specific leakage area at 4 Pa (SLA_4); (2) estimated seasonal infiltration at 4 Pa (infiltration ACH); (3) ACH_{50}; and (4) perfluorocarbon passive tracer gas infiltration rate ("PFT").
19. Lstiburek 1998 [256] presented an electrical circuit analog for envelope leakage.
20. Modera 1993 [279] discussed the merits of CFM_{25} vs. CFM_{50}, noting that duct pressure is closer to 25 Pa when the system fan is running.
21. National Association of State Energy Officials (NASEO) 1999 [295] defined annual average ACH, which is the normalized building leakage multiplied by W, a local weather factor defined in ASHRAE Standard 136 (ASHRAE 1993 [26]).
22. Robison and Lambert 1989 [351] discussed measurement metrics, including duct pressures, duct leakage, airflows, whole-house air infiltration, and fan pressurization results.
23. Sherman 1986 [373] defined effective leakage area (ELA), infiltration rate, leakage class, infiltration degree-days, and air changes per hour (ACH).
24. Sherman 1986 [374] defined a leakage area normalized by the floor area and height of a house. Normalized leakage area usually falls between 0.2 and 1.0, but large potential errors caused the authors to group leakage into classes. Classification ranges from A to J.
25. Sherman and Grimsrud 1980 [390] measured envelope leakage using fan pressurization and weather data.
26. Sherman et al. 1986 [382] defined infiltration degree days, a weather-based value used to calculate envelope infiltration rates in the same fashion that degree days are used to calculate building heat transfer rates.
27. Sherman and Matson 1997 [402] defined specific infiltration rate, stack and wind factors, hourly infiltration rate, and effective leakage area.
28. Walker et al. 1998 [448] defined a single-pressure-differential envelope leakage metric (Q_{25}).

AIR BARRIER TYPE AND LOCATION

1. Cummings and Withers 1998 [95] discussed eight configurations of thermal and air boundaries in commercial buildings.
2. Finley 1997 [422] evaluated interzonal airtightness to determine its effect on indoor air problems (mold and moisture) and their mitigation strategies.

Diagnostic

ENVELOPE LEAKAGE

1. Anderson 1995 [3] presented a history of the blower door and case studies of current users.

2. Anderson 1995 [4] in a letter to the editor, discussed how to diagnose and seal air leakage paths between conditioned space and the attic, using a blower door or pressure gages.
3. ASHRAE 1988 [26] specified a calculation methodology to determine annual effective ventilation rates, based on the weather factor (W), normalized leakage area (NL), and hourly ventilation fan airflows and schedules.
4. ASTM 1988 [33] presented a standard test method for airflow calibration of fan pressurization devices used for measuring air leakage rates through building envelopes.
5. ASTM 1992 [35] described multi-point fan-pressurization measurement of envelope leakage.
6. ASTM 1995 [38] described the five ASTM E1186-87 (1992) methods to detect air leakage sites in building envelopes: building [de]pressurization + infrared scanning; building [de]pressurization + smoke tracers; building [de]pressurization + airflow measurement devices; sound; and tracer gas.
7. ASTM 1995 [39] described a test procedure for measuring the performance of air retarder materials and systems for low-rise framed building walls.
8. ASTM 1995 [40] described the ASTM Standard E741-95 tracer-gas measurement method for single-zone air change rates.
9. ASTM 1997 [41] described the ASTM E1827-96 multi-point fan-pressurization envelope leakage measurement using a blower door, and included an uncertainty analysis.
10. Bahnfleth et al. 1999 [43] applied fan-pressurization and tracer gas methods to measure the envelope leakage of a tall building.
11. Berk et al. 1981 [51] discussed fan-pressurization measurement of envelope airtightness.
12. BII 1998 [53] used blower door depressurization to measure ACH_{50}.
13. Blasnik and Fitzgerald 1992 [55] proposed three blower-door methods to quantify zone leakage and better understand series leakage paths (interstitial leakage). Test 1: “add a hole” - calculates leakage between living space and attic by using a “calibrated hole”. Test 2: “opening a door” - measures leakage between living space and basement, garage, attics with doors or pull-down stairs. Test 3: “single point attic test for roof venting” - calculates “bypass leakage” from house to attic based on zone pressure differences and attic vent sizes.
14. Christian and Kosny 1995 [73] proposed using a combination of ASTM Standards (C236, C976, E1424, E283) to measure air leakage and heat loss through wall assemblies under simulated wind conditions ranging from 0 to 15 mph, and building pressure differentials ranging from 0 to 25 to 50 Pa.
15. CMHC 1998 [80] discussed a test procedure to measure air leakage and structural performance of air barrier systems in wood-frame walls.
16. CMHC 1998 [79] described the physics and mechanisms of airflow in buildings. Also discussed how to do air sealing.
17. Cummings 1998 [94] recommended performing the blower-door test in depressurization mode because building pressurization overestimates leakiness by pushing open dampers, skylights, windows, and ceiling tiles. Also, in a study of 150 Central Florida homes, used tracer gas and blower door measurements to find that infiltration increased four-fold when the central air handler unit was on; infiltration rates went from 1.13 ach to 0.54 ach after duct sealing.
18. Cummings and Withers 1997 [96] gave an example of using building fans to measure CFM_{50}, and included a chart used to determine CFM_{50} from CFM measured at some other pressure.
19. Downey and Proctor 1994 [125] briefly described blower-door measurement of CFM_{50}.
20. EPA 1997 [138] listed four tests used to ensure that subcontractors are performing quality work: a blower-door test to detect excessive envelope leakage, a duct leakage test, an HVAC system inspection, and testing airflow across the inside coil to ensure proper airflow to the duct system.
21. Forest et al. 1991 [165] compared three techniques for tracer gas measurement.
22. Forest et al. 1991 [165]measured indoor infiltration, attic ventilation, and indoor-attic exchange rates with a dual tracer gas technique. Measured airflow through wall panels with a small orifice plate flowmeter. Measured flow air resistances of porous insulation panels.
23. Gadsby and Harrje 1985 [172] discussed calibration errors in measuring fan flow from fan pressure when measuring envelope leakage by fan pressurization.

24. Gammage et al. 1986 [173] discussed tracer gas airflow measurements used to determine the effect of central fan operation and duct leakage on infiltration air change rates.

25. Grimsrud et al. 1981 [188] briefly described the Lawrence Berkeley Lab infiltration model relating total envelope infiltration to stack-, wind-, and mechanical-system-induced infiltration. In addition, related fan-pressurization measurements of envelope leakage to actual heating-season infiltration rates, and briefly described the ASTM 779-81(5) fan pressurization technique.

26. Grimsrud et al. 1981 [192] described the LBL infiltration model predicting envelope infiltration from effective leakage area and local weather conditions. Included formulas and parameter tables for standard terrain classes. Described use of infiltration in an instrumented audit. Described fan pressurization techniques and the use of specific leakage areas, nomographs, and component leakage guides by practitioners in determining building leakage and infiltration rates.

27. Grimsrud et al. 1999 [184] reported blower-door measurements of ACH_{50} rates in 111 homes.

28. Harrje 1981 [203] described a technique (blower-door depressurization + infrared thermography) for detecting envelope leakage sites and insulation defects.

29. Harrje et al. 1979 [204] used blower-door pressurization and infrared thermography to locate envelope leakage sites. These "bypass routes" by which warm air leaves the building include the furnace shaft, party-wall gap, party-wall convection, attic, basement, and thermal bridges.

30. Infiltec 1999 [217] presented specifications for the Infiltec blower-door.

31. Jump et al. 1996 [223] used a slight variant on ASTM Standard 779 to measure envelope leakage by fan pressurization.

32. Keefe 1994 [228] presented a how-to guide to blower-door measurement of envelope leakage by fan pressurization.

33. Knight et al. 1995 [239] discussed the development and testing of a hand-held device to detect air leakage sites on building surfaces. Soap is applied to a building surface and the PACT unit is used to apply a vacuum to the surface. Air leakage sites are identified by the appearance of soap bubbles, created by the vacuum. The unit is calibrated, relating pressure differences to leakage area. The PACT unit is able to detect smaller and more leaks than the use of smoke, however has trouble with larger leakage sites, most of which are better detected visually.

34. Modera et al. 1987 [276] described the "pulse pressurization" technique for acoustic measurement of a building envelope's effective leakage area. This is the reference paper on the subject.

35. NAHB 1997 [293] measured CFM_{50} and ACH_{50} with the ASTM E-779 house depressurization test. Also measured corrected envelope leakage rate ACH_{50}*, which is the envelope leakage minus the house-volume-normalized duct leakage.

36. Persily 1982 [321] measured the accuracy and repeatability of fan pressurization (blower-door) measurements of envelope airtightness by testing a home 80 times in one year. Discussed sources of error (fan calibrations, wind) and a temperature correction for blower door measurements.

37. Persily et al. 1988 [323] described tracer gas and fan pressurization measurements of air change rates.

38. Proctor 1997 [338] used a blower door test and Sherman's infiltration model (Sherman 1987 [384]) to estimate natural infiltration rate.

39. Reardon et al. 1987 [343] measured the envelope leakage of a home connected to another home by using a second, "balancing" fan to equalize the interior pressures in the two homes.

40. Retrotec 1998 [347] presented Retrotec's line of blower-door products and discussed their features.

41. Robison and Lambert 1989 [351] discussed fan pressurization, tracer gas, and flow hood measurement techniques to determine the relationships between duct leakage, envelope leakage, infiltration rates, and ventilation rates.

42. Saunders et al. 1994 [363] used manual-sampling and automated-sampling SF_6 tracer gas techniques to measure house infiltration rate (ACH), noting that the cost of automated sampling equipment is minor relative to labor costs. Also measured envelope ELA with a blower-door pressurization test.

43. Shapiro and James 1997 [367] described a simple measurement device to measure air leakage around windows.

44. Sherman et al. 1980 [378] surveyed tracer-gas techniques for measuring air infiltration. Also discussed non-tracer-gas methods (e.g., the LBL infiltration model, which estimates hourly infiltration flow rates based on measured leakage area, building characteristics and local weather data).

45. Sherman and Grimsrud 1980 [390] combined fan pressurization measurements with simple weather data to determine envelope air infiltration.

46. Sherman and Modera 1986 [375] used the "AC pressurization" technique to measure leakage area by using fluctuating building pressure instead of a static building pressurization. Preliminary results agreed fairly well with conventional pressurization testing.

47. Sherman and Modera 1988 [376] presented theory related to the "AC pressurization" acoustic technique for measurement of envelope leakage.

48. Sherman et al. 1989 [397] presented a method (based on AC pressurization) for measuring envelope leakage at low pressures (below 10 Pa) where traditional blower door tests become inaccurate.

49. Sherman and Palmiter 1994 [394] evaluated various standards and protocols for measuring ELA from a general perspective, looking at uncertainty (accuracy, measurement error, measurement uncertainty, precision, bias). Also proposed improved measurement procedures, including instrumentation specifications and analysis methods that lower uncertainties from the teens to 3-4%.

50. Siegel and Davis 1998 [403] used a depressurization blower-door test to measure CFM_{50}, and the LBL infiltration model to estimate natural infiltration, in eight manufactured (HUD-code) homes before and after retrofits.

51. Ternes 1987 [420] described data parameters to collect in single-family retrofit research projects and described data analysis approaches and issues. Data parameters include (a) basic data (house characteristics, leakage measurements, metered performance of HVAC systems, and verification of retrofit installation quality); (b) time-sequential data (submetered space-conditioning energy consumption, weather station measurements [dry bulb, horizontal solar radiation, humidity, wind speed and direction], indoor temperature and humidity, total fuel consumptions [billing meter data], wood heating usage, and submetered water heating energy consumption); (c) optional occupant-behavior data (additional indoor temperature and humidity, hourly heating and cooling thermostat setpoints); (d) geographic characteristics (terrain and shielding); and (e) distribution system data (duct leakage area measured using fan pressurization).

52. The Energy Conservatory 1998 [421] explained how to use their Automated Performance Testing (APT) system in conjunction with a blower door to automate blower-door leakage measurements.

53. The Energy Conservatory 1999 [422] answered FAQs related to using Energy-Conservatory's duct blaster, blower door, and Automated Performance Testing System (APT) to measure envelope leakage and duct leakage.

54. Tooley and Davis 1994 [428] discussed test methodology and problem diagnosis for attic ventilators, depressurization, moisture damage, and air barriers.

55. Torry 1994 [429] used a cruise-control blower door to measure envelope leakage by fan pressurization.

56. Tsongas and Nelson 1991 [439] located exterior wall air leaks via infrared thermography, and found wall moisture damage at the leakage sites.

57. Uniacke 1996 [444] discussed air sealing and testing strategies and priorities.

58. Walker et al. 1998 [448] specified single and multi pressure differential fan pressurization techniques for measuring envelope leakage.

59. Yuill and Yuill 1998 [466] used a blower-door test to measure the airtightness of several materials used to seal the outer surface of house walls.

60. Zmeureanu et al. 1998 [469] used infrared thermography and blower-door pressurization to locate leaks and measure the leakage area of nine row houses.

AIR BARRIER TYPE AND LOCATION

1. Bohac et al. 1996 [310] described a short-term monitoring protocol to determine the effectiveness of building envelope and/or mechanical system improvements. The protocol

works better on a sample of houses than on an individual house.

2. CMHC 1998 [79] described air and vapor barriers, including air and moisture transport and related problems, including air and moisture transport physics and mechanisms, construction requirements, and evaluation checklists.
3. Cummings 1998 [94] described how to identify a building's primary air boundary with a blower-door building-pressurization test.
4. Fitzgerald et al. 1994 [153] presented detailed instructions for locating a building's air boundary by using a blower door to pressurize a building, and then measuring the building's air-pressure distribution.
5. Lugano 1998 [257] discussed key air sealing and insulation locations by house type (colonial, contemporary, ranch, and finished half-attics).
6. Makepeace 1999 [261] described a technique to install the air barrier and insulation on the outside of the frame construction to minimize air leakage and moisture problems.
7. Obst and Hendricks 1991 [305] discussed air barriers and vapor retarders, providing construction details and specifications.
8. Tooley 1999 [426] discussed specifying and installing air barriers in houses. Provided installation details and responsibilities for each project team leader; discussed basics of air, moisture and heat movement. ([427] is Part 1 of this two-part article).
9. Tooley 1999 [427] explained thermal and air barrier basics, and provided examples using the 3C (continuous, contiguous and complete) method. ([426] is Part 2 of this two-part article).

Norm

Envelope and Interzone Leakage

1. ASHRAE 1988 [15] described requirements for residential building airtightness performance to reduce air infiltration thermal loads (does not apply to buildings that are conditioned for human comfort less than 876 hours of the year). It also provided a method of classifying the airtightness of residential buildings.
2. ASHRAE 1993 [27] specified that the envelope leakage-related prescriptive requirements of ASHRAE Standard 90.2-1993 consist of measured air leakage (in compliance with ASHRAE Standard 119-1981) or component leakage requirements (windows, doors, foundations, caulking and sealant, infiltration retardants).
3. ASTM 1995 [39] specified the minimum performance factor for air retarders for low-rise framed building walls, including air leakage, structural integrity, water resistance, and water vapor.
4. Berk et al. 1981 [51] presented envelope airtightness results for nine houses before and after retrofitting.
5. CEC 1999 [66] presented the California building code Title 24 standards for air leakage around exterior doors and windows.
6. CMHC 1998 [79] described the physics and mechanisms of airflow in buildings. Also discussed how to do air sealing.
7. CMHC 1998 [80] discussed proposed airtightness levels (L s^{-1} m^{-2} @ 75 Pa) for three construction classifications.
8. Cummings 1998 [94] recommended and justified ACH_{50} values for commercial buildings. He also specified building areas that should operate at positive pressure with respect to outdoors to avoid infiltration by humid outside air.
9. Cummings et al. 1990 [98], in a study of 150 Central Florida homes, used tracer gas and blower door measurements to find that infiltration increased four-fold when the central air handler unit was on; infiltration rates went from 1.13 ach to 0.54 ach after duct sealing.
10. Cummings and Withers 1997 [96] recommended ACH_{50} values for commercial buildings.
11. DOE 1995 [116] discussed background information on HERS infiltration-related policy options, and included DOE's 1995 request for comments on the HERS normalized leakage and infiltration levels for the reference and rated homes. At the time of this document, DOE proposed using 0.35 ACH as the minimum allowable air change rate on which energy savings may be calculated for the rated home. DOE proposed using ASHRAE Standards (119 for normalized leakage, 136 for effective ventilation) for the reference house, with a minimum of 0.35 ACH.
12. EPA 1998 [139] noted a commercial-building infiltration rate recommended by the National Association of Architectural Metal Manufacturers (not to exceed 0.06 cfm per ft^3. of

exterior wall at a pressure difference of 0.3 in. w.g.). Referenced to the ASHRAE Fundamentals Handbook, 1997, p. 25.19.

13. Grimsrud et al. 1981 [188] reported the median value of heating-season-averaged infiltration rates measured in 300 houses in the U.S. and Canada, and tabulated heating-season specific infiltration in 59 U.S. cities.

14. Katz 1997 [226] discussed Advanced Energy's targets for air tightness (envelope leakage less than 0.30 CFM_{50}/ft^2 of surface area) and presented results of air-tightness tests in 100 new homes.

15. Keefe 1994 [228] classified houses as tight or leaky based on values of CFM_{50} and ACH_{50}.

16. Kiel et al. 1986 [232] analyzed a large envelope-leakage data set and found correlations between housing construction type and flow exponent.

17. Matson and Feustel 1998 [263] presented leakage characteristics (air change rate at 50 Pa and normalized leakage values) for post-1980 construction homes (97 in New York and 66 in California) based on blower door tests.

18. Modera 1986 [277] described a database of 1,100 fan-pressurization test results (752 houses: 452 U.S. and 300 Canadian). Presented data included: leakage (averages of depressurization and pressurization test results such as leakage area, flow exponent, specific leakage area; the average flow at 100 Pa), leakage characteristics (descriptions of the depressurization and pressurization leakage measurements and analysis: flow exponents, flow coefficients, regression correlation coefficients, leakage areas, and air changes at 50 Pa), house characteristics (number of stories, floor type, roof type, wall type, building type [detached, duplex, townhouse], HVAC and fireplace descriptions, building height, shielding and terrain classes), and location (zip code).

19. Modera 1994 [280] presented envelope-leakage measurements performed in 31 California homes.

20. Murphy et al. 1991 [291] conducted studies to determine the repeatability of fan-pressurization measurements.

21. National Association of State Energy Officials (NASEO) 1999 [295] specified HERS-reference envelope leakage values for homes.

22. Parker 1989 [313] discussed blower-door and tracer-gas air-change-rate measurements of 1980-construction. Discussed conventional and Model Conservation Standards (MCS) for the construction of homes in the Pacific Northwest. Estimated mean seasonal air change rates were 0.55 ach for the conventional and 0.28 ach for the MCS homes. Using the tracer gas technique, average air change rates (December through March) were 0.31 ach (not corrected for non-uniform mixing) for the conventional homes and 0.35 (including heat recovery ventilation airflow) for the MCS homes.

23. Robison and Lambert 1989 [351] discussed the effect of duct leakage on house leakage, with duct leakage adding 10% to house leakiness in 20 Residential Standards Demonstration Program (RSDP) homes.

24. Schalch and Fryer 1992 [364] discussed the Energy Crafted Home's infiltration specifications (maximum of 1.0 in^2 of opening per 100 ft^2 of shell at 4 Pa of pressure difference).

25. Sherman 1986 [373] tabulated infiltration degree-days and acceptable envelope leakage classes in various U.S. cities. Also presented U.S. maps of infiltration degree-day zones, standard infiltration rates, and standard infiltration load.

26. Sherman et al. 1984 [395] surveyed leakage data from 500 houses. Flow coefficients and exponents were found to correlate with type of vapor barrier and wall construction. They did not correlate with age, but did correlate with climate; houses in cold climates were tighter.

27. Uniacke 1996 [444] discussed air sealing and air-tightness goals to obtain quality construction.

28. Werling et al. 1998 [460] presented Energy-Star required performance levels for the air change rate of homes.

AIR BARRIER TYPE AND LOCATION

1. ASHRAE 1995 [28] specified exterior joint sealing and optimizing ventilation openings.

2. Cummings 1998 [94] recommended locations for air and thermal barriers in commercial buildings.

1.5 Moisture Damage Susceptibility

Metric

1. ASTM 1995 [39] specified water resistance testing procedures of air retarder (AR) materials or systems for low-rise framed building walls.
2. CMHC 1998 [79] described air and vapor barriers, including air and moisture transport physics and mechanisms, construction requirements, and evaluation checklists.
3. Forest and Walker 1991 [161] discussed measurement and model input variables to determine airflow and moisture content in attics. Forest and Walker 1992 [162], 1993 [163], 1993 [164], and Walker and Forest 1995 [452] also discussed this research.
4. Forest et al. 1991 [165] measured wood's moisture content by weight.
5. NAHB 1997 [293] measured the installed moisture content (moisture by dry weight) of spray-insulated systems

Diagnostic

1. CMHC 1996 [78] discussed non-destructive test methods and equipment to assess the strength, serviceability, and deterioration of buildings.
2. CMHC 1998 [79] described air and vapor barriers, including air and moisture transport physics and mechanisms, construction requirements, and evaluation checklists. Also described the physics and mechanisms of moisture transport and related problems, including a checklist of possible moisture problems (water vapor, capillary water, and bulk water-related). Provided figures showing how to diagnose moisture problems in exterior finishes and materials. Discussed window moisture problems, including a checklist of typical problems and solutions.
3. Dubose and Odon 1994 [126] discussed sources of moisture-related building damage (e.g., infiltration of moist outside air into depressurized building spaces); building commissioning techniques to identify the source of moisture damage (e.g., zone depressurization); and ways to prevent moisture damage (e.g., rebalancing flows to positively pressurize interior spaces).
4. Finley 1997 [422] described diagnostic methods, and provided lists of possible moisture and mold sources and mitigation strategies.
5. Foarde et al. 1996 [159] discussed the use of a moisture conductivity meter to determine the moisture content of materials in relationship to fungal growth; found that any non-zero reading generally was related to some level of fungal growth. The moisture conductivity meter can be used to select sampling sites during microbial investigations.
6. Forest and Walker 1991 [161] discussed measuring and modeling airflow and moisture content in attics. Forest and Walker 1992 [162], 1993 [163], 1993 [164], and Walker and Forest 1995 [452] also discussed this research.
7. Forest et al. 1991 [165] used moisture pins to measure the moisture content of wood-based building components.
8. Knehans and Styer 1983 [238] broadly described the process of detecting wet roofing insulation by IR thermography.
9. Larson and Huelman 1992 [246] discussed a case study where dark streaks appeared on the outside of siding material, caused by the improper installation of a vapor barrier and interior moisture problems. Provided a detailed list of the problems and the solutions proposed to the homeowner.
10. Lichtman et al. [252] described concrete slab moisture measurement techniques. Qualitative tests included the "mat test" (laying a piece of impermeable material on an exposed section of slab and, after a period of time, inspecting the concrete surface below for signs of wetness), and the "bond test" (fixing or bonding a sample piece of flooring material to the slab and observing any adverse reactions to the flooring due to moisture). Quantitative tests included electrical conductivity measurements, coring, and the Vapor Emission Test (VET) (a small, airtight container covering a sample of absorbent material is taped down on a small section of bare slab, after a period of time [60-72 hours], the weight of water absorbed by the material is determined). The VET method allows the determination of the quantity and rate of moisture transmission through the slab, and is included in ASTM Standard E1907-97: Standard Practices for Determining Moisture-Related Acceptability of Concrete Floors to Receive Moisture-Sensitive Finishes.

11. Lstiburek and Carmody 1995 [255] provided moisture fundamentals, including definitions, explanation about conditions that are conducive to mold and moisture. Discussed diagnostic tests and tools, and discussed how to identify and control moisture problems.
12. NAHB 1997 [293] measured moisture content of wall insulation samples that had been extracted with a "cookie cutter".
13. National Research Council Canada 1996 [297] discussed applications of non-destructive test methods for assessing moisture and associated problems. Discussions include the advantages and limitations of methods, as well as the equipment required for the tests.
14. Tooley and Davis 1994 [428] presented test methodology and problem diagnosis for attic ventilators, depressurization, moisture damage, and air barriers.
15. Tsongas and Nelson 1991 [439] located exterior wall air leaks via infrared thermography, and found moisture damage at the leakage sites. They measured the moisture content of wooden wall sheathing with an electrical-resistance meter probe.
16. Walker 1993 [450] discussed an attic simulation model (airflow and moisture) and measured data to evaluate attic ventilation and moisture problems.
17. Walker et al. 1995 [454] presented the AVENT attic ventilation model and compared modeled results to measured data.
18. Warner 1991 [456] discussed how to avoid window condensation by increasing window R-values, sealing cracks and joints around windows, or by increasing house ventilation rates.

Norm

1. ASHRAE 1993 [27] specified that to meet the prescriptive requirements of ASHRAE Standard 90.2-1993, water vapor retarders and moisture barriers should be in accordance with chapters 20 and 21 of the 1989 ASHRAE Handbook of Fundamentals.
2. ASTM 2000 [36] discussed the prevention of moisture damage through proper design and construction of foundation systems, control of crawlspace moisture, prevention of rain penetration at exterior surfaces, condensation within wall construction, control of water leakage at the roof, and control of plumbing leaks.
3. Cheple and Heulman 1998 [70] discussed ways to decrease moisture problems in bathrooms, including "build tight, ventilation right"; included wall construction details.
4. Fisette 1996 [152] discussed how to prevent ice dams by air sealing, insulating, and providing attic ventilation; included construction details and specifications.
5. Foarde et al. 1996 [159] presented microbial and moisture conductance results from moisture investigations in homes and schools. Materials with higher moisture conductance values tended to have predominantly Aspergillus while materials with lower moisture conductance values tended to have predominantly Cladosporium. Corresponding room RH levels were in the 40-70% range.
6. Kirkland 1993 [236] discussed using spray foam insulation on floor trusses to prevent airborne moisture from coming in contact with building materials.
7. Lichtman et al. [252] described physical signs and conditions relating to moisture intrusion in concrete slabs. Discussed factors to consider and design specifications to put in place to minimize moisture intrusion.
8. Lstiburek 1999 [254] discussed un-vented attics in cold climates, including construction details.
9. Makepeace 1999 [261] described a technique to install the air barrier and insulation on the outside of the frame construction to minimize air leakage and moisture problems.
10. Obst and Hendricks 1991 [305] discussed air barriers and vapor retarders, providing construction details and specifications.
11. Schalch and Fryer 1992 [364] discussed the Energy Crafted Home's moisture control specifications, including vapor retarders and moisture retarders under floors and slabs.
12. Tsongas 1995 [437] discussed moisture damage found in manufactured houses (pre-1980) with vapor barriers on the outside of the wall cavity. No decay was found in homes without the vapor barrier. Defined conditions required for dry rot to occur, and briefly discussed an additional study to monitor moisture condensation, thermal performance and ventilation to determine how weatherization activities may cause or other affect moisture in houses.

2. HEATING, VENTILATION AND AIR CONDITIONING

2.1 Cooling Equipment - Air Conditioners and Heat Pumps

Metric

STEADY-STATE CAPACITY AND EFFICIENCY

1. ASHRAE 1995 [29] defined the seasonable energy efficiency rating (SEER) for unitary air conditioners and heat pumps.
2. Bittle and Goldschmidt 1985 [54] analyzed heat pump test performance measurements on 98 units and found that various performance factors (SEER, EER, HSPF, COP) were linearly related, with correlation coefficients near 0.8.
3. Farrar et al. 1998 [145] used AC power consumption as an indicator of the relative thermal performances of two side-by-side houses (one an energy-saving prototype, the other a control).
4. Kavanaugh 1992 [227] explained and compared metrics used to rate unitary air-source pumps, air-source (direct-expansion) cooling units, furnaces, and water-to-air heat pumps. These included seasonal energy efficiency ratio (SEER) and heating seasonal performance factor (HSPF) for air-source heat pumps and cooling units, and three Air-Conditioning and Refrigeration Institute (ARI) metrics used to rate ground-source heat pumps.
5. Neal 1998 [298] defined field-adjusted SEER (SEERFA), which can be appreciably lower than SEER, due to poor installation of AC equipment.
6. Nguyen et al. 1982 [303] found that the seasonal energy efficiency ratio (SEER) of a residential air conditioner is linearly related to its steady-state energy efficiency ratio.
7. Sherman et al. 1987 [401] measured EER and SEER using in-situ appliance efficiency measurements.
8. Walker et al. 1998 [449] concluded that nameplate ratings alone are a poor indicator of how much cooling will be delivered to the conditioned space, and that duct system efficiency is as important as SEER variations in cooling delivery.
9. Walker et al. 1998 [453] discussed REGCAP, a computer model that evaluates residential HVAC system component performance and whole house performance based on measured data (ducts, equipment, envelope, and climate) to provide an estimate of duct, equipment and envelope performance and net cooling delivered (tons at the register).
10. Walker et al. 1999 [447] compared installed capacity to nameplate and ARI ratings and to ACCA Manual J load estimates.

REFRIGERANT CHARGE

1. Neal 1998 [298] discussed the effect of improper refrigerant charge on SEER, and referred to other studies (Katz 1997 [226]; Proctor 1997 [338]) that measured refrigerant charge.

Diagnostic

STEADY-STATE CAPACITY AND EFFICIENCY

1. ASHRAE 1995 [28] described basic requirements for cooling equipment, including minimum equipment efficiency, field-assembled equipment and components, equipment controls, and maintenance.
2. ASHRAE 1995 [29] described measurements to determine the SEER of unitary air conditioners and heat pumps.
3. EPA 1998 [139] recommended a tune-up of a building's heat exchange equipment that includes (1) mechanically cleaning the air side of heating and cooling coils; (2) chemically cleaning the water side of heating and cooling systems; and (3) unblocking terminal fan coil units and baseboards. Noted that typical cooling and heating system savings can range up to 10%. Also recommended a tune-up of a building's heating and cooling systems (chiller and boiler).
4. Farzad and O'Neal 1993 [146] placed air conditioners in an environmental test chamber (simulating indoor and outdoor temperature and humidity) and measured capacity, EER, and SEER according to DOE/ARI and ASHRAE standards.
5. Groff 1987 [193] described a method to rate air conditioning equipment that reflects part load operating characteristics, proposed as part of ASHRAE/IES 90.1P.

6. LeRoy et al. 1998 [249] evaluated how well three heat exchanger simulation programs (PUREZ, HPSIM, and ACMODEL) predict the dehumidification performance of air conditioning systems over a wide range of conditions and off-design airflow rates. In general, PUREZ and HPSIM over-predicted the sensible heat ratio, while ACMODEL was able to accurately predict total capacity but over-predicted latent capacity.
7. Miller et al. 1989 [272] detailed an exploratory study in which motor-current signal analysis was used as a diagnostic tool for air conditioners and heat pumps, relating motor-current startup waveforms to level of refrigerant charge and coefficient of performance.
8. Proctor 1991 [333] discussed how to field-measure cooling system efficiency using airflows, temperatures and electrical input rates. Discussed the superheat method to determine charge, and new and replacement equipment sizing and installation criteria.
9. Proctor 1997 [338] compared installed capacity to design load estimated by ACCA Manual J.
10. Sherman et al. 1987 [401] found that EER and SEER accuracies were unacceptable due to problems measuring condenser airflow.
11. Sonderegger et al. 1980 [411] measured cooling efficiency of a central air conditioning system with the electric co-heat technique.
12. Ternes 1987 [420] described data parameters to collect in single-family retrofit research projects and described data analysis approaches and issues. Data parameters include (a) basic data (house characteristics, leakage measurements, metered performance of HVAC systems, and verification of retrofit installation quality); (b) time-sequential data (sub-metered space-conditioning energy consumption, weather station measurements [dry bulb, horizontal solar radiation, humidity, wind speed and direction], indoor temperature and humidity, total fuel consumptions [billing meter data], wood heating usage, and sub-metered water heating energy consumption); (c) optional occupant-behavior data (additional indoor temperature and humidity, hourly heating and cooling thermostat set-points); (d) geographic characteristics (terrain and shielding); and (e) distribution system data (duct leakage area measured using fan pressurization).
13. UL 1999 [442] named U.S. and Canadian test standards for measuring the energy efficiency of large and small air conditioners and heat pumps.
14. Walker et al. 1998 [453] discussed REGCAP, a computer model that evaluates residential HVAC system component performance and whole house performance based on measured data (ducts, equipment, envelope, and climate) to provide an estimate of duct, equipment and envelope performance and net cooling delivered (tons at the register).

Refrigerant Charge

1. CEC 1999 [66] presented California building code Title 24 energy efficiency requirements (EERs) and integrated part load values (IPLVs) for unitary air conditioners and heat pumps.
2. Damasceno et al. 1991 [102] discussed three modeling options (refrigerant mass inventory, coil circuitry mapping and internal volume calculations, and a void fraction model) used to correlate heat pump refrigerant charge to heating and cooling capacities.
3. EPA 1997 [138] listed Energy-Star qualifying energy efficiencies for HVAC devices including gas and oil furnaces, gas and oil boilers, central air conditioners, air source heat pumps, geothermal heat pumps, and gas-fired heat pumps.
4. Farzad and O'Neal 1993 [146] looked at the effect of the level of refrigerant charge and type of expansion device on AC system performance (total capacity, EER, SEER).
5. Kirby et al. 1998 [235] presented the results of research looking at non-uniform airflow across a room air conditioner condensing coil; over a wide range of operating conditions with superheated exit conditions, the resulting sensible and latent heat transfer and air-side pressure drop penalties were quite small.
6. Miller et al. 1989 [272] detailed an exploratory study in which motor-current signal analysis was used as a diagnostic tool for air conditioners and heat pumps, relating motor-current startup waveforms to level of refrigerant charge and coefficient of performance.
7. Neal 1998 [298] mentioned ACCA Manual J equipment sizing criteria.
8. Perry et al. 1999 [320] described a program to market the CheckMe! refrigerant-charge and airflow computer expert system (CES) to HVAC

contractors, technicians, and customers. Described the CES inputs, outputs, and apparatus, including the use of superheat and subcooling to determine refrigerant charge level on AC units with fixed and variable metering devices, respectively. Also described how the AC's measured superheat or subcooling can be compared to target values to determine if the unit is correctly charged.

9. Proctor and Downey 1999 [336] described a program to market the Check-Me! refrigerant-charge and airflow computer expert system (CES) to HVAC contractors, technicians, and customers. Briefly described the CES inputs, outputs, and apparatus. This material also covered in Proctor 1999 [334].

10. Rossi and Braun [355] presented a method designed to run in real-time for automated detection and diagnosis of faults in vapor compression air conditioners. It only requires temperature measurements and one humidity measurement. The differences between measured thermodynamic states and predicted states obtained from models for normal performance (residuals) are used as performance indices for both fault detection and diagnosis. For fault detection, uses statistical properties of the residuals for current and normal operation to classify the current operation as normal or faulty. Performs a diagnosis by comparing the directional change of each residual with a generic set of rules unique to each fault. States this diagnostic technique does not require equipment-specific learning, is capable of detecting about a 5% loss of refrigerant and can distinguish between refrigerant leaks, condenser fouling, evaporator fouling, liquids line restrictions and compressor valve leakage.

EVAPORATIVE COOLERS

1. Otterbein 1996 [309] discussed methods to determine evaporative cooler pad performance. Also presented cooler maintenance guidelines and sizing and installation guidelines for three evaporative cooling system types (air conditioner add-on, independent ducted and window mounted systems).

EQUIPMENT SELECTION AND SIZING

1. Neal 1992 [299] discussed air conditioning service call components (written report, coil cleaning, airflow, charge, capacity). Discussed factors to be taken into account to optimize performance when sizing and installing equipment in retrofit applications, including sensible/latent ratio, duct efficiency, charge, equipment location, and replacing indoor unit when replacing outdoor unit with higher efficiency condenser.

2. Parker 1991 [311] provided pointers for designing and installing whole house fan systems.

3. Proctor et al. 1995 [332] discussed different sizing methods, comparing various rules of thumb (for example, ft^2/ton) to ACCA Manual J and Manual S load calculations. Also discussed how oversized systems increase cost and decrease system efficiency.

4. Proctor and Albright 1996 [335] discussed sizing and retrofit recommendations to optimize cooling equipment performance (charge, sizing, airflow and ducts).

Norm

1. ASHRAE 1993 [27] specified equipment selection criteria, minimum equipment-efficiency levels, sizing procedures from ASHRAE Handbook of Fundamentals, sizing factors (not more than 125% of design sensible load, latent capacity not less than calculated design latent load), and design conditions to be used for compliance with the prescriptive requirements of ASHRAE Standard 90.2-1993.

2. ASHRAE 1995 [28] specified standard rating conditions, operating factors, applicable standards, and minimum performance factors for air conditioners and heat pumps.

3. BII 1998 [53] recommended a general procedure for sizing HVAC equipment, specifying who should perform the sizing.

4. Cummings et al. 1990 [98] found that after sealing duct leaks in 25 homes, cooling consumption dropped 18% in those homes.

5. DOE 1995 [116] discussed background information on HERS heating, air-conditioning and water heating equipment for HERS policy options being discussed in DOE's 1995 request for comments on fuel neutrality and adjustment factors, and standard efficiencies.

6. DOE 1995 [117] discussed (in greater detail than DOE 1995 [116]) the analysis of heating, air-conditioning, and water-heating equipment adjustment factors for the HERS guidelines.

7. Katz 1997 [226] discussed results of heat pump / air conditioner charge and sizing evaluations in 100 new homes; of 22 systems measured, 14 were over-charged, five were under-charged and only three were correctly charged. Of 50 house load calculations run (59 systems), one was undersized, six were within the correct range and 52 were oversized; median oversizing was 0.81 tons.
8. Parker 1991 [311] discussed and compared the thermal performance of whole house fans, air conditioning, and combined whole house fan / air conditioner systems in a Florida home. Discussed the impact of the systems on floor slab temperatures.
9. Perry et al. 1999 [320] reported the results of 264 CheckMe! refrigerant charge level tests performed in Fresno and Clovis, CA.
10. Proctor 1991 [333] discussed problems found in cooling systems in 15 existing Fresno, California homes.
11. Proctor 1997 [338] measured refrigerant charge level by weighing, compared levels to factory nameplate ratings and actual refrigerant line set lengths, and discussed demerits of various rules of thumb for using refrigerant gage pressure to predict charge level.
12. Skopek 1999 [406] described an alarm system triggered by a refrigerant leak.
13. Treidler and Modera 1994 [431] compared the energy impact of high-SEER AC units vs. the effect of downsized units with duct retrofits. Based on simulation results, high-SEER units saved energy over the cooling seasons while downsized units with duct retrofits saved peak demand consumption.
14. Walker et al. 1998 [453] discussed REGCAP, a computer model that evaluates residential HVAC system component performance and whole house performance based on measured data (ducts, equipment, envelope, and climate) to provide an estimate of duct, equipment and envelope performance and net cooling delivered (tons at the register). Applied in a Sacramento field test (2,000 ft^2 house), they found that tight ducts could save almost a ton of cooling.
15. Werling et al. 1998 [460] specified Energy-Star home SEER level requirements for homes in hot, moderate, and cold climates.

2.2 Heating Equipment - Furnaces, Boilers, and Heat Pumps

Metric

STEADY-STATE CAPACITY AND EFFICIENCY

1. Domanski et al. 1991 [124] defined heat pump performance metrics, including heating seasonal performance factor (HPSF), heating capacity at 47ºF (Q_{47}), and indoor coil scaling factor F_c (ratio of condensing capacities of a mixed and matched coil).
2. Kweller 1985 [243] defined part-load efficiency and off-period sensible heat loss of vented heating equipment.
3. Phillips 1998 [325] discussed furnace performance factors including cfm per 1000 Btu/hr, pressure drops, fan power consumption, power factors, furnace efficiency, and sizing factors.
4. Sherman et al. 1987 [401] measured parameters to determine furnace steady-state and seasonal efficiency, including electric energy use by fans, cycling losses, and flue losses.
5. Walker and Modera 1998 [451] compared measured data to calculated duct system delivery effectiveness using the ASHRAE Standard 152P and the ASHRAE 1996 Handbook delivery effectiveness methods. On average, the 152P methods adequately estimate delivery efficiency as measured. Conducted pre- and post-duct leakage reduction measurements and calculations.

Diagnostic

STEADY-STATE CAPACITY AND EFFICIENCY

1. ASHRAE 1993 [24] specified the ASHRAE test procedure for determining cyclic and part-load performance, methods for interpolating and extrapolating test data, and a calculation procedure for establishing seasonal performance using a test chamber and test rig. The test procedures can be used to compare energy consumption measures of various furnace and boiler models, rather than an absolute measure of performance of any specific installation configuration.

2. Bohac et al. 1996 [310] described a short-term monitoring protocol to determine the effectiveness of building envelope and/or mechanical system improvements. The protocol works better on a sample of houses than on an individual house.

3. Domanski et al. 1991 [124] described a procedure for calculating heat pump's heat capacity at 47ºF (Q_{47}) and heating seasonal performance factor (HPSF) without laboratory testing of a complete system; evaluates impact of indoor coil, expansion device, and fan on system performance.

4. Dutton 1994 [129] discussed flame adjustments for furnace and water-heater burners. A diagnosis table for burner problems included possible conditions, symptoms, and how to correct the problem. Discussed flue gas analysis and combustion efficiency, acceptable limits, testing devices (chemical or electronic flue gas analyzers, CO_2 and O_2 analyzer, stack thermometer, CO tester, draft gage, combustion efficiency calculators, manometer), troubleshooting table (symptoms, causes and repair strategies).

5. EPA 1998 [139] recommended a tune-up of a building's heat exchange equipment that includes (1) mechanically cleaning the air side of heating and cooling coils; (2) chemically cleaning the water side of heating and cooling systems; and (3) unblocking terminal fan coil units and baseboards. Noted that typical cooling and heating system savings can range up to 10%. Also recommended a tune-up of a building's heating and cooling systems (chiller and boiler).

6. Greely et al. 1992 [177] described the use of an elapsed-time meter to record furnace run time, the results of which are used with the measured firing rate and local weather data to determine pre- and post-retrofit furnace energy consumption.

7. Griffith 1983 [183] discussed measuring average furnace gas consumption using an inline gas meter. A year of weekly average gas consumption was plotted versus weekly average outdoor temperature to evaluate the effect of vent dampers on gas consumption. Also discussed the effect of pulse combustion furnaces and vent dampers on heating gas consumption in eight installations (seven in basements and one in a slab-on-grade house). The use of a pulse combustion furnace resulted in an 18.3% improvement in performance. The use of vent dampers resulted in an 8.8% improvement in performance in the slab-on-grade house, and a 3.8% improvement in performance for furnaces and water heaters located in the heated space of split-level houses. No improvement was seen in houses where the furnaces were located in unconditioned basements.

8. Hayden 1992 [209] discussed retrofit strategies (reduced firing rate, dilution air, delayed-action solenoid valve, flame retention head burner) to improve oil furnace efficiency.

9. Jenkins 1991 [220] discussed how to identify and troubleshoot heat pump heating performance problems (ducts, thermostats and controls, airflow, refrigerant charge and leakage), and how to measure heating efficiency.

10. Kweller 1985 [243] described an alternative to tracer-gas methods (controlled flow of gas to a small gas-fueled burned that simulates normal operating flue or stack temperatures) for measuring off-cycle energy loss from vented heating equipment.

11. Phillips 1998 [325] measured furnace performance factors including cfm per 1000 Btu/hr, pressure drops, fan power consumption, power factors, furnace efficiency, and sizing factors. Also, described a protocol for measuring the energy performance of residential forced-air heating systems installed in Canadian houses (occupant interview, collection of HVAC nameplate data, measurements of airflow, pressure, and power consumption). Also recommended that the minimum external static pressure rise used in furnace annualized fuel utilization efficiency (AFUE) tests be increased to at least 125 Pa, and that consumer-oriented furnace efficiency ratings include information on furnace electrical consumption.

12. Shen 1991 [370] described the Minnesota Low-Income Weatherization Program's "energy buster" computerized auditor training program; includes the "energy buster" furnace audit form that covers general information, controls, gas supply, distribution, operational tests, venting and chimneys.

13. Sherman et al. 1987 [401] found that the steady-state seasonal efficiency test takes approximately 2 hours.

14. Walker et al. 1998 [453] compared measured data to calculated duct system delivery effectiveness using the ASHRAE Standard 152P and the ASHRAE 1996 Handbook delivery

effectiveness methods. On average, the 152P methods adequately estimate delivery efficiency as measured. Conducted pre- and post- duct leakage reduction measurements and calculations.

EQUIPMENT SELECTION AND SIZING

1. Beers 1994 [47] discussed sizing and installation requirements for condensing furnaces (venting, chimney liners, condensate drainage, sizing, electrical consumption, filters and ductwork). Discussed how house indoor air quality may change due to upgrading to a condensing furnace, including higher humidity (the old naturally-vented furnace may have been acting as a continuously running exhaust fan because of stack effect), additional noise, and cooler air (due to higher airflow across the heat exchanger); provided troubleshooting recommendations.
2. Schalch and Fryer 1992 [364] discussed the Energy Crafted Home's requirement that heating and water heating equipment must have sealed or closed combustion.

Norm

STEADY-STATE CAPACITY AND EFFICIENCY

1. ASHRAE 1993 [27] specified equipment selection criteria, minimum equipment efficiency levels, sizing procedures (ASHRAE Handbook of Fundamentals), sizing factors (not more than 170% of design load), and design conditions to be used for compliance with the prescriptive requirements of ASHRAE Standard 90.2-1993.
2. ASHRAE 1995 [28] specified standard rating conditions, operating factors, applicable standards, and minimum performance factors for furnaces.
3. CEC 1999 [66] presented California building code Title 24 thermal efficiency requirements for warm-air furnaces.
4. Cummings et al. 1990 [98] found that after sealing duct leakage in 25 homes, heating capacity could be reduced 1.6 kW per house on average.
5. DOE 1995 [116] discussed background information on HERS heating, air-conditioning and water heating equipment for HERS policy options being discussed in DOE's 1995 request for comments on fuel neutrality and adjustment factors, and standard efficiencies.
6. DOE 1995 [117] discussed (in greater detail than DOE 1995 [116]) the analysis of heating, air-conditioning, and water heating equipment adjustment factors for the HERS guidelines.
7. EPA 1997 [138] listed Energy-Star qualifying energy efficiencies for various HVAC devices, including gas and oil furnaces, gas and oil boilers, central air conditioners, air-source heat pumps, geothermal heat pumps, and gas-fired heat pumps.
8. Macriss and Zawacki 1981 [259] discussed the furnace-related energy savings achieved from five retrofit options: reducing gas input rate; reducing gas input rate and adding a baffle to the flue outlet; adding a vent restrictor; adding a vent damper; and adding electronic ignition.
9. Parker 1989 [313] discussed the effect of heating system type on air change rates and energy consumption in electrically heated homes. Found that forced air systems use 17% to 22% more energy than non-forced-air electric resistance systems. Possible causes included duct air leakage and associated heat transfer, induced air leakage from combustion systems with chimneys, and differential pressures within the building envelope.
10. Phillips 1998 [325] conducted a field study of furnace performance factors, including airflow per unit heating capacity (newer post-1990 furnaces have double the cfm/kW of pre-1980 furnaces), duct sizing, system pressure drops and noise factors, fan power consumption, power factor, and furnace efficiency (AFUE). Reduced system airflow results in higher flue losses and lower AFUEs pressure drop across dirty filters are significant. Fan energy parasitics, static pressure drops over dirty filters, and effect of reduced airflow should be taken into account when determining AFUE values. Also, tabulated characteristics (fuel type, drive type, operation mode, rated output) of 71 furnaces surveyed in 68 Canadian homes.
11. Ternes 1987 [420] described data parameters to collect in single-family retrofit research projects and described data analysis approaches and issues. Data parameters include (a) basic data (house characteristics, leakage measurements, metered performance of HVAC systems, and verification of retrofit installation quality); (b) time-sequential data (submetered space-conditioning energy consumption, weather station measurements [dry bulb, horizontal solar radiation, humidity, wind speed and direction],

indoor temperature and humidity, total fuel consumptions [billing meter data], wood heating usage, and submetered water heating energy consumption); (c) optional occupant-behavior data (additional indoor temperature and humidity, hourly heating and cooling thermostat setpoints); (d) geographic characteristics (terrain and shielding); and (e) distribution system data (duct leakage area measured using fan pressurization).

EQUIPMENT SELECTION AND SIZING

1. ASHRAE 1993 [27] specified equipment selection criteria, minimum equipment efficiency levels, sizing procedures (ASHRAE Handbook of Fundamentals), sizing factors (not more than 170% of design load), and design conditions to be used for compliance with the prescriptive requirements of ASHRAE Standard 90.2-1993.
2. BII 1998 [53] recommended a general procedure for sizing HVAC equipment, specifying who should perform the sizing.

2.3 Thermal Distribution Systems— Air and/or Water Flow

Metric

DISTRIBUTION SYSTEM EFFICIENCY

1. Andrews 1996 [5] defined delivery efficiency and distribution efficiency.
2. ASHRAE 1999 [32] defined and formulated delivery effectiveness, distribution system efficiency, equipment efficiency, equipment factor, equipment capacity, design efficiency, and seasonal efficiency.
3. Francisco and Palmiter 1998 [168] presented a general equation for steady-state delivery efficiency [same as in ASHRAE 152P (ASHRAE 1999 [32])].
4. Francisco et al. 1999 [169] defined Francisco-Palmiter delivery efficiency, distribution efficiency, and regain.
5. Jump et al. 1996 [223] defined delivery efficiency and equipment efficiency.
6. Modera et al. 1992 [282] proposed a framework for characterizing the thermal distribution system efficiency that accounts for (a) the interaction between the thermal distribution system and the building envelope; (b) interactions with the space conditioning equipment; and (c) weather-dependent energy loss.
7. Modera and Jump 1995 [274] defined system delivery efficiency, fractional energy loss due to conduction, and distribution efficiency.
8. Palmiter and Francisco 1996 [310] defined air leakage efficiency and overall duct efficiency.
9. Proctor 1998 [339] defined distribution system efficiency.
10. Siegel and Davis 1998 [403] verbally defined system efficiency.
11. Walker et al. 1996 [446] defined power delivered to duct system, power lost from ducts due to supply leakage, fractional leakage loss for supply ducts, power delivered by ducts to the conditioned space, power lost from the ducts by conduction, fractional conduction loss, return loss, and fractional return loss.
12. Walker et al. 1999 [447] defined delivery efficiency.

DUCT LEAKAGE

1. ASHRAE 1988 [14] defined duct leakage classifications.
2. ASTM 1994 [37] defined effective leakage area and compared ELA_{25} to ELA_4.
3. Cummings 1998 [94] described duct leakage in terms of CFM_{25} per duct surface area and CFM_{25} per floor area.
4. Cummings and Tooley 1989 [97] measured duct leakage, as well as air change rates with and without the forced air system running, before and after duct sealing.
5. Cummings and Withers 1998 [95] defined CFM_{25}, $CFM_{25,out}$, and $CFM_{25,tot}$ duct leakage area metrics.
6. EPA 1997 [138] listed four tests used to ensure that subcontractors are performing quality work: a blower-door test to detect excessive envelope leakage, a duct leakage test, an HVAC system inspection, and testing airflow across the inside coil to ensure proper airflow to the duct system.
7. Kolb and Ternes 1995 [240] measured CFM_{50} before and after duct sealing in 96 houses to gage the benefits of retrofit.
8. Modera and Byrne 1997 [275] gave formulas for supply and return duct leakage flows.

9. National Association of State Energy Officials (NASEO) 1999 [295] discussed observable leakage pathways in relation to HERS rating.
10. Proctor et al. 1993 [337] discussed choice of leakage-flow exponent, and defined two duct leakage ratios (ratio of duct leakage inside envelope versus that outside envelope, and ratio of supply leakage area to return leakage area).
11. Siegel and Manclark 1998 [404] empirically related duct leakage to outdoors ($Q_{50,ext}$) to pressure-pan measurements via a "pressure-pan equation".
12. Walker et al. 1998 [453] discussed REGCAP, a computer model that evaluates residential HVAC system component performance and whole house performance based on measured data (ducts, equipment, envelope, and climate) to provide an estimate of duct, equipment and envelope performance and net cooling delivered (tons at the register).

REGISTER AIRFLOW & THERMAL CAPACITY FLOW

1. Foltz 1984 [160] found from calibrations of six type of airflow measurement devices that a laboratory-developed correction coefficient ("K-factor") is needed for each combination of measurement device and register type. However, he found that a flow hood could use a single correction coefficient for diffusers.
2. Walker et al. 1998 [449] defined tons at the register (TAR), a measure of the enthalpy flow delivered to the register.
3. Walker et al. 1998 [453] discussed REGCAP, a computer model that evaluates residential HVAC system component performance and whole house performance based on measured data (ducts, equipment, envelope, and climate) to provide an estimate of duct, equipment and envelope performance and net cooling delivered (tons at the register).

THERMAL DISTRIBUTION GLOSSARY

1. Home Energy 1993 [213] defined common terms associated with forced air distribution systems and their testing, and presented a schematic of a typical distribution system.

Diagnostic

DISTRIBUTION SYSTEM EFFICIENCY

1. Andrews 1996 [5] compared three ASHRAE 152P techniques for measuring duct efficiencies. Method A = directly measure heat input and output. Method B = use "Design Pathway" tool to estimate from measured fan flow and duct blaster + blower door duct leakage; Level 2 = replace duct-pressurization test of Method B with a faster technique based on P_{space} - P_{attic} and envelope leakage, and replace the fan flow measurement with an estimate based on the fan curve and the pressure difference across the fan.
2. Andrews et al. 1998 [7] compared design and seasonal distribution efficiencies measured for the same house by five teams using ASHRAE 152P; included error analysis.
3. ASHRAE 1999 [32] provided forms, procedure, and spreadsheet to compute forced-air duct-system efficiencies.
4. Francisco and Palmiter 1998 [168] measured and modeled delivery efficiency of seven manufactured homes, and evaluated the effect of ASHRAE 152P default values compared to measured data. As more default variables were used, greater variation from the measured results was observed.
5. Jump et al. 1993 [69] measured duct leakage areas, house and duct static pressure differences under different system configurations, leakage flow rate, system airflows, duct conduction losses, and duct thermal delivery efficiencies.
6. Jump et al. 1996 [223] monitored characteristic temperatures, weather, and HVAC power consumption for two weeks before and after duct retrofits of 24 Sacramento homes to measure the effect of retrofit on delivery efficiency and equipment efficiency.
7. Modera and Jump 1995 [274] measured distribution system efficiency by monitoring plenum, register, attic, house, and outdoor temperatures, as well as heat-pump strip-heat electricity demand, for two weeks.
8. Proctor 1998 [339] reported a verification test of ASHRAE 152P that found that the standard correctly predicted the change in cooling load induced by a supply leak, but underestimated by half that induced by a return leak.

9. Saunders et al. 1994 [363] described the measured performance rating (MPR) method, an overnight co-heat test that predicts building load coefficient (BLC), heating system efficiency, and annual fuel consumption of single-family detached home.
10. Siegel and Davis 1998 [403] used co-heating to measure system efficiency before and after retrofits.

DUCT LEAKAGE

1. Andrews 1996 [5] briefly described the blower door + flow hood and duct blaster + blower door methods, discussing sources of error and comparing the methods.
2. Andrews et al. 1996 [6] described an electric coheat test.
3. Andrews et al. 1998 [7] summarized and illustrated the house pressure test (HPT).
4. ASHRAE 1999 [32] specified procedures for duct leakage measurement (duct pressurization + blower door, house pressure test).
5. ASTM 2000 [36] discussed duct leakage criteria and evaluation methods using ASTM E1554. Measured duct leakage, expressed as an airflow rate at 25 Pa, should be no more than 5% of the total system airflow rate. Alternatively, the effective leakage area associated with duct leakage should be no more than 5% of the effective leakage area of the whole house as measured using ASTM E779.
6. BII 1998 [53] briefly described Duct Blaster measurement of CFM_{25} and CFM_{50}.
7. Coito et al. 1998 [83] briefly described blower-door subtraction, blower door + flow hood, and duct blaster test methods for measuring duct leakage.
8. Cummings 1998 [94] briefly described the duct-blaster test method.
9. Cummings and Tooley 1989 [97] described duct-leakage tests, as well as tracer-gas and blower-door tests to measure the effect of forced-air system operation on infiltration.
10. Davis et al. 1998 [103] used a screening protocol to determine if a home's duct system was leaky enough to warrant retrofit. Criteria included external supply duct CFM_{50}, fraction of ducts accessible, existence of safety/furnace problems, and the presence of duct and floor insulations.
11. EPA 1997 [138] discussed three duct-leakage measurement procedures: the house pressure test, the blower-door subtraction method, and the duct blaster test. Also listed four tests used to ensure that subcontractors are performing quality work: a blower-door test to detect excessive envelope leakage, a duct leakage test, an HVAC system inspection, and testing airflow across the inside coil to ensure proper airflow to the duct system.
12. Fugler 1989 [170] described the Duct Test Rig, a calibrated fan device for purposes including measurement of duct leakage (in the fashion of a duct blaster).
13. Gammage et al. 1986 [173] discussed tracer gas airflow measurements used to determine the effect of central fan operation and duct leakage on infiltration air change rates.
14. Jump and Modera 1993 [222] discussed distribution system tests, including register flow tests, duct leakage tests, and air-distribution-system performance tests. Also, measured duct leakage areas, house and duct static pressure differences under different system configurations, leakage flow rate, system airflows, duct conduction losses, and duct thermal delivery efficiencies.
15. Jump et al. 1996 [223] noted that the House Pressure Test used in their study was a slightly modified version of ASTM 779-91.
16. Kolb and Ternes 1995 [240] measured duct leakage in 96 homes via blower-door subtraction.
17. Modera 1993 [278] compared ASTM blower-door only and blower-door / capture-hood duct leakage measurement techniques.
18. Modera 1994 [280] described a 31-house field study of distribution system performance (including fan pressurization & flow-capture hood duct leakage measurements; duct pressure measurements; and pressure imbalance measurements). Also described a simulation tool designed to evaluate peak-load mitigation and overall energy conservation potential for improved distribution systems.
19. Modera and Byrne 1997 [275] presented a detailed and illustrated general-audience description of the House Pressure Test (HPT) duct leakage test.
20. NAHB 1997 [293] measured total and unconditioned duct leakage with the ASTM E-1554 duct pressurization tests.

21. National Association of State Energy Officials (NASEO) 1999 [295] briefly described the HERS procedure for visual inspection of duct system (i.e., looking for leaks).

22. Proctor 1997 [338] applied duct blaster and duct blaster + blower door test methods to determine duct leakage for 28 systems.

23. Proctor et al. 1993 [337] described a wide range of quantitative and qualitative duct leakage diagnostics, including (a) the blower door + flow hood, blower door subtraction, and duct blaster methods, comparing the methods and discussing their error sources; (b) the Blasnik method for calculating the ratio of duct leakage to outdoors versus leakage to indoors, and the "Half Nelson" method for estimating the ratio of supply leakage area to return leakage area; (c) the smoke stick method for determining which branches have major leaks; (d) the pressure-pan method for detecting duct leaks; and (e) a "blocked register pressure" extension of the pressure-pan technique that can be used while the registers are taped shut. This information is also presented in Downey and Proctor 1994 [125].

24. Retrotec 1998 [346] noted some issues to be aware of when sealing duct systems: (1) consider static pressure changes due to duct sealing (less airflow, increased noise at the registers due to higher velocities); (2) know how tight the house is (the duct leakage may be the primary driving force behind air infiltration, install a controlled ventilation system if the envelope is tight); (3) resolve existing health and safety issues; (4) address pressure imbalances caused by closed internal doors; (5) pursue comprehensive training (interactive effects between duct leakage, system static pressures, house tightness, interior door closure, moisture and combustion safety); (6) do pre- and post- testing to show leakage reduction; (7) address inaccessible duct leaks; (8) pay attention to the thermal envelope; (9) replace ductwork when appropriate; and (10) provide duct repair, not just duct sealing.

25. Robison and Lambert 1989 [351] measured duct leakage via (1) whole-house ELA measurement with ducts open and ducts sealed; (2) Q_{50} airflow measured similarly by blower door; (3) duct contribution to ELA extrapolated from flow hood measurements; and (4) duct contribution to Q_{50} extrapolated similarly. Also, discussed fan pressurization, tracer gas, and flow hood measurement techniques to determine the relationships between duct leakage, envelope leakage, infiltration rates, and ventilation rates.

26. Siegel and Manclark 1998 [404] described in detail the pressure-pan duct-leakage detection method and its associated errors.

27. Ternes 1987 [420] described data parameters to collect in single-family retrofit research projects and described data analysis approaches and issues. Data parameters include (a) basic data (house characteristics, leakage measurements, metered performance of HVAC systems, and verification of retrofit installation quality); (b) time-sequential data (submetered space-conditioning energy consumption, weather station measurements [dry bulb, horizontal solar radiation, humidity, wind speed and direction], indoor temperature and humidity, total fuel consumptions [billing meter data], wood heating usage, and submetered water heating energy consumption); (c) optional occupant-behavior data (additional indoor temperature and humidity, hourly heating and cooling thermostat setpoints); (d) geographic characteristics (terrain and shielding); and (e) distribution system data (duct leakage area measured using fan pressurization).

28. The Energy Conservatory 1999 [422] answered FAQs related to using Energy-Conservatory's duct blaster, blower door, and Automated Performance Testing System (APT) to measure envelope leakage and duct leakage.

29. Walker et al. 1998 [448] described in detail (and in most cases with extensive uncertainty analysis) various duct leakage measurement methods, including the Irvine Quality Plus (IQ+) Duct Pressurization, Duct and House Pressurization, House Pressure Test, and Nulling Pressure Test.

30. Walker et al. 1998 [453] discussed REGCAP, a computer model that evaluates residential HVAC system component performance and whole house performance based on measured data (ducts, equipment, envelope, and climate) to provide an estimate of duct, equipment and envelope performance and net cooling delivered (tons at the register).

31. Walker et al. 1999 [447] described in detail the Delta Q duct leakage test.

32. West et al. 1998 [461] referred to (but does not detail) the Eugene (Oregon) Water & Electric Board program called "Comfort S.E.A.L." (Stop Expensive Air Leaks) that uses simplified field protocols to identify duct-seal opportunities quickly and inexpensively.

SYSTEM AIRFLOW

1. ASHRAE 1988 [14] described air balancing stations, airflow measurement techniques (pitot-tube traverse of ducts, vane-anemometer readings of register flows), and estimation of flow rates at volume/pressure control assemblies for HVAC airflow measurement.
2. ASHRAE 1992 [21] described laboratory techniques for airflow measurement.
3. ASHRAE 1999 [32] included a fan-flow measurement procedure for air handler total flow.
4. Bevirt 1994 [52] listed nine airflow-measurement instruments, specifying recommended uses and limitations.
5. Cheong and Riffat 1993 [69] described an active (pumped) tracer gas system for measuring duct airflow.
6. Cohen 1995 [82] provided checklists and information to consider at all project phases (design, construction, start-up, final test and balance, final acceptance tests) to test performance of the HVAC system for air quality.
7. Cummings and Withers 1997 [96] discussed (a) shortcomings of TAB practices that neglect air leakage (equating register flow to system flow); (b) airflow measurement methods (flow hood, pitot-tube traverse, capture tent, building as capture tent, calibrated fan attached to HVAC system, and tracer gas injection); and (c) choice of method for HVAC airflow measurement.
8. EPA 1997 [138] listed four tests used to ensure that subcontractors are performing quality work: a blower-door test to detect excessive envelope leakage, a duct leakage test, an HVAC system inspection, and testing airflow across the inside coil to ensure proper airflow to the duct system.
9. EPA 1998 [139] recommended a building TAB analysis that includes both a complete review of a building's design documentation, and investigation of (1) air system flow rates; (2) water system flow rates; (3) temperatures of heating and cooling delivery systems (air and water side); (4) positions and functioning of flow control devices (air and water); (5) control settings and operation; and (6) fan and pump speeds and pressures. It noted that heating and cooling savings can range up to 10%.
10. Jump and Modera 1993 [222] discussed distribution system tests, including register flow tests, duct leakage tests, and air-distribution-system performance tests.
11. Modera and Jump 1995 [274] measured residential system-fan airflow with a constant-injection tracer-gas technique (ASTM Standard E741).
12. Perry et al. 1999 [320] described a program to market the CheckMe! refrigerant-charge and airflow computer expert system (CES) to HVAC contractors, technicians, and customers. Described the CES inputs, outputs, and apparatus, including how the AC's temperature split (difference between supply and return plenums' dry bulb temperatures) can be compared to target values to determine if the airflow is correct.
13. Phillips 1998 [325] described a protocol for measuring the energy performance of residential forced-air heating systems installed in Canadian houses (occupant interview, collection of HVAC nameplate data, measurements of airflow, pressure, and power consumption). Also recommended that the minimum external static pressure rise used in furnace annualized fuel utilization efficiency (AFUE) tests be increased to at least 125 Pa, and that consumer-oriented furnace efficiency ratings include information on furnace electrical consumption.
14. Proctor and Downey 1999 [336] described a program to market the Check-Me! refrigerant-charge and airflow computer expert system (CES) to HVAC contractors, technicians, and customers. Briefly described the CES inputs, outputs, and apparatus. This material also covered in Proctor 1999 [334].
15. Robison and Lambert 1989 [351] measured fan-driven air exchange via SF_6 tracer gas testing.
16. Sauer et al. 1996 [362] compared different methods to measure airflow through a short outside air duct (commercial application).
17. Walker et al. 1998 [449] described register flow measurement with a fan-assisted flow hood, fan flow measurement using supply ducts as a flowmeter (as proposed in ASHRAE Standard 152P (ASHRAE 1999 [32]) and CEC ACM appendix F), and tracer gas measurement of fan flow.

REGISTER AIRFLOW & THERMAL CAPACITY FLOW

1. Berckmans et al. 1993 [50] discussed a method to visualize and quantify the airflow pattern in a

ventilated room using smoke, a camera, and a computer.

2. BII 1998 [53] briefly described flow-hood measurement of register flow.
3. CMHC 1998 [79] described an inexpensive test to measure the flow out of heating registers using a wire coat hanger and a garbage bag.
4. EPA 1997 [138] listed four tests used to ensure that subcontractors are performing quality work: a blower-door test to detect excessive envelope leakage, a duct leakage test, an HVAC system inspection, and testing airflow across the inside coil to ensure proper airflow to the duct system.
5. Foltz 1984 [160] measured systematic and random errors of devices used to measure register flows (a rotating vane anemometer, three types of deflecting vane anemometer, a flow hood, and a hotwire anemometer).
6. Karki and Karjalainen 1999 [225] discussed performance factors for life-cycle analysis of commercial air handlers and practical fault-detection methods.
7. Modera and Jump 1995 [274] measured residential register airflows (low) with a calibrated fan + flow hood.
8. Ngo and Dexter 1999 [301] discussed cooling coil automated fault detection for commercial building air handlers.
9. Walker et al. 1996 [446] measured register flows in apartment buildings with a fan-assisted flow-capture hood.
10. Walker et al. 1996 [446] measured the system fan airflow in apartment buildings by blocking off the return from the system fan, attaching a flow hood + fan-assisted flowmeter to the air handler, and adjusting the flow through the fan-assisted flowmeter to recreate the operating-condition supply-plenum pressure.
11. Walker et al. 1998 [449] used the REGCAP software package to simulate initial and final delivered capacity at the registers (TAR). Also described in Walker et al. 1999 [447].

Duct Pressure Drop

1. de Salis et al. 1996 [105] discussed an acoustic technique used to measure duct pressure drop and detect duct obstructions.

Thermal Distribution Glossary

1. Home Energy 1993 [213] defined common terms associated with forced-air distribution systems and their testing, and included a schematic of a typical distribution system.

Water Flow Measurement

1. Bevirt 1994 [52] listed four instruments for measuring water flow and specified recommended uses and limitations.

System Selection and Sizing

1. SMACNA 1993 [407] discussed air system basics, including duct systems and fluid dynamics, and ducted air system testing and balancing procedures, checklists and troubleshooting pointers.

Norm

Duct Leakage

1. Andrews 1996 [5] mentioned that ASHRAE Draft Standard 152P specifies acceptable duct leakage flows.
2. ASHRAE 1995 [28] specified that energy distribution system leaks should be repaired. Specified minimum duct and plenum insulation levels; specified performance and energy factors for replacement motors.
3. Bevirt 1994 [52] presented a table of predicted leakage classes for sealed and unsealed ducts of various types.
4. BII 1998 [53] noted that several California utilities use 140 CFM_{50} as the maximum criterion leakage allowed for a tight duct system, and that CIEE's HVAC design states that acceptable CFM_{25} is 6-7% of fan flow.
5. Cummings 1998 [94] stated the SMACNA standard for duct leakage in terms of CFM_{25} per 100 ft^2 of duct surface area, and a HERS standard for duct leakage flow per floor area. He recommended 50 CFM_{25} per 1000 ft^2 floor area for commercial buildings. Also recommended certain ducting practices.
6. Cummings and Tooley 1989 [97] found that average infiltration rate increased from 0.14 ACH to 1.42 ACH with the forced-air system operating. After duct sealing, the average infiltration rate dropped to 0.31 ACH.

7. Cummings et al. 1990 [98] discussed test procedures to determine the relationship between duct leakage and infiltration and leakage sites using tracer gas tests, blower door testing, smoke testing and visual inspections. Found that, on average, infiltration rates measured with tracer gas correlated to blower-door test results for air handler fan on and off conditions. Also, found that return duct leakage equaled 10% of the air handler airflow and that repairing duct leakage reduced whole house infiltration.

8. Davis et al. 1998 [103] reported pre- and post-retrofit values of envelope leakage (CFM_{50}), supply duct leakage to outside (CFM_{25}, CFM_{50}) and average supply-side pressure-pan measurement (Pa) for 95 homes.

9. Hammon et al. 1999 [200] discussed changes, based on their study, to the CEC Title 24 criteria for tight ducts from a ratio of leakage to floor area to a ratio of leakage to fan flow. The leakage in a finished home must be less than 6% of fan flow to be considered tight. Fan flow can either be determined by direct measurement or by substituting measured return airflow. Also discussed in Hammon and Modera 1996 [199].

10. Jump and Modera 1993 [222] discussed duct leakage areas, house and duct static pressure differences under different system configurations, leakage flow rate, system airflows, duct conduction losses, and duct delivery efficiencies.

11. Katz 1997 [226] discussed Advanced Energy's target for duct leakage (in CFM_{25}, less than 3% of conditioned floor area in ft^2). Presented results of duct leakage tests in 100 new homes; of 130 systems in 96 houses. The median leakage measured was 261 CFM_{25} per system and 360 CFM_{25} per house (or a median leakage of 19.5% as a percentage of floor area).

12. Modera 1994 [280] presented duct-leakage measurements performed in 31 California homes.

13. Parker 1989 [313] discussed the effect of distribution systems on air change rates and energy consumption in electrically heated homes. Found that forced air systems used 17% to 22% more energy than non-forced-air electric resistance systems. Possible causes included duct air leakage and associated heat transfer, induced air leakage from combustion systems with chimneys, and differential pressures within the building envelope.

14. Retrotec 1998 [345] said that a new, well-installed supply and return residential duct system should have an ELA not exceeding 10 in^2.

15. Rose 1999 [353] reviewed SMACNA leakage classes.

16. Walker et al. 1998 [453] discussed REGCAP, a computer model that evaluates residential HVAC system component performance and whole house performance based on measured data (ducts, equipment, envelope, and climate) to provide an estimate of duct, equipment and envelope performance and net cooling delivered (tons at the register). Applied in a Sacramento field test (2,000 ft^2 house), they found that almost a ton of cooling could be saved by with tight ducts.

REGISTER AIRFLOW

1. BII 1998 [53] provided rule of thumb for airflow requirements (1 CFM per ft^2 in living areas), and recommended use of CIEE HVAC design, installation, and test guidelines to prevent excess duct leakage.

SYSTEM AIRFLOW

1. BII 1998 [53] noted that a typical air handler is designed to operate at 0.5 in. w.g.

DUCT INSULATION

1. EPA 1997 [138] listed typical and cost-effective insulation levels in moderate climates for attics, exterior walls, floors (over garage), basement walls (above grade), and ducts.

2. Treidler et al. 1996 [432] said that ducts should be better insulated.

SYSTEM SIZING

1. ASHRAE 1993 [27] specified distribution-system sizing methods (1989 ASHRAE Handbook of Fundamentals or ACCA's Manual D), installation methods (SMACNA, NAIMA), and air balancing methods required for compliance with the prescriptive requirements of ASHRAE Standard 90.2-1993.

2. Hammon et al. 1999 [200] discussed that, based on LBNL's longevity study of duct closure systems, cloth-backed rubber-adhesive tape would not to be permitted under Title 24. Also discussed in Hammon and Modera 1996 [199].

3. Treidler et al. 1996 [432] stated that when a duct system is sealed, resizing the HVAC system can reduce energy use by 20 to 30%.

2.4 Combustion Safety

Metric

BACKDRAFTING & SPILLAGE

1. ASTM 1998 [42] noted that the house depressurization level can be compared to continuous and intermittent pressure differentials (house level depressurizations).
2. CGSB 1995 [67] noted that House Depressurization Level can be compared to both continuous and intermittent pressure limits to predict backdrafting.
3. Grimsrud et al. 1999 [184] noted that house depressurization level may be compared to preset limits to predict backdrafting.
4. Keefe 1994 [228] noted that the draw from a combustion device's exhaust is what prevents backdrafting into the room.
5. Persily 1999 [322] described an IAQ performance guide being developed by ASTM that may include venting of naturally-vented water- and space-heating appliances, house depressurization, unvented space heaters, downdrafting, appliance backdrafting and cold vent establishment.
6. Wilson et al. 1986 [462] related flue gas spillage to depressurization conditions, indoor/outdoor temperature differences, and furnace conditions (standby, pilot light only). Provided depressurization limits for spaces with naturally-vented gas appliances.

Diagnostic

BACKDRAFTING & SPILLAGE

1. ASTM 2000 [36] discussed visual inspection and ASTM E1998 house depressurization, downdrafting, appliance backdrafting and cold vent establishment pressure tests.
2. ASTM 1998 [42] described (a) four tests conducted under induced conditions (house depressurization test with preset criteria, downdrafting test, appliance backdrafting test, and cold vent establishment pressure); (b) a continuous (natural condition) spillage test; and (c) a continuous backdrafting test.
3. CGSB 1995 [67] described a spillage test procedure for vented, fuel-fired, space-heating appliances; water heaters; and fireplaces. Included a checklist and a report form.
4. CMHC 1998 [79] discussed the physics, mechanisms, and corrective measures relating to backdrafting and spillage of combustion appliances.
5. Conibear et al. 1995 [87] discussed protocol and study to evaluate backdrafting, spillage, and CO levels in homes in Chicago. Protocols are based on CGSB 51.71-94 (pressure-induced spillage / backdrafting from vented fuel-fired appliances) and ANSI Standard Z 21.1-1993 (carbon monoxide measurements and determination of free-air CO from ovens).
6. deKieffer 1995 [106] discussed how to conduct combustion safety checks; included furnace and water heater inspection and performance specifications.
7. Dumont and Snodgrass 1990 [128] presented and experimentally validated a simplified theory that quantitatively predicts the conditions under which backdrafting will occur.
8. Dutton 1994 [129] described gas and combustion-related test procedures, including spillage, backdrafting, and gas line leaks.
9. Fugler 1989 [171] listed a variety of tests (flame motion, flue temperature, smoke pencil, flue-to-house pressure) to determine whether building exhaust could induce chimney backdrafting. An inexpensive heat sensor was made of temperature-sensitive color-changing dots, and heat sensing was used as a proxy for combustion gas spillage. This paper also presented a table of house depressurization limits for various appliances and chimneys.
10. Greiner 1997 [179] discussed how to evaluate new furnaces for CO problems, including vent failures, over-firing and heat exchanger failures.
11. Greiner 1997 [180] discussed detecting the presence and source of high CO levels associated with downdrafting.
12. Grimsrud et al. 1999 [184] presented a table summarizing the tests in ASTM 1998 [42].
13. Keefe 1994 [228] briefly described the nature of a worst-case induced-condition backdrafting test.
14. Moffatt 1991 [286] discussed factors leading to furnace and fireplace spillage and backdrafting,

and discussed possible solutions. Described chimney backdrafting tests.

15. NAHB 1997 [293] measured worst-case depressurization of the combustion zone by varying fan status and door positions. Also summarized backdrafting research.
16. Ponessa 1999 [330] discussed a moisture problem case study; the moisture was due to leaking furnace flue gas from a masonry chimney; included diagnostics specific to testing vented appliances.
17. Rajhans 1989 [342] presented a checklist to detect IAQ problems including problems related to combustion (CO), other pollutant sources, HVAC, maintenance, and design.
18. Wilson et al. 1986 [462] discussed depressurization conditions, indoor/outdoor temperature differences, and furnace conditions (standby, pilot light only) in relationship to flue gas spillage. Provided depressurization limits for spaces with naturally-vented gas appliances.

HEAT EXCHANGER LEAKAGE

1. DeWerth and Sobieski 1985 [109] described a three-step method for detecting unacceptable flue gas leakage from furnace heat exchangers (visual examination of heat exchanger, observation of burner flame pattern, and use of tracer gas). Method was field-tested by seven utility companies and found to be more reliable and accurate than their currently-used leak-detection methods (smoke bombs, odor tracing, and salt sprays).
2. Greiner 1997 [179] discussed how to evaluate new furnaces for CO problems, including vent failures, over-firing and heat exchanger failures.

CHIMNEY CONDITION

1. Oberholtzer 1993 [304] provided a step-by-step inspection protocol to diagnose chimney (flue) problems. Techniques included chim-scan tv monitoring check, combustion analyzer, rightsizing the vent, checking for pyrolysis problems, excess condensation development check, excess soot or creosote deposit check, downdraft problem diagnostics, CO testing for fume leakage, and pressure dynamics.

COMBUSTION AIR SUPPLY SIZING AND LOCATION

1. Dutton 1994 [129] discussed combustion air supply sizing, supply locations, and design factors for gas appliances (furnaces, water heaters, boilers).

VENTING SIZING AND LOCATION

1. ASTM 2000 [36] discussed the design and installation of venting systems in compliance with codes and standards.
2. Dutton 1994 [129] discussed vent sizing, draft control equipment and installation requirements.

Norm

BACKDRAFTING & SPILLAGE

1. CGSB 1995 [67] specified continuous and intermittent depressurization limits for various combustion appliances.
2. Conibear et al. 1995 [87] discussed results of a study to evaluate backdrafting, spillage, and CO levels in homes in Chicago. Found that 10.7% of the single-family detached homes tested showed evidence of depressurization conditions that could lead to backdrafting. 7% of homes showed visual evidence of spillage or poor drafting; indoor CO levels equaled or exceeded 10 ppm in 11% of the homes tested; many ovens were not functioning within manufacturer's guidelines.
3. Fugler 1989 [171] listed a variety of tests (flame motion, flue temperature, smoke pencil, flue-to-house pressure) to determine whether building exhaust could induce chimney backdrafting. An inexpensive heat sensor was made of temperature-sensitive color-changing dots, and heat sensing was used as a proxy for combustion gas spillage. This paper also presented a table of house depressurization limits for various appliances and chimneys.
4. Keefe 1994 [228] warned that backdrafting will occur if the room air pressure is more negative than the draw of a combustion device's exhaust (typically only 3 to 5 Pa).
5. Wilson et al. 1986 [462] related flue gas spillage to depressurization conditions, indoor/outdoor temperature differences, and furnace conditions (standby, pilot light only). Provided depressurization limits for spaces with naturally-vented gas appliances.

COMBUSTION AIR SUPPLY SIZING

1. ASHRAE 1993 [27] specified combustion air and automatic vent dampers for combustion

appliances and fireplace requirements (tight-fitting damper, doors and outside combustion air) required for compliance with the prescriptive requirements of ASHRAE Standard 90.2-1993.

CHIMNEY CONDITION

1. Oberholtzer 1993 [304] discussed the accelerated deterioration of chimney (flue) materials due to lower venting temperatures and shorter furnace run cycles.

2.5 Ventilation

Metric

VENTILATION AIRFLOWS AND AIR EXCHANGE RATES

1. Bearg 1999 [46] discussed the use of indoor CO_2 levels as an indicator of ventilation rate.
2. Dale and Ackerman 1993 [101] discussed the change in attic ventilation rate and effect on living space from attic turbine ventilators. Dale and Ackerman 1991 [100] also discussed this research.
3. Forest and Walker 1991 [161] discussed measurement and model input variables to determine airflow and moisture content in attics. Forest and Walker 1992 [162], 1993 [163], 1993 [164], and Walker and Forest 1995 [452] also discussed this research.
4. Koles et al. 1996 [241] discussed ventilation-fan energy efficiency (kW/cfm).
5. Li et al. 1996 [251] defined mean age of air, corrected mean age of air, and outdoor air exchange rate.
6. Mansson 1999 [253] discussed simplified tools for the evaluation of ventilation systems and their effects in new and existing residences.
7. Mudarri 1997 [290] noted several sources of error in estimating outdoor-air ventilation rates from "steady-state" indoor CO_2 levels, including (a) measurement before reaching steady-state state, which overestimates ventilation; (b) overestimation of CO_2 generation by women, children, and the elderly, which overestimates ventilation; and (c) underestimation of outdoor CO_2 levels, which underestimates ventilation. Presented a 10-step process and an assortment of tables to improve the accuracy of ventilation rates estimated from CO_2 levels.
8. Persily 1999 [322] described an IAQ performance guide being developed within ASTM, including a ventilation performance statement that includes whole-building air change rates, outdoor ventilation air distribution, and kitchen and bathroom exhaust rates, all based on ASHRAE Standard 62-1989 [18].
9. Rajhans 1989 [342] recommended using CO_2 level as a surrogate for fresh air supply.
10. Schell 1995 [365] noted that indoor CO_2 levels indicate ventilation rate, and provided tables of CO_2 level equilibrium setpoints for control of ventilation using CO_2.
11. Sherman et al. 1981 [399] validated the LBL air infiltration model with leakage measurements made in a small trailer (Mobile Infiltration Testing Unit) and in an occupied house.
12. Sherman and Grimsrud 1982 [393] calculated a pressure coefficient (relating the wind pressure on the face of a building to the dynamic pressure of the wind) from pressure measurements made with the Mobile Infiltration Test Unit. This study also used a terrain parameter to represent primarily large-scale effects caused by the roughness of the boundary layer in the region surrounding the structure.
13. Yuill and Lovatt 1986 [467] discussed determination of effective ventilation rates using a set pollutant concentration (pre-cursor to ASHRAE Standard 136).

TEMPORAL AND SPATIAL VENTILATION EFFECTIVENESS AND EFFICIENCY

1. ASHRAE 1988 [26] specified a calculation methodology to determine annual effective ventilation rates, based on the weather factor (W), normalized leakage area (NL), and hourly ventilation fan airflows and schedules.
2. ASHRAE 1989 [18] defined spatial ventilation effectiveness (i.e., the effectiveness with which outside air is circulated to occupied space).
3. ASHRAE 1993 [26] defined air change rate, effective air change rate, infiltration, mechanical and natural ventilation, normalized leakage, outdoor air change rate, and weather factor.
4. ASHRAE 1997 [31] defined air-change spatial and temporal effectiveness in terms of exhaust airflows and the tracer-gas-determined "age" of indoor air.
5. Ohnishi et al. 1998 [308] defined existing indices (ventilation rate, air change rate, room mean age

of air, air change efficiency) that deal with single spaces, and proposed new indices (supply rate fulfillment, exhaust rate fulfillment, overall ventilation rate fulfillment) that apply to an entire house with multiple rooms.

6. Sherman and Wilson 1986 [392] defined temporal ventilation efficiency, which takes into account the time variation of the ventilation; turnover time, which is the reciprocal of the ventilation rate; and instantaneous effective ventilation rate, which is the ratio of source concentration to room concentration.

INDOOR-OUTDOOR AND INTERZONAL PRESSURES

1. Finley 1997 [151] evaluated airflow paths to determine their effect on indoor air problems (mold and moisture) and to determine mitigation strategies.
2. Grimsrud et al. 1999 [184] discussed the use of building indoor-outdoor pressurization level as a metric.

AIR TO AIR HEAT EXCHANGER PERFORMANCE

1. Ciepliski et al. 1998 [75] defined metrics for the performance efficiency of air-to-air heat exchangers, including sensible, latent, and total energy effectivenesses, sensible heat recovery efficiency, total heat recovery efficiency, temperature ratio, and humidity ratio. Also compared the performance factors used in 10 test standards from ASHRAE, CHA, ENV, and ASME.
2. Johnson et al. 1998 [221] defined performance metrics for air-to-air heat exchangers, including sensible, latent, and total effectivenesses.
3. Simonson et al. 1999 [405] discussed latent, sensible, and total energy recovery effectivenesses of energy wheels.

Diagnostic

VENTILATION AIRFLOWS AND AIR EXCHANGE RATES

1. ASTM 1992 [35] described the ASTM E779-87 (1992) multi-point fan-pressurization measurement technique for envelope-leakage.
2. ASTM 1995 [40] described the tracer-gas measurement of single-zone air change rates.
3. Bearg 1999 [46] discussed the use of indoor CO_2 levels as an indicator of ventilation rate.
4. BII 1998 [53] used the LBL Infiltration Model to convert ACH_{50} to $ACH_{natural}$.
5. CMHC 1996 [77] outlined builder responsibilities to make sure ventilation systems meet the National Building Code (NBC) prescriptive requirements or CAN/CSA-F326 'Residential Mechanical Ventilation Systems'. Provided design, installation, and inspection checklists and figures for each of the six recommended system types.
6. CMHC 1998 [79] described the physics and mechanisms of airflow in buildings.
7. Fletcher and Johnson 1992 [157] described tracer-gas measurement of ventilation rates of several small factory units.
8. Grimsrud et al. 1978 [187] measured a house's envelope leakiness via fan pressurization, and measured its infiltration rate using nitrous oxide as a tracer gas.
9. Grimsrud et al. 1979 [186] compared building infiltration rates measured with various tracer gases (concentration decay method), and found that those measured with SF_6 slightly exceeded those made with CH_4 or N_2O.
10. Grimsrud et al. 1979 [189] compared tracer gas and fan pressurization based infiltration measurements in energy-efficient and standard-construction homes. Grimsrud et al. 1979 [191] presented a subset of these results.
11. Grimsrud et al. 1980 [190] found that air exchange rates measured using SF_6 as a tracer gas were slightly larger that those measured using CH_4 or N_2O.
12. Harrje 1981 [203] described a manual technique for tracer-gas sampling (squeeze bottles), for measuring building ventilation rate.
13. Harrje et al. 1979 [204] described a homeowner-performed tracer-gas technique for measuring the ventilation rate of a home (house is seeded with SF_6, then samples are taken every 30 minutes by squeezing a plastic sample bottle.)
14. Harrje et al. 1990 [206] compared three techniques for tracer gas measurement.
15. Nguyen Thi et al. 1995 [302] described the use of a portable tracer gas analyzer to measure air change rate via tracer gas decay.
16. Ohba and Irie 1999 [307] presented a videographic method of measuring air change rate using smoke tracers.

17. Rajhans 1989 [342] recommended using CO_2 level as surrogate for fresh air supply.
18. Roulet et al. 1999 [357] discussed using tracer-gas measurements to measure envelope exfiltration.
19. Saffell 1995 [359] compared two technologies (non-dispersive infrared gas cells and electrochemical cells) for the measurement of equilibrium CO_2 concentration, which in turn is used as an indicator of ventilation rate.
20. Sherman 1987 [383] reported that tracer gas methods underpredict ventilation rates.
21. Sherman 1989 [371] presented a highly mathematical analysis of the uncertainties associated with tracer-gas measurement of airflow calculations.
22. Sherman 1989 [385] described a multi-tracer measurement system (MTMS) for multizone ventilation measurement.
23. Sherman 1989 [386] noted that, although performing a tracer-gas decay test is straightforward, the analysis is more complicated. Methods discussed include (a) tracer gas constant injection; (b) tracer gas long constant concentration, which uses an active control system to control the gas release; (c) tracer gas long-term integral (a.k.a. long-term average method), which can be used with various injection patterns; and (d) tracer gas pulse technique, in which the measurement begins before the gas is injected.
24. Sherman et al. 1979 [396] evaluated the relationship between infiltration rates and surface pressures on a building.
25. Sherman et al. 1980 [378] surveyed various tracer-gas infiltration measurement techniques, including (a) decay - simple to conduct, uses minimum of equipment, is good for short term measurements; (b) constant flow - will run up to several days and give continuous infiltration measurements; (c) continuous flow - expensive to build apparatus; and (d) long-term average - yields average infiltration over a long period of time (e.g., a month).
26. Sherman et al. 1989 [379] described the MultiTracer Measurement System (MTMS), a tracer gas measurement system that uses multiple gases.
27. Sherman et al. 1989 [398] measured interzonal airflows with a multiple tracer-gas measurement system (MTMS).
28. Sherman 1990 [388] reviewed tracer gas literature (comparing the merits of various gases) and compared various tracer-gas techniques (decay, pulse, constant injection, long-term integral, constant concentration) for measurement of single-zone air change rate.
29. Sonderegger et al. 1980 [411] used the constant-injection tracer-gas technique to continuously monitor envelope infiltration.
30. Tseng et al. 1994 [434] recommended energy management system (EMS) monitoring stations for both supply and return airflows to ensure adequate outside airflow in VAV systems.
31. Walker et al. 1995 [454] presented the AVENT attic ventilation model and compared modeled results to measured data.

Temporal and Spatial Ventilation Effectiveness and Efficiency

1. ASHRAE 1993 [26] described determining the effective air change rate in a detached dwelling by combining shell leakage with a local weather factor. Included weather factor tables.
2. ASHRAE 1997 [31] described a method for the tracer-gas measurement of spatial and temporal air-change effectiveness.
3. ASTM 2000 [36] discussed performance statements (objectives, criteria, evaluation methods, and commentary) for whole-building ventilation, based on ASHRAE Standard 62. Evaluation methods include tracer gas techniques, fan pressurization test, and single-zone or multi-zone airflow models. Discussed airflow distribution within the building along with the need for evaluation methods. In addition, discussed kitchen, bath, and toilet exhaust systems and occupant control of ventilation components.
4. Condon et al. 1980 [86] described and compared tracer gas airflow measurement techniques using concentration decay, continuous flow in a single chamber, and continuous flow in multiple chambers.
5. Dale and Ackerman 1993 [101] discussed the change in attic ventilation rate and effect on living space from attic turbine ventilators. Dale and Ackerman 1991 [100] also discussed this research.
6. Federspiel and Wenger 1998 [147] described a methodology for modeling commercial multizone ventilation systems using flow rate

standards such as ASHRAE 62-1989 [18] with the age-of-air concept. The model can be used to model ventilation effectiveness, translating outdoor air requirements to age-of-air requirements and vice versa, and to develop new ventilation strategies for multizone systems.

7. Forest and Walker 1991 [161] discussed measuring and modeling airflow and moisture content in attics. Forest and Walker 1992 [162], 1993 [163], 1993 [164], and Walker and Forest 1995 [452] also discussed this research.
8. Modera et al. 1981 [284] collected infiltration data to verify an envelope leakage model (described in Sherman and Grimsrud 1980 [390]).
9. Pickering et al. 1987 [326] found that the videotaped motion of helium-filled, zero-net-buoyancy balloons was a useful indicator of indoor airflow (and worked better than smoke or bubbles).
10. Sandberg 1987 [360] discussed the accuracy of different tracer gas methods (constant concentration and decay methods) to predict mean airflow rates in naturally ventilated houses.
11. Sherman 1989 [385] described a portable MultiTracer Measurement System (MTMS) capable of measuring ventilation between different zones of a multiple zone building.
12. Sherman 1989 [386] discussed single and multi-zone tracer gas techniques for measuring airflow rates, including decay, pulse, constant injection, long-term integral, long-constant concentration; discussed analysis techniques and compared strategies.
13. Sherman 1989 [387] presented a method for estimating multizone ventilation rates from tracer-gas measurements.
14. Sherman 1994 [389] discussed how to determine ACH rates from blower door measurements.
15. Sherman and Dickerhoff 1989 [391] described the multi-tracer measurement system (MTMS) to measure time-varying interzonal flows and presented MTMS results for two houses.
16. Sherman et al. 1989 [398] described a portable MultiTracer Measurement System (MTMS) capable of measuring ventilation between different zones of a multiple zone building.
17. Tooley and Davis 1994 [428] discussed test methodology to diagnose problems with attic ventilators, zonal depressurization, moisture damage, and air barriers.
18. Turner and Bearg 1989 [440] discussed CO_2 and tracer gas determinations of outside air ventilation for an office building, including limitations, benefits, and appropriateness.

Indoor-Outdoor and Interzonal Pressures

1. ASHRAE 1989 [16] described pressure measurement.
2. Cummings 1998 [94] described how to map building air pressures.
3. Cummings and Withers 1997 [96] presented a brief overview of building pressure mapping.
4. Lstiburek 1998 [256] extensively discussed building air-pressure distribution and its relation to building airflow, including envelope leakage. Also discussed measurement of air pressure fields and air pressure differentials, and induction of pressure differentials.
5. Robison and Lambert 1989 [351] discussed fan pressurization, tracer gas, and flow hood measurement techniques to determine the relationships between duct leakage, envelope leakage, infiltration rates, and ventilation rates.

Air to Air Heat Exchanger Performance

1. Buchan Lawton Parent Ltd 1996 [60] discussed field-inspection and occupant-survey methodologies to determine heat recovery ventilator performance factor.
2. Ciepliski et al. 1998 [75] compared 10 performance-efficiency test standards from ASHRAE, CHA, ENV, and ASME, discussing required test facilities and instrumentation. Also discussed test uncertainty and proposed revisions to ASHRAE Standard 84-1991.
3. Federspiel and Wenger 1998 [147] described a methodology for modeling commercial multizone ventilation systems using flow rate standards such as ASHRAE 62-1989 [18] with the age-of-air concept. The model can be used to model ventilation effectiveness, translating outdoor-air requirements to age-of-air requirements and vice versa, and to develop new ventilation strategies for multizone systems.
4. Johnson et al. 1998 [221] analyzed uncertainty in the calculation of air-to-air heat exchanger effectiveness calculations due to bias and precision uncertainties in the measurements of air pressures and temperatures.

5. Simonson et al. 1999 [405] described a computer model for predicting the performance (energy recovery effectiveness) of energy wheels, and a laboratory experiment for validating the model. Included extensive error analysis.

EQUIPMENT SELECTION AND SIZING

1. Schalch and Fryer 1992 [364] discussed the Energy Crafted Home's ventilation requirements (systems must provide 60 cfm continuously in small homes and 100 cfm in larger homes).

Norm

VENTILATION AIRFLOWS AND AIR EXCHANGE RATES

1. ASHRAE 1989 [18] specified outdoor air requirements for residential and commercial buildings.
2. ASHRAE 1993 [27] specified the attic and crawlspace ventilation (free area per unit floor area) requirements, minimum house ventilation requirements (supplemental ventilation via kitchen and bathroom exhaust fans, mechanical ventilation systems, or operable windows if summer design infiltration rate is below 0.35 air changes per hour), and ventilation equipment performance factors (rated airflow performance in accordance with HVI-916 and HVI-924) for compliance with the prescriptive requirements of ASHRAE Standard 90.2-1993.
3. Berk et al. 1981 [51] presented tracer gas measurements (SF_6) of air change rates of two houses, with and without the central forced air systems running.
4. CEC 1999 [66] presented the California building code Title 24 outdoor air requirements for nonresidential, high-rise residential, and hotel/motel buildings.
5. CMHC 1996 [77] described ventilation requirements for residential buildings falling under Part 9 of Canada's 1995 National Building Code (NBC), including required system elements and required ventilation capacity based on number and types of rooms.
6. Cummings 1998 [94] briefly discussed sizing of outside airflows, noting that ventilation airflows should be sized appropriately (minimizing exhaust airflow and using as much indoor air as possible).
7. Dale and Ackerman 1993 [101] discussed the change in attic ventilation rate and effect on living space from attic turbine ventilators. Dale and Ackerman 1991 [100] also discussed this research.
8. Dols et al. 1995 [122] specified recommended outdoor-airflow rates.
9. EPA 1997 [138] mentioned that ASHRAE Standard 62-1989 [18] required rate for residential ventilation. It also specified prescriptive and performance standards for continuous exhaust fan sizing.
10. EPA/DOE 1999 [140] specified that the standard for ventilation and control of indoor air pollutants is ANSI/ASHRAE 62-1989 Ventilation for Acceptable Indoor Air Quality [18].
11. Feustel et al. 1986 [149] discussed TRNSYS modeling of the economic and ventilation performance (average and effective ventilation rates) of natural ventilation and several ventilation strategies (exhaust ventilation, heat recovery ventilation, exhaust ventilation with heat pump heat recovery, and exhaust air heat pump water heating).
12. Grimsrud et al. 1983 [185] gathered infiltration data for 300 houses; this data formed the basis of ASHRAE Standard 62 (ASHRAE 1989 [18]).
13. Matson and Feustel 1998 [263] presented effective annual air change rates for post-1980 construction homes (97 in New York and 66 in California) based on blower door tests. Also presented COMIS multi-zone airflow modeling results for ventilation strategies (single and multi-port exhaust fans with inlet louvers, single and multi-port exhaust fans with outside air ducts, balanced heat recovery) in one and two story houses in California and New York climates.
14. Modera and Jansky 1992 [281] discussed computer-simulated estimates of changes in building infiltration and interzonal airflow due to central ducted HVAC systems operating conditions (fan off, fan on, duct leakage).
15. NAHB 1997 [293] tabulated calculated monthly and seasonal air change rates for a range of house tightness in four U.S. cities.
16. Parker 1989 [313] discussed blower door and tracer gas air change rate measurements of 1980-construction conventional and Model Conservation Standards (MCS) construction

homes in the Pacific Northwest. Estimated mean seasonal air change rates were 0.55 ach for the conventional and 0.28 ach for the MCS homes; using the tracer gas technique, average air change rates (December through March) were 0.31 ach (not corrected for non-uniform mixing) for the conventional homes and 0.35 (including heat recovery ventilation airflow) for the MCS homes.

17. Dols et al. 1995 [120] specified an outdoor airflow rate for office buildings (source unknown).
18. Rajhans 1989 [342] specified recommended outdoor air rates for non-residential buildings.
19. Sherman 1986 [374] discussed the development of ASHRAE Standard 119: Air Leakage Performance for Detached Single-Family Residential Buildings (ASHRAE 1988 [15]).

INDOOR-OUTDOOR AND INTERZONE AIR PRESSURES

1. Dols et al. 1995 [122] recommended various interzonal pressures.
2. EPA/DOE 1999 [140] specified that certain spaces use (e.g. printing facilities, smoking lounges, restrooms) must be directly exhausted to the outdoors and be negatively pressurized relative to occupied spaces.

EQUIPMENT SELECTION AND SIZING

1. ASHRAE 1995 [28] specified exterior joint sealing and optimizing ventilation openings.
2. ConSol 1999 [89] briefly specified procedures for sizing and installation of residential mechanical ventilation to provide an "intentional and controllable" intake of outside air into the conditioned space. Touched on energy efficiency, IAQ, and noise.

2.6 Controls

Metric

ENERGY MANAGEMENT CONTROL SYSTEM (EMCS)

1. Keithly 1999 [229] discussed control installation, listing common deficiencies in control system specifications.

Diagnostic

ROOM THERMOSTATS

1. EPA 1998 [139] recommended that a tune-up of building controls include calibrating indoor and outdoor building sensors (e.g., thermostats, humidistats); inspection of damper and valve controls; review of building operating schedules; and review of utility rate schedule (to seek opportunities to use cheaper off-peak power). It noted that typical cooling and heating savings can range up to 30%.
2. Madsen et al. 1990 [260] found in laboratory and field tests that temperature variation in a living space can be reduced when the room thermostat is moved from the wall to a location within the room.

THERMAL EXPANSION DEVICES

1. Farzad and O'Neal 1993 [146] found that the TXV system performance variables showed a small variation with the refrigerant charge but a strong dependence on the outdoor temperature.

EMCS MONITORING

1. Brohard and Krieg 1994 [59] listed a series of steps for contractor commissioning of air, chilled-water, chiller, evaporative condenser, and DDC control systems.
2. Cole and Holness 1989 [84] discussed the use of programmable logic controllers (PLCs) to control HVAC equipment in a manufacturing plant, and compared them to pneumatic and direct digital control (DDC) systems.
3. Elovitz 1986 [134] discussed control installation, giving examples of EMCS sensor calibration and how it can go wrong.
4. Koran 1994 [242] used a building's energy management control system (EMCS) to monitor over 200 building performance parameters (e.g., chiller flows, temperatures, and powers) for a year.
5. Sabeff 1994 [358] described how an EMCS can be used for commissioning, but only the EMCS itself is commissioned first.
6. Tseng et al. 1994 [434] listed EMCS monitoring points for an air handling unit, an electric hot water thermal storage system, an ice harvester thermal cool storage system, and a cooling tower

for the ice harvester. Also discussed when to use hardware and software monitoring points.

VENTILATION CONTROL

1. Schell 1995 [365] noted that ventilation rates may be adjusted using CO_2 controls to achieve a desired indoor CO_2 level indicative of good air quality.

COILS AND MIXING BOXES

1. Haves et al. 1996 [208] used automated techniques for fault detection in HVAC coils and mixing box controls.

HVAC

1. Cole and Holness 1989 [84] described the use of programmable logic controllers for HVAC control, comparing the relative merits of such devices vs. pneumatic or direct digital control systems.
2. SMACNA 1993 [407] discussed HVAC electrical and thermostatic control basics.

Norm

ROOM THERMOSTATS

1. Werling et al. 1998 [460] noted that an Energy Star Home must have a programmable thermostat.

2.7 HVAC Installation Process

Metric

1. Allen Consultants 1996 [1] discussed potential changes in design and construction of forced-air duct systems.
2. Gupton 1986 [196] listed HVAC installation details to verify, and gave instructions on how to specify HVAC commissioning.
3. Hammon and Modera 1996 [199] discussed strategies and provided key action items to integrate tight duct construction parameters and factors into HERS, Title 24, and energy-efficient mortgages. Also provided material and performance metrics.
4. Persily 1999 [322] described an IAQ performance guide being developed within ASTM that stated that condensate from air conditioning equipment should be able to drain freely and completely. Also stated that HVAC equipment design and installation should ensure accessibility for inspection, maintenance, and cleaning.

Diagnostic

1. Brohard and Krieg 1994 [59] listed a series of steps for contractor commissioning of air, chilled-water, chiller, evaporative condenser, and DDC control systems.
2. EPA 1997 [138] listed four tests used to ensure that subcontractors are performing quality work: a blower-door test to detect excessive envelope leakage, a duct leakage test, an HVAC system inspection, and testing airflow across the inside coil to ensure proper airflow to the duct system.
3. Hammon and Modera 1996 [199] discussed strategies and provided key action items to integrate tight duct construction parameters and factors into HERS, Title 24, and energy-efficient mortgages. Also provided material and performance metrics.
4. Han et al. 1999 [201] discussed automated diagnostic techniques for DDC VAV systems in commercial buildings.
5. Meckler 1991 [267] detailed steps that contractors should take in the design, construction, and occupancy phases of HVAC installation to avoid IAQ problems.

Norm

1. Hammon and Modera 1996 [199] discussed costs and energy savings attributable to tight duct construction in new construction.
2. Persily 1999 [322] described an IAQ performance guide being developed within ASTM that stated that to prevent water vapor and dust from entering the building interior, exhaust from clothes dryers should be vented to the outdoors.

3. INDOOR AIR QUALITY

3.1 Room Air Temperature and Velocity (Occupant Comfort)

Metric

OCCUPANT COMFORT

1. ASHRAE 1992 [23] defined operative temperature range for thermal comfort (the temperature range in which no more than 10% of a building's occupants performing light activity will find the environment thermally unacceptable).
2. Fanger 1992 [143] described indoor air and thermal comfort metrics (percent mean vote [PMV], percent people dissatisfied [PPD], olfs, draft risk).
3. Fountain and Huizenga 1997 [167] discussed computer-predicted thermal comfort indices, including predicted mean vote (PMV), predicted percent dissatisfied (PPD), new effective temperature (ET), standard effective temperature (SET), and nine others.
4. Koles et al. 1996 [241] discussed a thermal comfort metric (Predicted Percent Dissatisfied [PPD]).
5. Levermore et al. 1999 [250] defined an Overall Liking Score that gages occupants' overall satisfaction with the building environment, and a Likeness Fingerprint that shows what in particular occupants like or dislike.
6. Persily 1999 [322] described an IAQ performance guide being developed within ASTM, including thermal comfort parameters based on ASHRAE Standard 55 and ISO 7730.
7. Rajhans 1989 [342] listed field measurements made with simple instruments (temperature, RH, CO_2, formaldehyde, CO, air movement) and those made with complex instruments (microorganisms, respirable suspended particulates, organic vapor, ozone, NO_x, asbestos).
8. Rajhans 1989 [342] listed field measurements made with simple instruments (temperature, RH, CO2, formaldehyde, CO, air movement) and those made with complex instruments (microorganisms, respirable suspended particulates, organic vapor, ozone, NO_x, asbestos.)
9. Sherman 1984 [372] defined simplified expressions for thermal comfort, including predicted mean vote (PMV), effective temperatures, and comfort temperatures. Provided tables of comfort of effective temperature coefficients, and charts of comfort temperatures versus various factors.
10. Sherman and Ashley 1984 [377] defined LBL effective temperature (an environmental temperatures that depends on air temperature, mean radiant temperature, dew point, and wind speed), NCEL effective temperature, and comfort temperature.
11. Walker et al. 1998 [453] discussed REGCAP, a computer model that evaluates residential HVAC system component performance and whole house performance based on measured data (ducts, equipment, envelope, and climate) to provide an estimate of duct, equipment and envelope performance and net cooling delivered (tons at the register).

Diagnostic

OCCUPANT COMFORT

1. Arens et al. 1986 [10] updated a 1950's-vintage "bioclimatic" human-comfort chart to reflect current (1986) ASHRAE comfort criteria, and to use a "rationally-derived" index for determining comfort. Parameters include dry bulb temperature, humidity, wind speed, and radiation intensity.
2. ASTM 2000 [36] discussed performance statements (objectives, criteria, evaluation methods, and commentary) for thermal comfort, referencing ASHRAE Standard 55 and mentioning the need to develop evaluation criteria suited for residential applications.
3. Chan et al. 1999 [68] described a portable indoor environmental quality data logger that monitors the indoor environment and lets occupants register their comfort satisfaction with the environment on panel switches.
4. CMHC 1998 [79] discussed thermal comfort issues related to inefficient mechanical systems, poor quality or poorly installed materials, poor maintenance or faulty equipment, or building envelope problems. A thermal comfort checklist was included to help diagnose problem.
5. Dols et al. 1995 [120] described a methodology to measure IAQ effectiveness in commercial building commissioning, including ventilation

performance (outdoor airflow rate and pressure relationships between zones), pollutants (CO_2, CO, formaldehyde, particulates, radon and VOCs), and thermal comfort (temperature, relative humidity, and operative temperature).

6. Fountain and Huizenga 1996 [166] described a software tool for thermal comfort prediction that may be integrated into tools to model thermal comfort conditions for research, design, and system operation.

7. Fountain and Huizenga 1997 [167] developed a user-friendly computer program that uses three heat-balance, three empirical, and two adaptive models to predict thermal comfort given input parameters including temperature, humidity, air speed, clothing, and metabolic rate.

8. Hassani and Stetz 1994 [207] used a low-thermal- mass, porous, fiberglass screen in conjunction with an infrared camera to measure room air temperature.

9. Lane et al. 1989 [245] discussed four main components of a procedure to diagnose a sick building or confirm a healthy building: knowledge of what to measure, availability of appropriate instrumentation, expertise in interpreting results of measurements, and capability of predicting building performance.

10. Levermore et al. 1999 [250] described an occupant comfort satisfaction feedback questionnaire that yields a "fingerprint" and score indicating their liking of their environment.

11. Mansson 1999 [262] described a tool that inputs parameters describing a building's ventilation system, envelope, and climate, and outputs ratings of IAQ (material, hours with too high CO_2, tobacco smoke, cooking emission); level of condensation; energy required to heat indoor air; dryness feeling (low RH); high winter RH (leading to dust mite growth), and indoor-outdoor pressure difference.

12. Rajhans 1989 [342] listed field measurements made with simple instruments (temperature, RH, CO_2, formaldehyde, CO, air movement) and those made with complex instruments (microorganisms, respirable suspended particulates, organic vapor, ozone, NO_x, asbestos). Also provided an occupant IAQ survey.

13. Ross and Sterling 1997 [354] presented, for a commercial building, the results of pre- and post-occupancy measurements of TVOC, formaldehyde, respirable suspended particles (RSP), CO_2, CO, temperature, and relative humidity. Testing apparatus included integrated sampling and direct reading (instantaneous) automated analyzers. Plans and materials specifications were reviewed prior to the on-site testing.

14. Walker et al. 1998 [453] discussed REGCAP, a computer model that evaluates residential HVAC system component performance and whole house performance based on measured data (ducts, equipment, envelope, and climate) to provide an estimate of duct, equipment and envelope performance and net cooling delivered (tons at the register).

15. Zmeureanu et al. 1998 [469] monitored room and register air temperatures with a data logger.

Norm

Occupant Comfort

1. ASHRAE 1992 [23] specified the combinations of indoor space environment and personal factors that will produce thermal environmental conditions acceptable to 80% or more of the occupants within a space (temperature, thermal radiation, humidity and air speed; excludes IAQ, acoustics, illumination).

2. Dols et al. 1995 [120] presented a table of existing IAQ criteria including outdoor airflow rate, pressure relationships between zones, CO_2, CO, formaldehyde, particulates, radon, total VOCs and thermal comfort.

3. Dols et al. 1994 [121] included, in an indoor air quality commissioning protocol, thermal comfort and ventilation norms based on the BOCA National Mechanical Code, ASHRAE Standard 62-1989 and ASHRAE Standard 55-1992. Dols et al. [123] discussed this protocol, subsequent commissioning results, and lessons learned.

4. EPA/DOE 1999 [140] specified that the standard for thermal comfort is ANSI/ASHRAE Standard 55-1992, Thermal Comfort Conditions for Human Occupancy [23].

5. Odom 1997 [306] discussed the types of IAQ problems (high-frequency/low-consequence vs. low-frequency/high-consequence). Also discussed how IAQ problems are more apt to be seen in the first few years of occupancy in new buildings or in older buildings were usage patterns and occupancy has changed.

6. Zhivov et al. 1994 [468] discussed the international differences in thermal comfort, ventilation and energy-efficient construction standards and codes.

3.2 Non-Biological Gaseous Pollutant Generation, Transport, and Concentration

Metric

POLLUTANT LEVEL OR INDEX

1. ASHRAE 1989 [18] specified CO exposure level limits in terms of average concentration and cumulative concentration over a particular measurement period.
2. Bearg 1999 [46] noted that CO levels in occupied areas can indicate the extent to which the HVAC system is removing vehicle exhaust from building loading docks and parking areas. Also noted that CO_2 concentrations are an indicator of ventilation performance.
3. CMHC 1998 [79] described soil gas transport and indoor air quality physics and mechanisms.
4. Dols et al. 1995 [122] noted that CO levels can be monitored to detect the transport of garage fumes into a building.
5. Karg 1999 [224] discussed metrics for CO levels.
6. Moschandreas and Sofuoglu 1999 [289] defined an Indoor Air Pollution Index (IAPI), a metric for overall air quality that sums the effects of multiple pollutants.
7. Su et al. 1999 [417] measured pollutant levels in units of PPM or $\mu g\ m^{-3}$.

Diagnostic

POLLUTANT LEVEL OR INDEX

1. ASTM 2000 [36] discussed performance statements (objectives, criteria, evaluation methods, and commentary) for radon control, referencing ASTM Standard E1465 and testing to make sure indoor radon concentrations are less than 4 pCi/L. Discussed reducing pollutant transport from unconditioned spaces, garages, and outside the building, as well as reducing emissions within the building.
2. Barbat et al. 1999 [44] measured CO_2 levels with a B&K 1302 gas analyzer.
3. Bearg 1998 [45] noted that CO level can be used to detect building infiltration by vehicle exhaust.
4. Bearg 1999 [46] discussed CO_2 level measurement techniques, including grab samples, one monitor at one location, several monitors at several locations, or a shared-sensor system with many sample lines; the author prefers the latter. Measured CO_2, CO, and dew point to track commercial building HVAC performance during commissioning.
5. Benton et al. 1996 [49] mentioned a particular CO_2 monitor that costs $450.
6. Berk et al. 1981 [51] discussed gas measurements (formaldehyde, radon, CO, CO_2, SO_2, NO, NO_x, O_3) conducted in nine houses, pre- and post-retrofit.
7. Cheong and Riffat 1993 [69] measured CO_2, CO, and HCHO with a Miran Portable Ambient Analyzer (accuracy +/- 15%).
8. Dols et al. 1995 [122] measured CO levels with an unspecified automated CO monitoring system.
9. Lane et al. 1989 [245] discussed four main components of a procedure to diagnose a sick building or confirm a healthy building: knowledge of what to measure, availability of appropriate instrumentation, expertise in interpreting results of measurements, and capability of predicting building performance.
10. Rajhans 1989 [342] recommended instrumentation for simple field IAQ measurements (including pollutant levels), and specified when and where to measure pollutant levels.
11. Ross and Sterling 1997 [354] presented, for a commercial building, the results of pre- and post-occupancy measurements of TVOC, formaldehyde, respirable suspended particles (RSP), CO_2, CO, temperature, and relative humidity. Testing apparatus included integrated sampling and direct reading (instantaneous) automated analyzers. Plans and materials specifications were reviewed prior to the on-site testing.
12. Schalch and Fryer 1992 [364] discussed the Energy Crafted Home's indoor air quality recommendations (avoid materials with high urea-formaldehyde content and provide a sub-

slab layer of stone that permits the installation of a sub-slab depressurization system if necessary).

13. Schell 1995 [365] noted that indoor CO_2 levels indicate the ventilation rate, and that a controller can be used to control ventilation rates to maintain a CO_2 level setpoint.
14. Stock et al. 1999 [416] compared the performance of 3M OVM diffusive (passive) VOC sampler with a reference VOC monitoring method (canister sampling). Found a good correlation for 8 of 12 target compounds; however, the passive sampler exhibited a statistically significant low bias for all but two of the VOCs.
15. Su et al. 1999 [417] specified techniques used to measure many pollutants.
16. Tsongas 1995 [436] recommended equipment for monitoring CO levels and specified an oven CO test protocol. Also stated the US EPA, WHO, and Health Canada recommended limits for CO exposure.

CONTAMINANT SOURCES

1. Persily 1999 [322] described an IAQ performance guide being developed within ASTM, including radon-related construction requirements and measurement of indoor radon concentration after construction (not to exceed 4 pCi/L). Also included emission rates from furnishings and materials using tests based on ASTM D5116.
2. Rajhans 1989 [342] discussed indoor and outdoor sources of indoor air contaminants. Also presented a checklist to detect IAQ problems related to combustion (CO), other pollutant sources, HVAC, maintenance and design.
3. Tsongas and Hager 1994 [438] discussed testing procedures to measure CO from gas ovens.

CONDENSATION POTENTIAL

1. CMHC 1998 [79] discussed window moisture problems, including a checklist of typical problems and solutions.
2. Warner 1991 [456] discussed how to avoid window condensation by increasing window R-values, sealing cracks and joints around windows, or by increasing house ventilation rates.

Norm

POLLUTANT LEVEL OR INDEX

1. ASHRAE 1989 [18] specified indoor, outdoor, and industrial-workplace CO exposure limits.
2. Berk et al. 1981 [51] presented gas measurement results (formaldehyde, radon, CO, CO_2, SO_2, NO, NO_x, O_3) from nine houses, pre- and post-retrofit.
3. Dols et al. 1994 [121] included, in an indoor air quality commissioning protocol, pollutant exposure levels and maximum concentration levels for carbon dioxide, carbon monoxide, formaldehyde, radon and volatile organic compounds. Dols et al. [123] discussed this protocol, subsequent commissioning results, and lessons learned.
4. Dols et al. 1995 [122] presented recommended office-building pollutant levels (CO_2, CO, formaldehyde, particulates, radon, TVOC) predicted to satisfy 90% of occupants.
5. Nagda et al. 1987 [292] described an IAQ-monitoring guideline that lists exposure limits (from various organizations) to biological, non-biological, and particulate airborne pollutants.
6. Odom 1997 [306] discussed the types of IAQ problems (high-frequency/low-consequence vs. low-frequency/high-consequence). Also discussed how IAQ problems are more apt to be seen in the first few years of occupancy in new buildings or in older buildings were usage patterns and occupancy has changed.
7. Rajhans 1989 [342] provided indoor air quality guidelines prepared by the World Health Organization (1984).
8. Seifert et al. 1999 [366] presented German government guidelines for Lowest Observed Adverse Effect Level (LOAEL) of various pollutants (toluene, styrene, dichloromethane, penetachlorophenol, carbon monoxide, nitrogen dioxide), and also presented guidelines value for the indicator total volatile organic compounds (TVOC).
9. Tsongas and Hager 1994 [438] presented EPA 1-hour and 8-hour limits for CO exposure.

3.3 Moisture Generation, Storage, Transport, Concentration, and Absorption

Metric

HUMIDITY LEVEL

1. Bearg 1998 [45] noted that dew point (humidity level) can be monitored with a shared sensor (for comfort, to prevent fungal growth, and to check that the humidification systems are working properly).
2. Forest and Walker 1991 [161] discussed measurement and model input variables to determine airflow and moisture content in attics. Forest and Walker 1992 [162], 1993 [163], 1993 [164], and Walker and Forest 1995 [452] also discussed this research.
3. Moschandreas and Sofuoglu 1999 [289] defined an Indoor Air Pollution Index (IAPI), a metric for overall air quality that sums the effects of multiple pollutants.
4. Persily 1999 [322] described an IAQ performance guide being developed within ASTM, including issues related to excessive condensation within exterior wall construction. Criteria are based on the analysis of the design, followed by a lack of evidence of condensation after construction. Also included issues relating to moisture (foundation, crawl space, grade enclosures, roofs, exterior walls, windows, and doors) and minimization of water entry. Referenced ASTM E241 and the ASTM Moisture Control in Buildings Manual.

Diagnostic

HUMIDITY LEVEL

1. Bearg 1998 [45] noted that dew point (humidity level) can be monitored with a shared sensor (for comfort, to prevent fungal growth, and to check that the humidification systems are working properly).
2. Bearg 1999 [46] measured CO_2, CO, and dew point to track commercial building HVAC performance during commissioning.
3. Finley 1997 [151] evaluated airflow paths to determine their effect on indoor air problems (mold and moisture) and to determine mitigation strategies.
4. Forest and Walker 1991 [161] discussed measuring and modeling airflow and moisture content in attics. Forest and Walker 1992 [162], 1993 [163], 1993 [164], and Walker and Forest 1995 [452] also discussed this research.
5. Lane et al. 1989 [245] discussed four main components of a procedure to diagnose a sick building or confirm a healthy building: knowledge of what to measure, availability of appropriate instrumentation, expertise in interpreting results of measurements, and capability of predicting building performance.
6. Tooley et al. 1994 [428] presented testing methodology to diagnose problems with attic ventilators, house or zone depressurization, moisture damage, and air barriers.
7. Walker 1993 [450] discussed an attic simulation model (airflow and moisture) and measured data to evaluate attic ventilation and moisture problems.

Norm

HUMIDITY LEVEL

1. Odom 1997 [306] discussed how buildings in hot and humid climates are more prone to failure due to problems with the building envelope and related barriers.

3.4 Bioaerosol (Fungi/Molds/Mites) Generation, Transport, and Concentration

Metric

POLLUTANT LEVEL OR INDEX

1. Deng et al. 1999 [107] measured dust mite concentration by counting the number of microscopically-observable dust mites per sticky sampling sheet.
2. Fluckiger et al. 1999 [158] measured fungal concentration in terms of colony forming units (CFU) per m^{-3}, and biological units (BU) per m^{-3}.
3. Moschandreas and Sofuoglu 1999 [289] defined an Indoor Air Pollution Index (IAPI), a metric for overall air quality that sums the effects of multiple pollutants.
4. Rajhans 1989 [342] listed field measurements made with simple instruments (temperature, RH, CO_2, formaldehyde, CO, air movement) and

those made with complex instruments (microorganisms, respirable suspended particulates, organic vapor, ozone, NO_x, asbestos).

5. Su et al. 1999 [417] used CFU m^{-3} as a metric for fungal concentration, and μg allergen per g dust for allergens.
6. Womble et al. 1999 [464] used CFU m^{-3} as a metric for fungal concentration.

Diagnostic

POLLUTANT LEVEL OR INDEX

1. CMHC 1998 [79] described the physics, mechanisms, health hazards of mold growth and transport, including a checklist of ways to reduce and control moisture and mold growth.
2. Deng et al. 1999 [107] collected dust mites from air by deposition on sticky sampling tape.
3. Finley 1997 [151] evaluated airflow paths to determine their effect on indoor air problems (mold and moisture) and to determine mitigation strategies.
4. Fluckiger et al. 1999 [158] sampled mold using slit-samplers. Petri dishes filled with malt extract agar collected viable mold spores and allergens from air, and multistage liquid impingers with phosphate buffered saline were used for multi-stage sampling.
5. Kemp et al. 1999 [231] compared three methods of extracting fungi from dust samples, and was satisfied only with sprinkling dust onto agar plates.
6. Lane et al. 1989 [245] discussed four main components of a procedure to diagnose a sick building or confirm a healthy building: knowledge of what to measure, availability of appropriate instrumentation, expertise in interpreting results of measurements, and capability of predicting building performance.
7. Rajhans 1989 [342] recommended instrumentation for simple field IAQ measurements (including pollutant levels), and specified when and where to measure pollutant levels.
8. Womble et al. 1999 [464] collected airborne fungi on an inertial impactor and sent the samples to a lab for culture and analysis.

CONTAMINANT SOURCES

1. Flannigan 1992 [156] discussed microbial sampling techniques, including pros and cons, potential problems; highlights need for simpler techniques that can be used in the field.
2. Morey and Horner 1997 [287] discussed measurement and mitigation strategies for microbiological VOCs (MVOCs); included references to documents on diagnostic and mitigation.
3. Rajhans 1989 [342] discussed indoor and outdoor sources of indoor air contaminants.

Norm

POLLUTANT LEVEL OR INDEX

1. Morey and Horner 1997 [287] presented microbiological VOC (MVOC) sampling results from buildings in all major geographical areas of the U.S.
2. Nagda et al. 1987 [292] described an IAQ-monitoring guideline that lists exposure limits (from various organizations) to biological, non-biological, and particulate airborne pollutants.

CONTAMINANT SOURCES

1. EPA/DOE 1999 [140] specified that a building should be free of microbiological sources (e.g., no visible microbial growth on walls).
2. Flannigan 1992 [156] discussed classifications of microbial species based on a_w ("water activity," a ratio of vapor pressures, which provides a truer indication of moisture availability for microbial growth).
3. Odom 1997 [306] discussed how biological pollutants are often more expensive to mitigate as removal of building materials that have significant infestations of mold and mildew must be conducted very carefully to prevent contamination of additional surfaces and prevent exposure of workers or adjacent occupants.

3.5 Particulate Generation, Transport, and Concentration

Metric

POLLUTANT LEVEL OR INDEX

1. ASHRAE 1989 [18] described pollutant level in terms of concentration averaged over a particular measurement period.
2. Holopainen et al. 1999 [212] gaged the dust concentration in duct air in terms of dust deposition on the duct wall (g m^{-2}).
3. Moschandreas and Sofuoglu 1999 [289] defined an Indoor Air Pollution Index (IAPI), a metric for overall air quality that sums the effects of multiple pollutants.
4. Rajhans 1989 [342] listed field measurements made with simple instruments (temperature, RH, CO_2, formaldehyde, CO, air movement) and those made with complex instruments (microorganisms, respirable suspended particulates, organic vapor, ozone, NO_x, asbestos). Also provided IAQ guidelines prepared by the World Health Organization (1984).
5. Turner et al. 1996 [441] compared particle-sampling methodologies (PM-10, PM-2.5) to near real-time particle samplers (laser diode-based counter) in three commercial settings (pre- and post- IAQ remediation).

Diagnostic

POLLUTANT LEVEL OR INDEX

1. Berk et al. 1981 [51] discussed particulate measurements conducted in nine houses, pre- and post-retrofit.
2. Deng et al. 1999 [107] collected dust (settled particles and fibers) for a week on glass covered with a thin Vaseline layer, then examined the collection with a 150X optical microscope.
3. Fluckiger et al. 1999 [158] collected dust samples with an allergen mouthpiece attached to a household vacuum cleaner.
4. Holopainen et al. 1999 [212] compared three duct-air sampling methods: vacuum collection onto a pre-weighed filter, mass of dust deposited on a sampling tape, and optical transmission through a dust sampling tape.
5. Lane et al. 1989 [245] discussed four main components of a procedure to diagnose a sick building or confirm a healthy building: knowledge of what to measure, availability of appropriate instrumentation, expertise in interpreting results of measurements, and capability of predicting building performance.
6. Rajhans 1989 [342] recommended instrumentation for simple field IAQ measurements (including pollutant levels), and specified when and where to measure pollutant levels.
7. Ross and Sterling 1997 [354] presented, for a commercial building, the results of pre- and post-occupancy measurements of TVOC, formaldehyde, respirable suspended particles (RSP), CO_2, CO, temperature, and relative humidity. Testing apparatus included integrated sampling and direct reading (instantaneous) automated analyzers. Plans and materials specifications were reviewed prior to the on-site testing.
8. Turner et al. 1996 [441] compared particle-sampling methodologies (PM-10, PM-2.5) to near real-time particle samplers (laser diode-based counter) in three commercial settings (pre- and post- IAQ remediation).

CONTAMINANT SOURCES

1. Rajhans 1989 [342] discussed indoor and outdoor sources of indoor air contaminants.

Norm

POLLUTANT LEVEL OR INDEX

1. ASHRAE 1989 [18] specified indoor, outdoor, and industrial workplace asbestos exposure limits.
2. Berk et al. 1981 [51] presented particulate measurements from nine houses, pre- and post-retrofit.
3. Dols et al. 1994 [121] included, in an indoor air quality commissioning protocol, pollutant exposure levels and maximum concentration levels for particulates. Dols et al. [123] discussed this protocol, subsequent commissioning results, and lessons learned.
4. Dols et al. 1995 [122] presented recommended office-building pollutant levels (CO_2, CO, formaldehyde, particulates, radon, TVOC) predicted to satisfy 90% of occupants.

5. Nagda et al. 1987 [292] described an IAQ-monitoring guideline listing exposure limits (from various organizations) to biological, non-biological, and particulate airborne pollutants.

4. OTHER

4.1 Domestic Hot Water

Metric

1. Sherman et al. 1987 [401] discussed water-heater recovery efficiency (gas only), and water-heater standby losses (gas and electric).

Diagnostic

1. ASHRAE 1993 [25] specified the ASHRAE test procedure for rating the efficiency of residential water heaters. Test procedures include measuring water and ambient temperatures (nine thermocouples), water flow, energy supply (electric, gas, oil), and tank storage capacity; test results include an energy factor and the hot water delivery capability in terms of a first-hour rating.
2. Sherman et al. 1987 [401] discussed water-heater recovery efficiency (gas only), and water-heater standby losses (gas and electric).
3. Stewart et al. 1999 [415] discussed modeling techniques to determine system losses in residential and commercial hot water systems, using the transient convective energy equation and Fourier's conduction model along with system characteristics and usage patterns. Calculated system losses can be taken into account when sizing hot water heaters and boilers.

Norm

1. ASHRAE 1993 [27] specified domestic water heater selection (efficiency, performance) and installation requirements for compliance with the prescriptive requirements of ASHRAE Standard 90.2-1993.
2. ASHRAE 1995 [28] described basic and prescriptive requirements for water heating systems, including sizing of systems, equipment efficiency, piping insulation, and controls. Also specified standard rating conditions, operating factors, applicable standards, and minimum performance factors for boilers and water-heating equipment; specified minimum pipe-insulation levels for distribution piping.
3. BII 1998 [53] briefly specified procedures for water heater jackets and pipe insulation.
4. CEC 1999 [66] presented the California building code Title 24 requirements for insulation of and heat loss from water heater tanks.
5. DOE 1995 [116] discussed background information on HERS heating, air-conditioning and water heating equipment for HERS policy options being discussed in DOE's 1995 request for comments on fuel neutrality and adjustment factors, and standard efficiencies.
6. DOE 1995 [117] discussed (in greater detail than DOE 1995 [116]) the analysis of heating, air-conditioning, and water heating equipment adjustment factors for the HERS guidelines.
7. Schalch and Fryer 1992 [364] discussed the Energy Crafted Home's requirement that heating and water heating equipment must have sealed or closed combustion.
8. Weingarten and Weingarten [457] discussed water heater types, maintenance tasks, and options and specifications related to installing and upgrading water heaters.
9. Weingarten and Weingarten 1996 [458] in a response to a letter to the editor, discussed how to remove and replace water heater anodes.

4.2 Lighting

Metric

NONE

Diagnostic

1. EPA 1998 [139] detailed a three-step process for a lighting system tune-up: (1) green lights (follow a strategic lighting maintenance plan of schedule groups relamping and fixture cleaning); (2) measure and ensure proper light levels; and (3) calibrate lighting controls. It noted that savings from cleaning fixtures can range from 10 to 60%, and that calibration of occupancy sensors and photocells can reduce energy use in served areas by 50% or more.
2. UL 1999 [442] names U.S. and Canadian test standards for the energy efficiency of fluorescent lamp ballasts.

Norm

1. CEC 1999 [66] presented the California building code Title 24 standards for lighting controls.
2. EPA 1997 [138] listed both standard and energy-efficient choices for lighting living spaces, bathrooms, laundry areas, and garage/utility areas.
3. Schalch and Fryer 1992 [364] discussed the Energy Crafted Home's lighting requirements, including hard-wired fluorescents and compact fluorescents in bare bulb and decorative fixtures.

4.3 Plug Loads

Metric

1. Sherman et al. 1987 [401] discussed monthly refrigerator energy consumption. Long-term monitoring was needed due to large daily fluctuation in energy consumption. This included measuring fridge and freezer compartment temperatures, door openings/closings, and the ambient temperature.

Diagnostic

1. Coyle 1999 [91] extended building commissioning to electric systems, listing representative electric integrity tests, representative functional performance tests, who should performs the tests, and specifications for said tests.
2. EPA 1998 [139] noted opportunities for improving the efficiencies of a building's electric power systems, including evaluating and correcting voltage imbalances, voltage deviations, poor connections, undersized conductors, poor power factors, insulation leakage, and harmonics.
3. Mixon and Meier 1990 [273] compared and listed sources for four different electric-load monitoring methods.
4. Sharp 1994 [369] discussed the hardware, installation, capabilities, and application of non-intrusive (electric) load monitoring systems (NILMS).
5. Sherman et al. 1987 [401] discussed refrigerator energy consumption, including measuring refrigerator and freezer compartment temperatures, openings and closing of compartment doors, ambient temperature, and electric energy use.

Norm

1. Meier 1993 [268] reported that the Energy Guide labels affixed to new refrigerators predict actual energy consumption fairly well, though they may under predict energy use in warm southern U.S. states.
2. Meier 1993 [269] listed typical month power consumption of many common household appliances.
3. Parker and Stedman 1993 [312] measured kitchen, refrigerator, and freezer temperatures, door openings, and plug loads to determine the refrigeration performance improvements and energy savings achieved by replacing an old refrigerator with a new, similarly-featured, energy efficient model.
4. Parker et al. 1998 [314] measured miscellaneous energy loads (e.g. security system, portable phones, aquarium pump, computer), reporting watts, hours/day, and annual kWh.
5. Sherman et al. 1985 [381] examined the overall energy impacts of two energy-efficient refrigerators in four types of houses with and without space cooling equipment. The heating and cooling loads of each of the houses are determined with an hour-by-hour simulation program (TRNSYS) for three climates in the Pacific Northwest.

4.4 Air Filters and Cleaners

Metric

1. ASHRAE 1992 [22] defined arrestance (ability of a device to remove dust from air), dust-holding capacity, dust-spot opacity (percentage decrease in light transmission due to dust buildup on target), opacity index.
2. Persily 1999 [322] described an IAQ performance guide being developed within ASTM, including objectives related to filtration (particulate filtration should be provided in forced-air heating and cooling systems in order to control particulate levels in the indoor air and the maintain the cleanliness of HVAC components).

Diagnostic

1. ASHRAE 1992 [22] described gravimetric and dust-spot procedures for measuring the efficiency with which air-cleaning devices arrest (remove) dust.
2. ASTM 2000 [36] discussed HVAC-system air-filtration criteria and visual inspection requirements.
3. Hanley et al. 1994 [202] described a laboratory test method to test fractional filtration efficiency of air cleaners used in general ventilation. The test method requires a test rig that pre-filters air, adds potassium chloride as a test particulate, and measures and differentiates penetration rates based on particulate size.

Norm

1. Hanley et al. 1994 [202] presented fractional filtration efficiency test results, based on particulate size, using a laboratory test rig. Provided results for pleated-paper filters, electronic air cleaners (electrostatic precipitator type), and fiberglass furnace filters.

4.5 Noise

Metric

NONE

Diagnostic

1. CMHC 1998 [79] discussed noise transmission in houses and mitigation through house layout and installation of insulation.

Norm

NONE

4.6 Maintenance Ease and Necessity

Metric

NONE

Diagnostic

NONE

Norm

NONE

4.7 Instrumentation

Metric

NONE

Diagnostic

1. Arney and Frey 1995 [12] explained why short-term monitoring is better than one-time functional performance tests when evaluating HVAC system temperatures, humidity levels, fan energy, and evaporative cooler pump energy.
2. ASHRAE 1989 [17] presented the ASHRAE standard orifice-flowmeter method for measurement of liquid flow in pipes, for use with fluids associated with HVAC systems.
3. ASHRAE 1991 [19] presented the ASHRAE standard method for measuring temperatures.
4. ASHRAE 1991 [20] presented the ASHRAE standard method for measurement of gas flow.
5. Benton et al. 1996 [49] described assorted data loggers and sensors for short-term monitoring.
6. Bevirt 1994 [52] listed six temperature-measurement instruments, specifying recommended uses and limitations.
7. Bowman and Goldberg 1994 [58] extensively discussed how to choose electric-load monitoring instruments suitable for a particular project.

8. Cummings et al. 1990 [98] discussed tracer gas, blower door, smoke and visual inspection methods to study the effects of duct leakage on airflow, infiltration, heating and cooling.

9. Davis 1995 [104] discussed the use of color-coded pressure tubing, rather than all clear tubing, to keep track of measurements and reduce errors.

10. Dodier and Kreider 1999 [113] described an Energy Consumption Index (ECI) that can be used with a neural net to track and detect energy usage problems in commercial buildings, based on usage patterns and weather factors.

11. Dutton 1994 [129] discussed gas and combustion-related testing and measuring device, including pressure gages, portable explosion meters, regulators, chemical or electronic flue gas analyzers, CO_2 and O_2 analyzer, stack thermometer, CO tester, draft gage, combustion efficiency calculators, and manometers.

12. Farrar et al. 1998 [145] used a data logger, weather tower, and indoor sensors to form a thermal performance monitoring system that measured outside weather, indoor climate, and electric power consumption over several weeks.

13. Griffith 1993 [183] discussed the use of an in-line gas meter to measure gas consumption over a set period of time.

14. Home Energy 1997 [216] presented a discussion about data loggers with Danny Parker (Florida Solar Energy Center), Frederic Goldner (Energy Management and Research Associates), Jonathon Beers (Madison Gas & Electric), and David Springer (Davis Energy Group).

15. Kelley and Keefe [230] described the telltale house, an interactive exhibit to demonstrate how pressure differences affect different parts of a house.

16. Kinney 1993 [234] discussed the use of elapsed time meters and/or thermostats with run-hour memory to evaluate the effectiveness of weatherization work.

17. Kinney 1995 [233] discussed the use of a wiring analyzer to check electric circuits before installing blown-in insulation.

18. Knight et al. 1995 [239] discussed the development and testing of a hand-held device to for detecting air leakage sites on building surfaces. Soap is applied to a building surface and the PACT unit is used to apply a vacuum to the surface. Air leakage sites are identified by the appearance of soap bubbles, created by the vacuum. The unit is calibrated, relating pressure differences to leakage area. The PACT unit is able to detect smaller and more leaks than the use of smoke, however has trouble with larger leakage sites, most of which are better detected visually.

19. Koles et al. 1996 [241] listed various instruments for measuring temperature, airflow, air motion, and humidity. These included (a) for temperature, a liquid-in-glass thermometer, resistance thermometer, thermocouple or bimetallic thermometer; mean radiant temperature (MRT) measurement with a globe thermometer or a two-sphere radiometer; (b) for air motion, a hot-wire anemometer, heater sphere anemometer, heater resistance anemometer, vane anemometer or a cup anemometer; (c) for humidity, a psychrometer, dew-point hygrometer, electrical conductivity or capacity hygrometer, radiant temperature asymmetry measured with a net radiometer or a directional radiometer; and (d) for surface temperature, a contact thermometer or an infrared sensor.

20. Lawton 1992 [247] gave methods for and case examples of short-term monitoring (here, pressure gages, temperature sensors and humidity sensors used to characterize building-envelope heat flow).

21. Lutz 1991 [258] described and discussed tools for use in audits, including knowledge, senses, utility bills, heat loss calculations, thermometers, psychrometers, wood moisture meters, CO testers, pressure gages, duct flow measurement tools, combustion analyzers, blower door, infrared camera, short-term monitoring, mirrors and flashlights.

22. Modera and Jump 1995 [274] used a cellular modem to upload data acquired by an on-site data logger to laboratory computer each night, allowing remote monitoring of the experiment.

23. Reichmuth 1992 [344] discussed lighting audit tools and how to use them in residential settings. Lighting auditing tools discussed include portable wattmeters, watt loggers, CT loggers, current loggers, and occupancy analyzers.

24. Sherman and Dickerhoff 1989 [391] describe the multi-tracer measurement system (MTMS) to measure time-varying interzonal flows and presented MTMS results for two houses.

25. SMACNA 1993 [407] described testing and balancing equipment, including: airflow measuring instruments (manometers, pitot tubes, pressure gages, anemometers, flow hoods, and smoke devices), hydronic measuring instruments (manometers and pressure gages), rotation measuring instruments (tachometers), temperature measuring devices (thermometers, thermocouples, electronic thermometers, psychrometers and electronic thermohygrometers), electrical measuring instruments (volt-ammeter), communication devices, and hydronic flow measuring devices (venturi tube and orifice plate, annular flow indicator, calibrated balancing valves and location of flow devices).
26. Ternes 1987 [420] described data parameters to collect in single-family retrofit research projects and described data analysis approaches and issues. Data parameters included (a) basic data (house characteristics, leakage measurements, metered performance of HVAC systems, and verification of retrofit installation quality); (b) time-sequential data (sub-metered space-conditioning energy consumption, weather station measurements [dry bulb, horizontal solar radiation, humidity, wind speed and direction], indoor temperature and humidity, total fuel consumptions [billing meter data], wood heating usage, and sub-metered water heating energy consumption); (c) optional occupant behavior data (additional indoor temperature and humidity, hourly heating and cooling thermostat set-points); (d) geographic characteristics (terrain and shielding); and (e) distribution system data (duct leakage area measured using fan pressurization).
27. The Energy Conservatory 1999 [422] presented specifications of its Automated Performance Testing System (APT), an eight pressure channel data logger.
28. Trombly 1991 [433] discussed a hand-held low-E window coating detector device.

Norm

1. ASHRAE 1993 [24] specified test apparatus tolerance requirements for temperature, pressure, draft, weight, time, energy consumption and energy flow rate, heating value, combustion products, and smoke measuring devices and instruments to be used with the ASHRAE test procedure for rating the efficiency of residential central furnaces and boilers.
2. ASHRAE 1993 [25] specified test apparatus tolerance requirements for temperature, pressure, draft, weight, time, energy consumption and energy flow rate, heating value, water flow, combustion products, and smoke measuring devices and instruments to be used with the ASHRAE test procedure for rating the efficiency of residential water heaters.
3. Snell 1993 [408] discussed infrared imaging system pros and cons, and how to select a system.

5. Non-Technical

5.1 Commissioning Process

Metric

1. Tseng et al. 1994 [435] specified 10 criteria to assess the effectiveness of a commissioning program (e.g., number & severity of defects, quality of maintenance training).

Diagnostic

1. Allen 1999 [2] discussed Canada's rating system, based on a site evaluation and HOT2XP analysis, which provides homeowners with an energy-efficiency rating label and provided energy-efficiency improvements suggestions for their house.
2. Arney 1998 [11] discussed using calibrated models and short-term monitoring to reduce risk and increase the confidence of energy savings estimates for complex retrofit projects by ESCos in non-residential buildings.
3. Arney and Frey 1999 [13] discussed tune-ups (retro-commissioning) as a way to increase energy savings, including short-term diagnostic testing, measurement and verification, and performance service system (maintenance tracking system).
4. ASHRAE 1995 [28] specified requirements and procedures to survey total energy use in existing buildings, including building type classification, building area, energy use and electric demand data, data requirements, and data analysis. Energy survey results include electric index (EI, total electricity used annually per unit floor area), fuel usage, Energy Utilization Index (EUI, total energy used annually for all fuels [in kBtu/yr or kWh/yr] per unit floor area), and the

Cost Index (CI, total cost for all fuels used annually per unit floor area).

5. ASHRAE 1996 [30] specified a recommended process to use when commissioning HVAC equipment. Procedures, methods, and document requirements described cover each phase of the commissioning process, from pre-design through final acceptance and post-occupancy, including changes in building and occupancy requirements after initial occupancy. Documentation procedures include owner's assumptions and requirements; design intent, Basis of Design, and expected performance; verification and functional performance testing; and operation and maintenance criteria. Process-related details include conducting verification and functional performance testing and maintaining system performance to meet the current design intent after initial occupancy. Outlined a training program for operation and maintenance personnel.

6. Benner and Stum 1993 [48] discussed commissioning and re-commissioning opportunities in buildings, giving examples of the needs for commissioning (e.g., duct leakage, improper refrigerant charge levels). Also listed costs and benefits to builders, contractors, and utilities. Provided guidelines to buildings and utilities for incorporating commissioning and re-commissioning into their programs.

7. Bevirt 1994 [52] described the services of TAB professionals and their role in the commissioning process, with an emphasis on very large buildings.

8. BII 1998 [53] described a classroom and on-site program to train builders to comply with building energy codes.

9. Boner and Dasher 1997 [57] briefly described a Oregon Office of Energy commissioning toolkit developed to help state agencies commission their buildings, including boilerplate pre-functional and functional tests.

10. Brohard and Krieg 1994 [59] listed a four-part commissioning plan for EEMs (static installation test, functional performance test, site environmental quality test, recommissioning test) that enumerates the tests needed to determine whether EEMs are properly installed and operating correctly.

11. Cavallo 1999 [64] compared side-by-side HERS ratings on two houses (one new and one old). For the older house, ratings varied based on the raters' interpretation of what defined conditioned space. However, the spread of rating values did not affect the suggested energy-efficiency improvements.

12. CMHC 1998 [79] provided a checklist of potential problems and retrofit activities relating to different parts of a house (for example: foundation problems and construction techniques, structural considerations, water damage, air leakage).

13. Cohen and Goldman 1991 [81] discussed technical recommendations that have been included in various weatherization programs: blower-door guided infiltration reduction and infrared scanning, high-density blown cellulose wall insulation, high-efficiency condensing furnaces, additional attic insulation, low-cost water heater retrofits, and duct sealing.

14. Cooper et al. 1997 [90] discussed opportunities for performance contracting in the Canadian residential sector, primarily in multi-family buildings.

15. Dodds et al. 1994 [111] described a procedure for evaluating the commissioning process in commercial buildings (objectives, scope, steps, responsibilities).

16. Dodds et al. 1998 [110] gave flowcharts for the new-construction commissioning and retro-commissioning processes. Also identified commissioning providers and providers of technical, information, and training services.

17. Dodge 1996 [112] described the outlook for U.S. residential construction, including forecasts of single family, multi family, attached, low-rise, and high-rise homes in various regions of the country.

18. DOE 1995 [116] discussed background information and request for comments regarding DOE's 1995 proposed phased-in compliance period for the HERS program. DOE's 1995 proposal included one year to come into "basic compliance" by meeting a specific set of guideline provisions, and two years to come into "full accreditation" by meeting all the guideline provisions.

19. DOE 1997 [118] presented the components of the International Performance Measurement and Verification Protocol (IPMVP), which is used to measure and verify energy and water efficiency savings related to energy efficiency retrofits and energy savings performance contracts (ESPCs).

20. DOE 1998 [119] discussed commissioning practices, protocols, and techniques for existing buildings and retrofit activities. Provided examples, cost analyses, checklists, and project-phase specific information.

21. DOE 1999 [114] presented DOE's summary of building energy software tools, including energy simulations, load calculation, renewable energy, retrofit analysis, and sustainability/green buildings.

22. DOE 1999 [115] discussed model energy code, the MECcheck program, state-by-state information on buildings, links to other building codes, and standards-related web sites.

23. Dols et al. 1994 [121] described an indoor air quality commissioning protocol, including specific testing protocols and instrumentation requirements. The protocol included comparing ventilation system design with codes and standards, determining reference indoor environment parameter values and measuring the indoor environment parameters at three construction phases. Indoor environment parameters relate to ventilation performance (outdoor airflow rate and relative pressurization between zones), pollutants (carbon dioxide, carbon monoxide, formaldehyde, particulates, radon and volatile organic compounds), and thermal comfort (temperature, relative humidity and operative temperature). Dols et al. 1995 [123] discussed this protocol, subsequent commissioning results, and lessons learned.

24. Dols et al. 1995 [120] described a methodology to measure IAQ effectiveness in commercial building commissioning, including ventilation performance (outdoor airflow rate and pressure relationships between zones), pollutants (CO_2, CO, formaldehyde, particulates, radon and VOCs), and thermal comfort (temperature, relative humidity, and operative temperature).

25. Elberling et al. 1998 [132] presented lessons learned in a retrofit process, including choice of building design team, design constraints, equipment selection, contractors and sub-contractors, and commissioning errors.

26. Elovitz 1986 [134] described a series of commissioning case studies of problems found with system design, combined design/installation, installation, balancing and controls, equipment, and calibration and monitoring. Discussed how commissioning requires a systems approach and viewing the building as a whole.

27. Elovitz 1992 [135] discussed the why and how of the HVAC commissioning process and procedures, including preparing for commissioning, developing a commissioning plan, who commissions mechanical systems, and commissioning and Design/Build. Also gave examples from actual HVAC commissioning experiences (e.g. with heat exchangers, thermostats, pumps, and fans) to illustrate the processes of investigation and analysis.

28. EPA 1998 [139] recommended that a building tune-up should be implemented in the following order: (1) lighting; (2) building envelope; (3) controls; (4) testing adjusting, and balancing; (5) heat exchange equipment; and (6) heating and cooling system.

29. EPA/DOE 1999 [140] described the Energy Star Benchmarking Tool, a computer program that rates a building based on physical attribute, operating characteristic, and energy consumption data.

30. FEMP 1999 [148] discussed the measurement and verification procedures and options for FEMP's Super Energy Savings Performance Contract program.

31. Gardiner and Piette 1985 [174] discussed the benefits and limitations of using whole-building energy data. Also discussed the additional benefits of sub-metered data to assess the impacts of energy efficiency retrofits in commercial buildings.

32. Gerardi and Sweeney 1994 [175] summarized the instrumented audit technique (software tool) developed for use in weatherization procedures. The protocol included health and safety, blower door measurements, and heating systems problem diagnostics; the software leads the auditor through a decision tree to determine most important issues to address.

33. Greely et al. 1992 [176] discussed recommended installation standards and checklists for weatherization programs (heating, insulation, water heating, air tightness and repairs).

34. Grimsrud et al. 1981 [192] described utility bill and weather data analyses to predict building energy performance.

35. Guven and Spaeth 1994 [197] described the process of large building commissioning through a detailed example of the commissioning of a thermal energy storage unit. Included a glossary of commissioning-related terms.

36. Hammon and Modera 1996 [199] discussed strategies and provided key action items to integrate tight duct construction parameters and factors into HERS, Title 24, and energy-efficient mortgages. Provided material and performance metrics.

37. Haberl et al. 1998 [198] presented a general diagnostic for discovery of problem areas affecting energy savings, and states that an occupant training program is necessary to obtain and maintain energy savings.

38. Heinz and McCray 1996 [210] discussed the commissioning of four new teaching and research science buildings at the University of Washington, with attention to problems encountered.

39. Hitchcock et al. 1997 [211] discussed the conceptual development of tools for use in commissioning and life-cycle tracking of commercial building performance, including a tool for capturing design intent, a chiller commissioning tool kit to assist in verifying and documenting installed chiller performance, building design advisor, and a performance evaluation and tracking tool (chiller emulator and data visualization module). Also discussed interoperability (concurrent access to project/building information relating to building design, construction, commissioning and use) via BLISS (Building Life-cycle Information Support System).

40. Kjellman et al. 1996 [237] assessed building commissioning practices by reviewing the literature of 72 organizations that have or plan to publish commissioning guidelines, standards, or data; found that 42 organizations had published approximately 44 guidelines, standards, manuals, and codes. Also conducted a phone survey of 16 building-commissioning firms, 75% of whom had commissioned primarily office buildings; found that all but one described their activities as systems commissioning, rather than whole-building commissioning. Found that performance testing occupied 40 to 80% of the time required for the commissioning project. Presented table showing the construction phases in which the various commissioning firms were involved.

41. Koles et al. 1996 [241] discussed an energy-use index as a metric to determine if a given building is performing within reason for its climate and size.

42. Koran 1994 [242] presented a case study of a large building energy conservation measure (ECM) verification project, noting the unintended benefits of finding (and solving) problems not anticipated.

43. Lane et al. 1989 [245] discussed four main components of a procedure to diagnose a sick building or confirm a healthy building: knowledge of what to measure, availability of appropriate instrumentation, expertise in interpreting results of measurements, and capability of predicting building performance.

44. Linder et al. 1999 [253] discussed standards of performance for commercial HVAC&R equipment, plumbing systems, and building envelope systems, and described the components of the standards of performance (general information, standards of performance, information to be recorded, calculations, interpretation, other information, and corrective action).

45. Meyers et al. 1995 [270] presented the use of building data visualization (the acquisition and graphical and statistical analysis and presentation of building operational data) to evaluate and serve as a feedback loop to building operators in commercial buildings.

46. Mill et al. 1985 [271] described the need for trans-disciplinary efforts (i.e., cooperation among various professional design and measurement disciplines) to ensure total building performance (i.e., meeting the functional and comfort needs of the occupants, and maintaining building integrity over time). Listed a five-level plan for building envelope analysis: (1) plan/archive; (2) expert walkthrough; (3) occupancy and use; (4) simple instrumentation; and (5) complex instrumentation.

47. Morrison Hershfield Ltd 1996 [288] discussed a procedure for commissioning the building envelope, from design intent to post-installation.

48. National Institute of Building Sciences and the Florida State University Energy Center 1999 [296] provided a detailed overview of the general principles and procedures of total building commissioning, including a description of the processes, plans, specifications, validation reports related to commissioning. They also provided a discussion of the responsibilities of commissioning participants, a model request for commissioning services, and a set of model building-system guidelines. Also provided a glossary of terms.

49. NEBB 1999 [300] presented a guide for development and implementation of commercial HVAC system commissioning plans. Included a model specification, HVAC systems commissioning procedures and sample reporting forms. Also provided procedural standards for building system commissioning (i.e. guidance for organizing, planning, verifying, and documenting building performance). Included model reporting forms, check sheets, and functional performance checklists.

50. Peach 1992 [315] discussed contractual and other factors to take into account when doing residential performance contracting.

51. PECI 1992 [316] presented building commissioning guidelines, including procedures, forms, protocols, performance tests, minimum test plan requirements, monitoring requirements, report outline, design intent document, commissioning specification, O&M specification, and commissioning agent qualifications. Included a detailed manual with specifications, guidelines, and test procedures for the commissioning of commercial buildings. Chapters include Commissioning (Cx) Overview, Integrating Cx into the Building Project, Roles of the Cx Team Members, The Cx Process, Cx Plan, Cx Test Plans. Appendices include Sample Cx Specification, Sample List of Cx Agent Qualifications, Operation and Maintenance Manuals, Sample Design Intent Documentation, Sample Cx Final Report Outline, Sample Forms, Sample Cx Plan, Sample Pump Pre-functional Performance Test Checklist, Sample Minimum Test Plan Requirements Outline, Sample Cooling Tower Test Plan Packet, and The Thought Process of Cx.

52. PECI 1997 [317] provided a detailed manual with specifications, guidelines, and test procedures for commissioning of commercial buildings. It covers the design, specification, and construction phases of a project.

53. PECI 1999 [318] overviewed procedures for commissioning of commercial buildings.

54. Piette and Nordman 1996 [327] discussed commissioning benefits, procedures, examples of non-energy benefits, cost-effectiveness, and commissioning techniques considered in a 16 commercial building study.

55. Richalet and Henderson 1999 [348] discussed the progress of European home energy rating systems.

56. Rieger 1993 [349] described the CHEERS program, procedures, and implementation plans.

57. Robison and Reichmuth 1999 [350] discussed a spreadsheet tool that allows quick adjustment of a simplified engineering model to match utility bills. The tool can be used to diagnose energy patterns and end use consumption, calibrate savings estimates to agree with actual usage; verify vendor claims regarding performance factors; and generate performance targets and compare against actual bills.

58. Rose 1999 [353] reviewed potential problems related to testing and balancing of commercial HVAC system.

59. Schalch and Fryer 1992 [364] discussed the Energy Crafted Home's program design, which allows for design flexibility along with prescriptive measures.

60. Sonderegger 1998 [410] analyzed utility bills for non-residential facilities by correlating past utility bills to observable variables, then projecting that correlation into the future. Techniques included variable-base degree days synchronized to utility bills, incorporating other independent variables, tuning the baseline equation, accounting for the degree-day threshold, and regression analysis.

61. Sterling et al. 1992 [414] presented, for each commissioning phase, a checklist of tests, issues and questions to consider to help avoid IAQ problems.

62. Sterling and Collett 1994 [413] discussed the role of commissioning as quality assurance; commissioning activities at the various project phases (program, design, construction, acceptance, post-acceptance); the commissioning team; and commissioning costs (0.25% to 2% of construction budget).

63. Ternes 1987 [420] described data parameters to collect in single-family retrofit research projects and described data analysis approaches and issues. Data parameters included (a) basic data (house characteristics, leakage measurements, metered performance of HVAC systems, and verification of retrofit installation quality); (b) time-sequential data (sub-metered space-conditioning energy consumption, weather station measurements [dry bulb, horizontal solar radiation, humidity, wind speed and direction], indoor temperature and humidity, total fuel consumptions [billing meter data], wood heating usage, and sub-metered water heating energy

consumption); (c) optional occupant behavior data (additional indoor temperature and humidity, hourly heating and cooling thermostat set-points); (d) geographic characteristics (terrain and shielding); and (e) distribution system data (duct leakage area measured using fan pressurization).

64. Thomas 1992 [423] discussed performance-contracting guidelines, including standard contracts, evaluation of bids, comprehensive programs, and guarantees.

65. Thomas 1999 [424] discussed the state of the U.S. home energy rating systems, the number of houses tested under the Energy Star program, financing tie-ins and marketing efforts.

66. Uniacke 1992 [443] discussed how important it is to use field-based hands-on training to educate builders. Discussed how the effectiveness of building education should be based on the builders' willingness to integrate new strategies into their work. Also discussed how the building science perspective can be used to synthesize efficiency, comfort, indoor air quality, health, safety, affordability, and durability and show builders how a home should perform. N.B.: this reference consists only of an abstract.

67. Weir 1996 [459] discussed the results of a survey and assessment of current Canadian commissioning procedures.

68. Yoder and Kaplan 1992 [465] described a utility-sponsored program (Energy FinAnswer) that provides financing and engineering services for new large commercial buildings and for major remodels that include energy efficiency improvements. The utility works with the owner to commission the building to ensure that the funded measures are properly implemented. Details commissioning (Cx) protocol (scoping meeting, design intent documentation, Cx outline, pre-Cx tests, functional performance testing, end-use monitoring and seasonal testing, operations and maintenance summary and training, documentation) and attributes of the Cx agents. Also, discussed, based on knowledge gained in Bonneville Power's Energy Edge program, the role of building commissioning in the application of demand-side technologies; commissioning strategies and protocols; liability, and payment and commissioning schedules.

Norm

1. Eash 1998 [130] discussed the Irvine IQ+ program, a voluntary program to improve energy-efficiency of new homes; presented 1998 results (53 homes certified by third party inspector).

2. EPA 1997 [138] recommended that one person, rather than multiple subcontractors, take responsibility for all air sealing in a building.

3. Gardiner and Piette 1985 [174] discussed the commissioning process and the evaluation of whole-building energy savings.

4. Kjellman et al. 1996 [237] discussed some problems encountered in commercial buildings. Also discussed the necessity for re-commissioning to keep energy savings.

5. Prince 1986 [331], as an experienced contractor, identified common commissioning problems and the parties responsible. Recommended specific personnel and procedures needed for successful HVAC system startup and final building commissioning.

6. Sterling and Collett [413] described the phases of the building commissioning process (program, design, construction, acceptance, post-acceptance), the composition of the commissioning team, and the costs and benefits of commissioning.

5.2 Economics

Metric

1. Eley and Wilcox 1992 [133] detailed the cost-effectiveness analysis used to develop energy efficiency levels required by the 1992 California low-rise residential building energy-efficiency standards (Title 24). Charted the cost-effectiveness of attic, ceiling, wall, and floor, and slab-edge insulation.

2. Lerman 1998 [248] found little correlation between the cost of duct sealing and the energy savings yielded (and the same for change in energy use vs. change in duct leakage).

3. Piette et al. 1995 [328] discussed simple-payback time metrics (years, ratio of first costs to annual energy savings) and average present value of energy saving measures estimates ($/ft^2), and commissioning cost ($/ft^2).

4. Vieira et al. 1998 [445] defined several cost-benefit indicators (e.g. simple payback, NPV) useful for ranking energy conservation measures.

Diagnostic

1. ASHRAE 1993 [27] specified how the annual energy cost method is used to show compliance with ASHRAE Standard 90.2-1993. The annual cost method compares the annual energy cost of the proposed design to the annual energy cost of a prescriptive design (same floor plan and design) whose characteristics meet the prescriptive requirements of the Standard.
2. Byrne 1995 [62] proposed HERS guidelines (as of 1995) and discussed California-related issues.
3. CEC 1995 [65] detailed California historical energy statistics, including supply, demand, and prices of petroleum, petroleum products, natural gas, and electricity. Demand was subdivided by sectors, including residential vs. commercial.
4. Greely et al. 1992 [176] compared program costs and energy savings for the existing and pilot weatherization programs in Virginia.
5. Greely et al. 1992 [177] described the evaluation of various weatherization techniques and materials considered for mild-climate weatherization activities. Evaluation included PRISM savings and cost-effectiveness evaluation, literature reviews, engineering and economic calculations, and short-term monitoring of furnace performance.
6. Grimsrud et al. 1983 [185] presented a computer program for evaluating the cost-effectiveness of energy efficiency measures for a particular house, for use at an energy audit.
7. Home Energy 1999 [214] provided a resource list of North American trainers, training opportunities, and conferences related to home performance.
8. Home Energy 1999 [215] listed education, government, and organizational resources related to home energy issues.
9. PECI 1999 [318] presented examples of costs and benefits of commissioning in commercial buildings.
10. Peterson and Haasl 1994 [324] used a tuned DOE2.1 building simulation model to estimate the additional energy and monetary saving that would have been possible had a building retrofitted with ECMs been commissioned at the design phase, rather than after the retrofit.
11. Sharp 1995 [368] discussed North Carolina's weatherization programs. Measure costs and related savings were broken down by measure (insulation, repairs, air sealing, storm windows, labor, other).
12. Stein 1997 [412] evaluated the accuracy of four states' HERS programs, and suggested ways to improves HERS, including training, fool proofing the process, and educating homeowners about HERS results.
13. Vieira et al. 1998 [445] described a Florida computer program (Energy Gauge/Optimization) that measures and reports the economic and financial impacts of home energy technology decisions.
14. Walter and Lewis 1996 [455] described a "whole-house" service provider and the provider's work plan, including house diagnostics, tune-ups, installation, trouble-shooting, and duct sealing.
15. Yoder and Kaplan 1992 [465] described a utility-sponsored program (Energy FinAnswer) that provides financing and engineering services for new large commercial buildings and for major remodels that include energy efficiency improvements. The building owner receives 50% of the ECM cost upon presentation of process billings from contractors, 20% after passing pre-commissioning tests, and 30% upon passing functional performance tests.

Norm

1. Bodzin 1999 [56] discussed energy and cost savings of specific Building America components and energy-efficient measures.
2. CA State 1999 [63] provided estimates of California population and housing.
3. CEC 1999 [66] presented historical California energy statistics including supply, demand, and price of energy resources by sector.
4. Claridge et al. 1998 [76] found that in almost all older commercial buildings, and even in many new buildings, use of the building is quite different from the original plan. Consequently, they developed a process of "continuous commissioning" that tunes the systems of the building for optimal comfort and peak efficiency based on the current use. Implementing that process has saved an average of over 20% of the

total energy cost (over 30% of the heating and cooling cost) in more than 80 buildings in which it has been applied. Simple payback times under two years were achieved in nearly all of the 80 buildings.

5. Cohen and Goldman 1991 [81] discussed the energy and cost savings performance of several weatherization programs.
6. Cummings et al. 1990 [98] discussed repair costs and energy savings (consumption and peak demand) related to duct leakage repair.
7. Dodge 1996 [112] presented a quarterly housing forecast, by state and dwelling type, for 1994 to 2000.
8. Energy Information Administration 1999 [137] presented statistics on the types of air conditioners, heating units, water heaters, and lighting equipment found in U.S. homes.
9. Feustel et al. 1986 [149] discussed TRNSYS modeling of the economic and ventilation performance (average and effective ventilation rates) of natural ventilation and several ventilation strategies (exhaust ventilation, heat recovery ventilation, exhaust ventilation with heat pump heat recovery, and exhaust air heat pump water heating).
10. Hammon and Modera 1996 [199] discussed costs and energy savings attributable to tight duct construction in new construction.
11. Hayden 1992 [209] discussed energy savings due to oil-furnace retrofit options.
12. Jenkins 1991 [220] discussed economic impact of heat pump system retrofits (percent heating savings, repair cost, life cycle benefits to the homeowner and utility).
13. Kjellman et al. 1996 [237] discussed the cost effectiveness of commissioning a building, presenting a table of commissioning cost data ($0.10 to $2.50 per ft^2) for 12 buildings supplied by surveyed commissioning practitioners. In addition, tabulated energy savings results from deficiency repairs in seven buildings, including annual savings (kWh, $, kWh/ft^2), % energy savings, and simple payback time.
14. Matson and Feustel 1998 [263] presented equipment costs, installation costs, annual operating costs and life cycle costs, based on RESVENT airflow modeling, for ventilation strategies (single and multi-port exhaust fans with inlet louvers, single and multi-port exhaust fans with outside air ducts, balanced heat recovery) in one and two story houses in California and New York climates.
15. McBride 1992 [264] discussed the energy conservation measure cost/savings analysis used to form the residential building performance prescriptive criteria in ASHRAE 90.2P (ASHRAE 1993 [27]).
16. Parker 1991 [311] discussed cost savings possible by coupling whole house fan operation with air conditioning systems.
17. Parker et al. 1998 [314] discussed the economics of various installed measures, including installed cost, estimated annual savings (kWh, $), and simple payback time (years) of radiant barrier systems, high-SEER AC, solar water heaters, efficient pool pumps, high-efficiency refrigerators, high-efficiency lighting, and attic ventilation.
18. Piette et al. 1995 [329] discussed the energy savings found in the Energy Edge project (commercial) buildings; savings would be higher with commissioning and feedback to the building owners.
19. Piette and Nordman 1996 [327] presented commissioning results for a 16 commercial building sample. Results included average present value of energy saving measures ($0.21/ft^2); average commissioning cost ($0.23/ft^2); and median simple payback (6.5 years for Pacific Northwest energy prices, 3 years for national average energy prices).
20. Proctor 1991 [333] discussed project program savings and costs for improving the efficiency of existing cooling systems in Fresno, California.
21. Robison and Lambert 1989 [351] discussed annual energy savings estimates, retrofit costs, simple paybacks, and benefit cost ratio for duct sealing in 20 Residential Standards Demonstration Program (RSDP) homes.

6. Not Annotated

1. Edwards and Irwin 1994 [131] is just an abstract.
2. Farhar and Coburn 1999 [144] discussed homeowner attitudes toward electricity providers.
3. Meal et al. 1985 [266] is relevant only to commercial buildings.

APPENDIX B: ALPHABETICAL LIST OF REFERENCES*

		Links		
		M	D	N
[1]	Allen Consultants. 1996. "Optimizing Residential Forced-Air HVAC Systems". Ottawa, ON, Canada; Canadian Mortgage and Housing Corporation Technical Series 96-218.	2.7		
[2]	Allen, D.R. 1999. "Canadian Ratings Warm Up". Home Energy Magazine, Vol. 16, No. 5, September/October, pp. 19-20. Berkeley, CA; Energy Auditor & Retrofitter, Inc.		5.1	
[3]	Anderson, A. 1995. "The History of the Blower Door". Home Energy Magazine, Vol. 12, No. 6. Berkeley, CA; Energy Auditor & Retrofitter, Inc.		1.4	
[4]	Anderson, G.D. 1995. Letter to the Editor: "More on Ventilating Attics". Home Energy Magazine, Vol. 12, No. 4, July/August, pp. 3-4. Berkeley, CA; Energy Auditor & Retrofitter, Inc.		1.4	
[5]	Andrews, J.W. 1996. "Field Comparison of Design and Diagnostic Pathways for Duct Efficiency Evaluation". Proceedings of the 1996 ACEEE Summer Study on Energy Efficient Buildings, 1.21. Washington, D.C.; American Council for an Energy-Efficient Economy.	2.3	2.3 2.3	2.3
[6]	Andrews, J.W., R.F. Krajewski, and J.J. Strasser. 1996. "Electric coheating in the ASHRAE standard method of test for thermal distribution efficiency—Test results on two New York State homes". ASHRAE Transactions, Vol. 102, Part 1, pp. 870-880.		2.3	
[7]	Andrews, J.W., R.L. Hedrick, M.R. Lubliner, B.P. Reid, B.L. Pierce, and D.W. Saum. 1998. "Reproducibility of ASHRAE Standard 152P: Results of a Round-Robin Test". ASHRAE Transactions, Vol. 104, Part 1B, pp.1376-1388.		2.3 2.3	
[8]	Arasteh, D.K., F.A. Beck, B.T. Griffith, N. Byars, and M. Acevedo-Ruiz. 1992. "Using infrared thermography for the study of heat transfer through building envelope components". ASHRAE Transactions, Vol. 98, Part 1, pp. 819-824.		1.2	
[9]	Arasteh, D.K., F.A. Beck, B.T. Griffith, N. Byars, and M. Acevedo-Ruiz. 1992. "Using infrared thermography to study building heat transfer". ASHRAE Journal, October, Vol. 34, No. 10, pp. 34-36.		1.2	
[10]	Arens, E., R. Gonzalez, and L. Berglund. 1986. "Thermal comfort under an ext ended range of environmental conditions". ASHRAE Transactions, Vol. 92, Part 1B, pp. 18-26.		3.1	

* Section numbers in columns labeled M, D, and N are hyperlinks to Metrics, Diagnostics, and Norms in Appendix A (Annotated Bibliography). For example, the entry "3.1" in the column "D" is a link to a diagnostic in Section 3.1 [Room Air Temperature and Velocity (Occupant Comfort)].

		Links		
		M	D	N
[11]	Arney, W.M. 1998. "Utilizing Calibrated Computer Models to Reduce Risk in Performance Contracting". Proceedings of the 6th National Conference on Building Commissioning, Lake Buena Vista, Florida, Lake Buena Vista, Florida. Portland, OR; Portland, OR; Portland Energy Conservation Institute.		5.1	
[12]	Arney, W.M. and D.J. Frey. 1995. "Short-Term Diagnostic Testing to Streamline Commissioning". Proceedings of the 3rd National Conference on Building Commissioning, Sacramento, CA. Portland, OR; Portland Energy Conservation Institute.		4.7	
[13]	Arney, W.M. and D.J. Frey. 1999. "Long-Term Energy Efficiency Strategy: Building Tune-ups and Performance-based Maintenance". Proceedings of the 7th National Conference on Building Commissioning, Portland, OR. Portland, OR; Portland Energy Conservation Institute.		5.1	
[14]	ASHRAE. 1988. "ANSI/ASHRAE Standard 111-1988 Practices for Measurement, Testing, Adjusting, and Balancing of Building Heating, Ventilation, Air-Conditioning and Refrigeration Systems". Atlanta, GA; American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.	2.3	2.3	
[15]	ASHRAE. 1988. "ANSI/ASHRAE Standard 119-1988 (RA 94), Air Leakage Performance for Detached Single-Family Residential Buildings". Atlanta, GA; American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.			1.4 2.5
[16]	ASHRAE. 1989. "ANSI/ASHRAE Standard 41.3-1989 Standard Method for Pressure Measurement". Atlanta, GA; American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.		2.5	
[17]	ASHRAE. 1989. "ANSI/ASHRAE Standard 41.8-1989, Standard Methods of Measurement of Flow of Liquids in Pipes Using Orifice Flowmeters". Atlanta, GA; American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.		4.7	
[18]	ASHRAE. 1989. "ANSI/ASHRAE Standard 62-1989, Ventilation for Acceptable Indoor Air Quality". Atlanta, GA; American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.	2.5 2.5 3.2 3.5	2.5 2.5	2.5 2.5 2.5 2.5 3.2 3.5
[19]	ASHRAE. 1991. "ANSI/ASHRAE Standard 41.1-1986 (RA 91), Standard Method for Temperature Measurement". Atlanta, GA; American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.		4.7	
[20]	ASHRAE. 1991. "ANSI/ASHRAE Standard 41.7-1984 (RA 91), Standard Method for Measurement of Flow of Gas". Atlanta, GA; American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.		4.7	
[21]	ASHRAE. 1992. "ANSI/ASHRAE Standard 41.2-1987 (RA 92), Standard Methods for Laboratory Airflow Measurement". Atlanta, GA; American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.		2.3	

		Links		
		M	D	N
[22]	ASHRAE. 1992. "ANSI/ASHRAE Standard 52.1-1992, Gravimetric and Dust-Spot Procedures for Testing Air-Cleaning Devices Used in General Ventilation for Removing Particulate Matter". Atlanta, GA; American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.	4.4	4.4	
[23]	ASHRAE. 1992. "ANSI/ASHRAE Standard 55-1992, Thermal Environmental Conditions for Human Occupancy". Atlanta, GA; American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.	3.1		3.1 3.1
[24]	ASHRAE. 1993. "ANSI/ASHRAE Standard 103-1993, Method of Testing for Annual Fuel Utilization Efficiency of Residential Central Furnaces and Boilers". Atlanta, GA; American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.		2.2	4.7
[25]	ASHRAE. 1993. "ANSI/ASHRAE Standard 118.2-1993, Method of Testing for Rating Residential Water Heaters". Atlanta, GA; American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.		4.1	4.7
[26]	ASHRAE. 1993. "ANSI/ASHRAE Standard 136-1993, A method of determining air change rates in detached dwellings". Atlanta, GA; American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.	1.4 2.5 2.5	1.4 2.5	
[27]	ASHRAE. 1993. "ANSI/ASHRAE Standard 90.2-1993, Energy-Efficient Design of New Low-Rise Residential Buildings". Atlanta, GA; American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.		5.2	1.1 1.1 1.2 1.2 1.4 1.5 2.1 2.2 2.2 2.3 2.4 2.5 4.1 5.2
[28]	ASHRAE. 1995. "ANSI/ASHRAE Standard 100-1995, Energy Conservation in Existing Buildings". Atlanta, GA; American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.		2.1 5.1	1.1 1.4 2.1 2.2 2.3 2.5 4.1
[29]	ASHRAE. 1995. "ANSI/ASHRAE Standard 116-1995, Methods of Testing for Rating Seasonal Efficiency of Unitary Air Conditioners and Heat Pumps". Atlanta, GA; American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.	2.1	2.1	

		Links		
		M	D	N
[30]	ASHRAE. 1996. "ASHRAE Guideline 1-1996, The HVAC Commissioning Process". Atlanta, GA; American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.		5.1	
[31]	ASHRAE. 1997 "ANSI/ASHRAE Standard 129-1997, Measuring Air-Change Effectiveness". Atlanta, GA; American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.	2.5	2.5	
[32]	ASHRAE. 1999. "BSR/ASHRAE Draft Standard 152P-1999, Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems". Atlanta, GA; American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.	2.3 2.3	2.3 2.3 2.3 2.3	
[33]	ASTM. 1988. "Standard Test Method for Airflow Calibration of Fan Pressurization Devices, ASTM Standard E1258-88 (RA 92)". Philadelphia, PA; American Society for Testing and Materials.		1.4	
[34]	ASTM. 1990. "ASTM Standard C1060-90, Standard Practice for Thermographic Inspection of Insulation Installations in Envelope Cavities of Frame Buildings". Philadelphia, PA; American Society for Testing and Materials.		1.1	
[35]	ASTM. 1992. "ASTM Standard E779-87, Standard Test Method for Determining Air Leakage Rate by Fan Pressurization". Philadelphia, PA; American Society for Testing and Materials.	1.4	1.4 2.5	
[36]	ASTM. 2000. "ASTM Draft Standard Guide for Specifying and Evaluating Performance of Single Family Attached and Detached Dwellings – Indoor Air Quality". Philadelphia, PA; American Society for Testing and Materials.		2.3 2.4 2.4 2.5 3.1 3.2 4.4	1.5
[37]	ASTM. 1994. "Standard Test Methods for Determining External Air Leakage of Air Distribution Systems by Fan Pressurization". Philadelphia, PA; American Society for Testing and Materials.	2.3		
[38]	ASTM. 1995. "ASTM Standard E1186-87, Standard Practices for Air Leakage Site Detection in Building Envelopes". Philadelphia, PA; American Society for Testing and Materials.		1.4	
[39]	ASTM. 1995. "ASTM Standard E1677-95, Standard specification for an air retarder (AR) material or system for low-rise framed building walls". Philadelphia, PA; American Society for Testing and Materials.	1.4 1.5	1.4	1.4
[40]	ASTM. 1995. "ASTM Standard E71-95, Standard Test Method for Determining Air Change in a Single Zone By Means of a Tracer Gas Dilution". Philadelphia, PA; American Society for Testing and Materials.		1.4 2.5	

		Links		
		M	D	N
[41]	ASTM. 1997. "ASTM Standard E1827-96, Standard Test Methods for Determining Airtightness of Buildings Using an Orifice Blower Door". Philadelphia, PA; American Society for Testing and Materials.	1.4	1.4	
[42]	ASTM. 1998. "Guide For Assessing Depressurization-Induced Backdrafting and Spillage From Vented Combustion Appliances". Philadelphia, PA; American Society for Testing and Materials.	2.4	2.4 2.4	
[43]	Bahnfleth, W.P., G.K. Yuill, and B. Lee. 1999. "Protocol for Field Testing of Tall Buildings to Determine Envelope Air Leakage Rate". ASHRAE Transactions, Vol. 105, Part. 2, 4275 (RP-935). Atlanta, GA; American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.	1.4	1.4	
[44]	Barbat, M., V. Richalet, and G. Guarracino. 1999. "Experimental Studies of the Air Quality Evaluation". Proceedings of the 8th International Conference on Indoor Air Quality and Climate, Edinburgh, Scotland.		3.2	
[45]	Bearg, D.W. 1998. "Commissioning and Indoor Air Quality". Proceedings of the 6th National Conference on Building Commissioning, Lake Buena Vista, Florida. Portland, OR; Portland Energy Conservation Institute.	3.3	3.2 3.3	
[46]	Bearg, D.W. 1999. "The Use of Multipoint Monitoring as a Tool for Commissioning Buildings for IAQ". ASHRAE Transactions, Vol. 105, Part 1, CH-99-19-3.	2.5 3.2	2.5 3.2 3.3	
[47]	Beers, J. 1994. "Condensing Furnaces: Lessons from a Utility". Home Energy Magazine, Vol. 11, No. 6, November/December, pp. 13-17. Berkeley, CA; Energy Auditor & Retrofitter, Inc.		2.2	
[48]	Benner, N. and K. Stum. 1993. "Commissioning and Recommissioning Opportunities in Residential Buildings". Proceedings of the 1st Innovative Housing Conference, Vancouver, BC, Canada, Vol. 4, pp. 126-137. Canada National Research Council.		5.1	
[49]	Benton, C.C., C. Huizenga, R. Marcial, M. Hydeman, and J. Chace. 1996. "Taking a Building's Vital Signs: A Lending Library of Handheld Instruments". Proceedings of the 1996 ACEEE Summer Study on Energy Efficient Buildings, 4.11. Washington, D.C.; American Council for an Energy-Efficient Economy.		3.2 4.7	
[50]	Berckmans, D., K. Van De Weyer, and M. De Moor. 1993. "Visualization and quantification of the airflow pattern using image analysis". ASHRAE Building Design, Technology, and Occupant Well-Being in Temperate Climates, Brussels, February, pp. 207-215. Atlanta, GA; American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.		2.3	
[51]	Berk, J.V., R.A.Young, S.R. Brown, and C.D. Hollowell. 1981. "Impact of energy-conserving retrofits on indoor air quality in residential housing". Berkeley, CA; Lawrence Berkeley Laboratory report LBL-12189.		1.4 3.2 3.5	1.4 2.5 3.2 3.5

		Links		
		M	D	N
[52]	Bevirt, W.D. 1994. "What engineers need to know about testing and balancing". ASHRAE Transactions, Vol. 100, Part 1, pp. 705-714.		2.3 2.3 4.7 5.1	2.3
[53]	BII. 1998. "Building Energy Code Training: Final Report 1995-1998". Sacramento, CA; Building Industry Institute.	1.1	1.4 2.3 2.3 2.5 5.1	1.1 1.2 1.2 2.1 2.2 2.3 2.3 2.3 4.1
[54]	Bittle, B.R. and V.W. Goldschmidt. 1985. "Trends of residential heat pump cyclic tests". ASHRAE Transactions, Vol. 91, Part 1A, pp. 64-79.	2.1		
[55]	Blasnik, M. and J. Fitzgerald. 1992. "In Search of the Missing Leak". Home Energy Magazine, Vol. 9, No. 6. Berkeley, CA; Energy Auditor & Retrofitter, Inc.		1.4	
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APPENDIX C: LITERATURE CATEGORIZATION GUIDELINE

1. Building Envelope
    - 1.1 opaque building assemblies
        - 1.1.1 assembly thermal conductance
        - 1.1.2 insulation level and location
        - 1.1.3 design-condition interior surface temperature (comfort)
    - 1.2 windows and skylights
        - 1.2.1 assembly thermal conductance
        - 1.2.2 radiative behavior
        - 1.2.3 design-condition interior surface temperature (comfort)
        - 1.2.4 design-condition condensation potential
    - 1.3 thermal mass
        - 1.3.1 amount and location
        - 1.3.2 time constant
    - 1.4 airtightness
        - 1.4.1 envelope and interzone leakage
        - 1.4.2 air barrier type and location
    - 1.5 moisture-damage susceptibility
        - 1.5.1 vapor barrier type and location
        - 1.5.2 design-condition dew-point temperature location
        - 1.5.3 assembly moisture content (plus permeability and drying potential)
2. HVAC
    - 2.1 cooling equipment - air conditioners and heat pumps
        - 2.1.1 room cooling loads (sensible and latent)
        - 2.1.2 equipment selection and sizing
        - 2.1.3 refrigerant charge
        - 2.1.4 coil total airflow
        - 2.1.5 supply air temperature drop
        - 2.1.6 steady-state capacity and efficiency
    - 2.2 heating equipment - furnaces, boilers, and heat pumps
        - 2.2.1 room heating loads (sensible)
        - 2.2.2 equipment selection and sizing
        - 2.2.3 refrigerant charge
        - 2.2.4 coil total airflow
        - 2.2.5 supply air and/or water temperature rise
        - 2.2.6 steady-state capacity and efficiency
    - 2.3 thermal distribution systems - air and/or water flow
        - 2.3.1 system selection and sizing
        - 2.3.2 air handler total flow
        - 2.3.3 pump total flow
        - 2.3.4 water supply line location and insulation
        - 2.3.5 zone coil water flow, temperature, and air fraction
        - 2.3.6 duct location, support, and insulation
        - 2.3.7 duct leakage
        - 2.3.8 register flow and outlet temperature
        - 2.3.9 register location and jet distribution
        - 2.3.10 distribution system efficiency
        - 2.3.11 system operating external static pressure

- 2.4 combustion safety
  - 2.4.1 combustion air supply sizing and location
  - 2.4.2 vent sizing and location
  - 2.4.3 house depressurization level
  - 2.4.4 backdrafting and spillage (combustion gas flow and concentration)
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   - 4.3 plug loads
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   - 4.7 instrumentation (e.g. sensors and data loggers)
5. Non-technical
   - 5.1 Commissioning process
   - 5.2 Economics
6. Irrelevant

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Practical Diagnostics for Evaluating Residential Commissioning Metrics

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LIST OF SYMBOLS

I_i	Instantaneous air change rate in period i, 1/time.
I_m	Effective air change rate, 1/time.
$\overline{C}$	Time-averaged concentration.
$\overline{F}$	Time-averaged contaminant source strength, cfm (m^3/s).
i	Hour of year.
N	Number of discrete time periods in period of interest.
$\overline{Q}$	Effective ventilation rate, cfm (m^3/s).
V	Volume of occupied space, ft^3 (m^3).
Δt	Length of each discrete time period.
$\overline{\tau_e}$	Time-averaged effective turn-over time.
$\tau_{e,i}$	Instantaneous turn-over time in period i.
$\tau_{e,i-1}$	Instantaneous turn-over time in previous period.

OVERVIEW

Background: Currently, houses do not perform optimally or even as many codes and forecasts predict, largely because they are field assembled and there is no consistent process to identify problems or to correct them. The emerging process of residential commissioning can rectify this situation by providing performance assurances.

Residential commissioning is defined within this report as a performance assurance process in the form of agreed upon metrics, diagnostics, and norms that goes beyond assuring the owner that all required equipment is correctly installed, the final product is correctly assembled, and the house can perform as intended. It includes activities such as rating, auditing, super-commissioning, and 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. For California, this expansion includes the energy performance of the large number of existing houses, as well as the indoor environmental performance of all houses. Components and systems in a house that need commissioning include building envelopes, air distribution systems, cooling equipment, heat pumps, combustion appliances, controls, and other electrical appliances.

The work reported here is the second step in a larger project that is laying the groundwork for a residential commissioning industry in California focused on end-use energy and non-energy issues. This report describes our assessment of 107 diagnostic tools for evaluating residential commissioning metrics in the areas described above. Our assessment expands upon our recent literature review and annotated bibliography (Wray et al. 2000), which facilitates access to 469 documents related to residential commissioning published over the past 20 years.

Parallel work in the project includes ascertaining what potential benefits one can realistically expect from residential commissioning. A separate report describes the potential benefits in detail and the analyses we used to assess these benefits (Matson et al. 2002).

We will use the results of these efforts to prepare a separate commissioning guide that describes how non-experts could achieve the benefits that we identify. That guide will contain specific recommendations on what diagnostics to use and how to use them to commission new and existing houses. The guide will also explain the potential benefits of using these diagnostics.

Purpose, Scope, and Structure: In this report, we identify and describe 24 practical diagnostics that are ready now to evaluate residential commissioning metrics, and that we expect to include in the commissioning guide. Our discussion in the main body of this report is limited to existing diagnostics in areas of particular concern with significant interactions: envelope and HVAC systems. These areas include insulation quality, windows, airtightness, envelope moisture, fan and duct system airflows, duct leakage, cooling equipment charge, and combustion appliance backdrafting with spillage. Appendix C describes the 83 other diagnostics that we have examined in the course of this project, but that are not ready or are inappropriate for residential commissioning. Combined with Appendix B, Table 1 in the main body of the report summarizes the advantages and disadvantages of all 107 diagnostics.

We first describe what residential commissioning is, its characteristic elements, and how one might structure its process. Our intent in this discussion is to formulate and clarify these issues, but is largely preliminary because such a practice does not yet exist. Subsequent sections of the report describe metrics one can use in residential commissioning, along with the consolidated set of 24 practical diagnostics that the building industry can use now to evaluate them.

Where possible, we also discuss the accuracy and usability of diagnostics, based on recent laboratory work and field studies by LBNL staff and others in more than 100 houses. These studies concentrate on evaluating diagnostics in the following four areas: the DeltaQ duct leakage test, air-handler airflow tests, supply and return grille airflow tests, and refrigerant charge tests. Appendix A describes those efforts in detail.

In addition, where possible, we identify the costs to purchase diagnostic equipment and the amount of time required to conduct the diagnostics. Table 1 summarizes these data. Individual equipment costs for the 24 practical diagnostics range from a few hundred dollars to many thousands of dollars. The higher costs are associated with infrared thermography and state-of-the-art automated diagnostic systems. Most tests can be performed in one hour or less, using equipment priced toward the lower end of the cost spectrum.

Duct Leakage Tests: Much of our focus in evaluating duct leakage tests was on the DeltaQ test, because it is new. In cooperation with other projects that involve developing the DeltaQ test, LBNL and Brookhaven National Laboratory (BNL) have carried out repeatability tests to estimate uncertainties in this test method. In addition, several research teams have carried out the DeltaQ test in more than 100 houses to show that it is usable in a wide range of houses and to identify limits or problems in field applications. Many of these field tests also involved duct leakage tests using other methods.

Our initial analyses of duct leakage tests show that the DeltaQ test procedure is fairly rugged, unlike other test methods that use pressures measured across the building envelope. In windy conditions, indoor-outdoor pressure differences can vary widely during the test. However, these large variations do not lead to large variations in the test results. The test is also relatively insensitive to large changes in duct reference pressure. This is in contrast to the large leakage flow uncertainty in the duct pressurization test associated with estimating the pressures across the duct leaks.

Precision of the DeltaQ test is limited to about 10 to 20 cfm. Leakage flows less than this typically will be less than about 1% of fan flow and therefore are not significant in terms of energy losses or poor distribution.

Air-Handler Airflows: Several diagnostic tools and techniques are available to measure air-handler airflow. Two of the most promising tools include a fan-assisted flow meter, and a flow plate and grid. Both are commercially available. The following describes our field studies to evaluate these two methods, along with three other methods that one might consider.

Data from our field tests indicate that both a fan-assisted flow meter and a fan-assisted flow hood are borderline acceptable devices for determining air-handler airflow. The accuracy of these measurements is likely about ±10%. The latter method requires an accurate measurement of duct leakage. Methods that are more accurate (±5%) would be preferable for assessing airflow through an evaporator equipped with a fixed-orifice refrigerant control, given the significant impact of air-handler airflow on cooling performance with this type of control.

Based on data reported in the literature, the flow plate and grid appears to be an accurate device for determining air-handler airflow. However, we observed a consistent negative bias near 10% compared to the fan-assisted devices that we evaluated. We suggest that the calibration of this device be assessed further in the laboratory.

One of the non-powered flow hoods that we evaluated (Hood 8) was a prototype. At this time, it is not a reliable means of determining air-handler airflow. Improving the accuracy of this hood

and including duct leakage will enable the diagnostic package that includes it to provide better estimates of air-handler airflow. Because of our tests, we understand that the manufacturer of the hood is already trying to improve its accuracy.

The temperature drop method of assessing air-handler airflow adequacy, which is contained in Title 24, may be able to find the worst cases of low airflow, but is unreliable for identifying airflow inadequacies in many systems. It seems unlikely that this test can be improved, because of the large spatial variations in temperature that can occur in supply plenums, even after refrigerant charge problems are corrected.

A new air-handler airflow measurement standard needs development to address the use of fan-assisted flow meters and the flow plate and grid in field applications. This standard should cover the most common air-handler and duct system configurations found in residential systems. Further work is needed to develop a prototype for this standard test procedure.

Supply and Return Grille Airflows: In order to determine the magnitude of errors associated with applying flow hoods to measure flows at residential supply and return grilles, we have performed detailed laboratory testing and field studies. We used several commercially available flow hoods together with some state-of-the-art fan-assisted flow hoods.

Of the flow hoods that we tested in the laboratory (i.e., ones that are reasonably available), active flow hoods are the most reliable and consistent for measuring distribution system airflows if the measurements are to be used in estimating duct leakage, air handler flow, and individual grille flows for room load and comfort. This does not mean that active hoods are the only ones that can work. There is no fundamental problem with passive hoods, and our field test results showed that some passive hoods can obtain good results when they are used with appropriate care on the right set of grille types and locations. Laboratory and field tests of a wider range of flow hoods should be pursued, in addition to evaluating improvements for residential flow hoods. Because the active flow hood is the most accurate, it can be used as a reference in field evaluations of other hoods.

A new flow hood measurement standard should be developed to address how flow hoods are operated in the field. This standard should have some standard grille sizes, types, and placements that would cover most common geometries found in residential systems. The laboratory tests we used are a prototype for this standard test procedure. Possible agencies for development of this standard are ASHRAE and ASTM.

Refrigerant Charge: Several diagnostics are available to assess the amount of refrigerant charge in a residential cooling system without a thermostatic expansion valve (TXV) control, but only the superheat test is practical, well developed, and reliable (when properly done). In our field study, we evaluated three commercially available methods for doing a superheat test, each involving different hardware, software, and measurements. All three methods, which we broadly characterize as “Superheat Calculation Methods”, claim to make the superheat test easier.

Methods 2 and 3 correctly assess refrigerant charge levels. At this time, Method 1 seems inappropriate for assessing refrigerant charge levels of residential cooling equipment. Note that the reference method is too complicated and time intensive for a service technician to consider it as a practical alternative. However, this is not really a consideration, because it is intended only for research use.

There are problems with all of the methods, such as lost data for Methods 2 and 3, and some problems with deviations in pressure and temperature measurements. In the short term, diligence

on the part of the service technician and the use of well-developed, reliable automation techniques seem to be the best solutions to these problems.

To address the significant performance degradation associated with refrigerant charge, we recommend that the building industry develop a standard method or methods to assess refrigerant charge. The results of this project suggest that the challenge will be to design a robust tool that works in most field conditions, rather than to measure the required quantities accurately enough. In particular, research is needed to develop a method of assessing refrigerant charge in cool weather. The utility of temporarily elevating indoor enthalpy also needs to be examined to extend the periods when the superheat method can be used to test cooling equipment in hot, dry climates. Ultimately, the performance of residential air conditioning systems would be dramatically improved by the development, application, and contractor training of a standard methodology to conduct refrigerant charge testing.

Research and Development Needs: It is important to recognize that many practical diagnostics are available now. However, some of these diagnostics require further research and development to assess or improve their usefulness and accuracy, so that the building industry can use them more extensively and reliably. In summary, the following nine 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. Further research is needed to assess the impact of wind effects, as well as envelope and duct leakage, on the accuracy and repeatability of duct leakage tests, including the new DeltaQ test.
4. Formal standards are needed for the calibration and use of airflow diagnostic tools, such as flow hoods with and without fan assist, fan-assisted flow meters to measure air-handler airflow, 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. Research is needed to examine the utility of temporarily elevating indoor enthalpy, in order to extend the periods when the superheat method can be used to test cooling equipment in hot, dry climates.
8. Further research is needed to assess the accuracy and repeatability of methods that determine the potential for backdrafting and combustion gas spillage.
9. A simple and reliable test for furnace heat exchanger leakage still needs to be developed. The norm for the current tracer gas test is poorly defined and may be unreliable for defining acceptable leakage levels of combustion gas products.

INTRODUCTION

A Problem with a Solution

California has one of the most advanced energy codes in the country: Title 24 (CEC 1998). In spite of this, houses still do not perform optimally, or even as many forecasts predict based on expectations of this code. For example, Walker et al. (1998a) found large variations in duct leakage, even between side-by-side houses with the same system design and installation crew. This has resulted in as much as factor of two variations in thermal distribution system efficiency for these houses. This and other studies (e.g., Jump et al. 1996) indicate that duct leakage testing and sealing can readily improve thermal distribution system efficiency and achieve a 25 to 30% reduction in installed cooling capacity and energy consumption. As another example, consider that for at least 20 years the building industry has recognized the substantial impact of envelope airtightness 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 related energy and non-energy problems or to correct them. Solving the problems requires field performance evaluations of new and existing houses using appropriate and agreed upon procedures. Many procedural elements already exist in a fragmented environment; some are ready now to integrate 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.

Components and systems in a house that need commissioning include building envelopes, air distribution systems, cooling equipment, heat pumps, combustion appliances, controls, and other electrical appliances. For simplicity and practicality, one might consider only evaluating individual components and systems. However, this approach is insufficient, because 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.

A barrier to this solution is that the building industry and the consumer currently view commissioning as a cost, without sufficient perceived compensating benefit. Such a view has resulted in little demand and effort to provide commissioning services. To overcome this barrier, it is important to not only provide an integrated set of simple, rapid, inexpensive, and reliable commissioning methods, but also to quantify the potential benefits of commissioning.

Qualitatively, there are several potential benefits for builders, consumers, code officials, utilities, and energy planners. 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.

Report Structure

The work reported here is part of a project that is laying the groundwork for a residential commissioning industry in California focused on end-use energy and non-energy issues. Its ultimate goal is to increase the commissioning of houses, which will in turn improve or even optimize their energy and indoor environmental performance. To achieve this goal, the technical objective of the project is to collect and analyze data on the methods and techniques of residential commissioning, as well as on its costs and benefits. This includes identifying existing tools and techniques for verifying house performance. The results of this work will provide new insights on how to address the problems of energy and indoor environmental performance in new and existing houses. These results will also foster the discussion of how to integrate aspects of commissioning with other building industry processes to improve the value of a single site visit.

A literature review and annotated bibliography (Wray et al. 2000) have already been prepared as the first step toward meeting the project goal and objective. The bibliography facilitates access to 469 documents published over the past 20 years, which represents the active reporting period for building commissioning and closely related issues. Our review discussed metrics, diagnostics, and norms that those documents describe and that one might use within the residential commissioning process. The review also highlighted gaps in existing knowledge that require further research and development.

The work reported here expands upon the literature review. Specifically, it identifies and describes practical diagnostics that are ready now to evaluate residential commissioning metrics. Our discussion in the main body of this report is limited to existing diagnostics in areas of particular concern with significant interactions: envelope and HVAC systems. These areas include insulation quality, windows, airtightness, envelope moisture, fan and duct system airflows, duct leakage, cooling equipment charge, and combustion appliance backdrafting with spillage. Appendix C describes other diagnostics that we have examined in the course of this project, but that are not ready or are inappropriate for residential commissioning.

The remainder of this report first describes what residential commissioning is, its characteristic elements, and how one might structure its process. Our intent in this discussion is to formulate and clarify these issues, but is largely preliminary because such a practice does not yet exist. Subsequent sections describe metrics that can be used in residential commissioning, along with a consolidated set of practical diagnostics that the building industry can use now to evaluate them. Where possible, we also discuss the accuracy and usability of these diagnostics, based on recent laboratory work and field studies that are described in Appendix A. In addition, where possible, we identify the costs to purchase diagnostic equipment and the amount of time required to conduct the diagnostics. We conclude by describing areas in need of research and development, such as practical field diagnostics for envelope thermal conductance and combustion safety.

In a parallel part of the project, we have carried out a simulation study to demonstrate the potential benefits of residential commissioning for a sample of both new and existing California houses. A separate report describes the potential benefits in detail, along with the analyses we used to assess these benefits (Matson et al. 2002). So that non-experts in the building industry can achieve these benefits, we are developing a separate guide to document the commissioning procedures. It will contain specific recommendations on what diagnostics to use and how to use them. The guide will also explain the potential benefits of using these diagnostics. In addition, we are transferring project findings to the building industry through workshops and presentations.

WHAT IS RESIDENTIAL COMMISSIONING?

Commissioning has its roots in shipbuilding, where the term describes the process that ensures a new vessel is sea worthy 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 very 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 correctly installed, the final product is correctly assembled, 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 report, we broaden our definition of residential commissioning to include many other activities such as auditing, rating, super-commissioning (optimizing performance beyond design intents), or retro-commissioning (adjusting performance of existing houses). 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 three characteristic elements. The following defines these elements and offers examples to aid understanding:

Metrics: There are three broad whole-building objectives related to achieving a safe, healthy, comfortable, and affordable house that has a minimal adverse impact on the external environment. They are: energy performance, indoor environmental performance, and durability. Various qualitative or quantitative metrics can represent each objective. For energy related to providing building services, they include fuel consumption, peak demand, and operating costs. For the indoor environment, they include indoor air quality and comfort. For durability, they include material degradation due to moisture and maintenance costs. Each metric is simply a scale to rank the performance element of interest. Metrics can also represent the performance of building components or systems. Three examples of such metrics 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 metrics, due to the energy, indoor environmental, and durability 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 the use of airflow measuring equipment that creates and measures pressure

differences, which one can then use in subsequent computerized analyses to calculate duct leakage.

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 commissioning. These limitations will largely depend 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: A norm is a benchmark or set of benchmarks (e.g., California Title 24) against which one compares component, system, or whole-building performance. 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

Many in the building industry think commissioning applies only to commercial buildings, even though 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 unique compared to one another, are large, have complex control systems, and have personnel that 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 personnel. 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 we envision has three main phases that can probably be encompassed in generic guidelines for specific commissioning issues or system and component types:

Audit and Diagnostic: The first phase of commissioning uses audit and diagnostic techniques to survey metrics for the house and then compares survey results with appropriate 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, one might base the norms on design intents (if any were ever documented). Alternatively, one might base them upon what a particular component should be able to do relative to those in 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. Examples include sealing leaky ducts or correcting a refrigerant charge deficiency in a central air conditioner. 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. Examples include adding insulation to areas such as the ceiling, walls and floors; replacing windows that a homeowner wishes to change anyway for aesthetic reasons or to solve comfort, condensation, or maintenance problems; and replacing an oversized inefficient cooling or heating system that is near the end of its service life with a properly sized and more efficient system.

METRICS AND DIAGNOSTICS OVERVIEW

Tables 1a through 1g provide an overview of metrics and diagnostics for residential commissioning that we have considered in this project. Within each area of concern, we have grouped diagnostics into metric classifications. We include a "go/no-go (Y/N)" rating that we assigned to the diagnostics within each classification, based on our judgment of the practicality of using the diagnostic now for routine residential commissioning. Although we made these judgments after a careful review of the available relevant information, other reviewers of that information might select a different rating. We do not intend the "go/no-go (Y/N)" ratings in this report to reflect the usefulness of diagnostic procedures for any activity other than residential commissioning. To understand the reasons for our ratings, indexed footnotes to the tables (Appendix B) summarize the advantages and disadvantages of each diagnostic. The remainder of this report provides further information about these metrics and diagnostics, as do the references in the annotated bibliography by Wray et al. (2000).

The "go (Y)" ratings indicate which diagnostics are practical and ready now to commission houses. For each such diagnostic, the tables include a hyperlink to subsequent textual descriptions. Where applicable in these cases, the tables also identify the approximate amount of time required to conduct the diagnostics (including equipment setup and takedown) and the costs to purchase diagnostic equipment (excluding any taxes and shipping). Our time estimate for the DeltaQ duct leakage test assumes the diagnostician will use an automated procedure. The test will take about 50% longer if a non-automated procedure is used. We have excluded specific time and cost estimates for the "no-go (N)" rated diagnostics, because those data are often poorly defined. Instead, table footnotes in Appendix B describe relative time and cost.

Diagnostics involving airflow and pressure measurements must be carried out one at a time. To estimate the time required to carry out multiple tests of this type, one needs to add the individual times listed. In some cases, there may be some minor time reductions associated with having equipment already setup (e.g., 5 to 10 minutes). An example is measuring envelope airtightness with a blower door and then duct leakage only to outside using the duct pressurization test, which requires the use of the blower door as well. One exception is the DeltaQ test, which

simultaneously measures envelope airtightness and duct leakage. Other diagnostics such as insulation inspection or window characterization can be carried out while these types of tests are underway, as long as envelope airtightness remains undisturbed during the test.

Table 1a. List of diagnostics related to building envelope metrics.

Category	Class	Metric	Diagnostic	Rating	Time, h	Cost, $
Building Envelope	Walls, Ceilings, Floors	Assembly Deficiencies	Visual inspection	Y01	0.5	N/A
			Infrared thermometer	Y02	0.5	200-1.3K
			Infrared thermography	Y03	0.5	12K - 60K
			Insulation sampling	N01		
		Assembly Conductance	ETTU	N02		
			Heat flux transducer	N03		
			Hot box	N04		
			Whole-building tests	N05		
		Material Conductivity	Guarded hot plate	N06		
			Heat flowmeter	N07		
	Windows	Glazing Emissivity	Portable spectrometer or solar transmission meter	Y04	0.5	170-250
		Low-E Coating Location	Handheld laser thickness gauge	Y05	0.5	130-700
		Interpane Gap Thickness	Handheld laser thickness gauge	Y06	0.5	130-700
	Airtightness	Air Leakage	Multi-/two-point with blower door	Y07	0.5	1.6K-3.5K
			Single-point test with blower door	N08		
			AC pressurization	N09		
			Pulse pressurization	N10		
		Leak Location	Smoke tube	Y08	0.5	30-50/tube
			Infrared thermography	Y09	1	12K - 60K
			Component masking or on-site sealing	N11		
			Anemometry	N12		
			Acoustic transmitters and sensors	N13		
			Draft sensation	N14		
	Moisture	Moisture	Visual inspection, including component dismantling	Y10	0.5	N/A
			Subsurface impedance scanning	Y11	0.5	300-6K
			Subsurface resistance probe	Y12	0.5	150-900
			Surface analysis using impermeable or absorbent materials	N15		
			Infrared thermography	N16		

Table 1b. List of diagnostics related to air distribution system metrics.

Category	Class	Metric	Diagnostic	Rating	Time, h	Cost, $
Air Distribution Systems		Duct Leakage	Duct pressurization test	Y13	0.5	1.5K-2K
			Delta-Q test	Y14	0.5	1.6K-7K
			House pressure test	N17		
			Nulling pressure test	N18		
			Pressure pan test	N19		
		Air-Handler Airflow	Fan-assisted flow meter	Y15	0.5	1.5K-2K
			Flow plate and grid	Y16	0.5	1.1K
			Sum of grille flows	N20*		
			Temperature split	N21		
			Tracer gas	N22		
			Fan curve interpolation	N23		
		Thermal Distribution System & Ventilation System Airflows	Fan-assisted flow hood	Y17	1	1.5K-2K
			Conventional flow hood	N24		
			Anemometry	N25		
			Flow grid	N26		
			Pitot-static-tube traverse	N27		
			Plastic bag test	N28		
		Delivery Efficiency and Room Distribution Effectiveness	Short-term monitoring	N29		
		Air Exchange	Tracer gas	N30		

* If a fan-assisted flow hood that can cover each grille in turn is used along with accurate measurements of duct leakage flows, this method is acceptable. Conventional flow hoods that we have tested can be accurate enough for this technique, if they are used with appropriate care on the right set of grille types and locations.

Equipment prices in Tables 1a through 1d are based on data provided by manufacturers and distributors as of April 2001. These prices may change in the future as residential commissioning activities increase. Note that the total price for a diagnostic toolkit to carry out all tests is not the sum of each cost listed. In many cases, the equipment from one diagnostic can be used for other diagnostics, often with only slight modifications. An example is the envelope airtightness test and DeltaQ duct leakage test, where both tests use the same equipment (the DeltaQ test uses a blower door and a pressure measurement device to simultaneously determine envelope airtightness and duct leakage). Another example is using the fan-assisted flow meter to determine air-handler airflow and the fan-assisted flow hood to determine duct airflows. Both devices use a fan-assisted flow meter; the latter also has a flow capture hood.

BUILDING ENVELOPE

Background

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 all based on having the envelope perform as intended. In new houses, installation failures cause immediate problems.

Table 1c. List of diagnostics related to cooling equipment metrics.

Category	Class	Metric	Diagnostic	Rating	Time, h	Cost, $
Cooling Equipment		Steady-State Capacity, Power Consumption, and Efficiency	Short-term monitoring of evaporator airflow, air-over-evaporator enthalpy change, and condenser fan and compressor power	N31		
			Coheating	N32		
		Refrigerant Charge Level	Superheat/subcooling	Y18	1	400-500
			Gravimetric test	Y19	2	1.5K-2K
			Sight glass	N33		
			TXV frosting	N34		
			Motor signature analysis	N35		
		Fault Detection	Short-term monitoring	N36		

For example, Christian et al. (1998) indicate that insulation installation deficiencies can increase whole-wall heat transfer by about 14%, which will increase energy consumption and reduce comfort. 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.

Having an appropriate window type installed correctly can be even more important. For example, Carmody et al. (2000) indicate that the solar heat gain coefficient (SHGC) for a double-glazed window can be reduced about 60% by using a low-solar-gain low-emittance (low-e) coating and a vinyl frame, compared to using clear glazing and an aluminum frame. In turn, this can reduce the peak-cooling load for a typical southern-climate house by about 25%. Glazing emittance and the location of the low-e coating (on the inside surface of the outer pane) are the most important contributors to this difference. In spite of the importance of these factors, mislabeled windows are still installed in some new California houses. A recent survey involving about 110 houses (approximately 2,800 windows) found on average that 3% of the windows are mislabeled (ConSol 2000). In two of the houses, as many as 17% of their windows were mislabeled. The mislabeling occurs during window manufacturing and is related to placing the virtually invisible low-e coating on the wrong pane (increases SHGC by about 20%) or to having clear glazing instead of low-solar-gain low-e glazing.

Moisture problems are becoming increasingly prevalent throughout the country due to changes in the way buildings are constructed. Increasing energy efficiency and changes in the markets have driven construction practices toward designs that are much more susceptible to moisture problems. Even in California, whose dry climate normally exempts it from moisture concerns, the growth of moisture-related problems is troubling for builders, consumers, and policy-makers.

Various studies have attributed poor durability, material degradation, odors, and unhealthy indoor environments to these moisture problems. Poor durability can lead to increased maintenance costs (e.g., repairing peeling paint or wallpaper, removing efflorescence). Moisture

in building components can produce a "self-composting house" in which wood rot and fastener corrosion eventually causes structural failure (Halvorsen et al. 2000). Loss of structural integrity is particularly troublesome in California, because the ability to withstand seismic loading may be impaired. While odors may only be unpleasant, they can indicate the presence of toxigenic molds. Microbiological growth adjacent to infiltration paths due to moisture within the building envelope can contaminate the indoor air and increase health problems. Snell et al. (2000) have linked asthma to mold growth supported by increased moisture levels in the indoor air and on surrounding surfaces. The American Lung Association (1999) now lists asthma as the leading serious chronic illness of children in the U.S.

Table 1d. List of diagnostics related to combustion appliance metrics.

Category	Class	Metric	Diagnostic	Rating	Time, h	Cost, $
Combustion Appliances		Backdrafting and Spillage Potential	Visual inspection of vent sizing and clearances	Y20	0.5	N/A
			House depressurization test	Y21	0.5	450-750
			Downdrafting test	Y22	0.5	N/A
			Appliance backdrafting test	Y23	0.5	N/A
			Cold-vent establishment pressure test	Y24	3	450-3.5K
			Long-term monitoring	N37		
		Combustion/Dilution Air Supply	Fan-assisted flow hood for active device	N38		
			Fan-assisted flow meter + pressure differences for active or passive device	N39		
			Duct design tools + pressure differences	N40		
			Anemometry	N41		
			Pitot-static-tube traverse	N42		
		Furnace Heat Exchanger Leakage	Heat exchanger surface and flame observation	N43		
			Tracer gas injection and detection	N44		
		Fuel- and Electricity-Related Performance	Fuel pressure measurement	N45		
			Input capacity based on meter clocking	N46		
			Output capacity based on air-handler airflow and temperature rise	N47		
			Temperature, CO_2, and O_2 analysis for combustion efficiency	N48		
			Visual inspection of flame	N49		
			Furnace AFUE short-term monitoring	N50		
			Water heater recovery efficiency	N51		
			Water heater EF short-term monitoring	N52		

Metrics

The literature that we have reviewed reports several metrics of interest for commissioning the building envelope. Insulation level and location are simple metrics to determine for opaque envelope elements under construction. The insulation level can be defined in terms of its type, thickness, and/or density. Other related qualitative metrics include the presence of anomalies such as missing insulation, insulation settling in a wall, or uneven distribution over a ceiling. These metrics are more difficult to determine in existing houses.

Table 1e. List of diagnostics related to indoor environmental quality metrics.

Category	Class	Metric	Diagnostic	Rating	Time, h	Cost, $
Indoor Environmental Quality	Thermal Comfort	Air Temperature	Aspirated shielded thermometer	N53		
			Porous media thermography	N54		
		Humidity	Wet-bulb psychrometer	N55		
			Electronic capacitance psychrometer	N56		
			Dewpoint psychrometer	N57		
		Air Velocity	Hot-wire anemometer	N58		
			Kata thermometer	N59		
			Vane anemometer	N60		
		Radiant Environment	Ellipsoid operative temperature sensor	N61		
			Globe thermometer	N62		
			Plane radiant asymmetry sensor	N63		
	Sources of Indoor Contaminants	Source Characterization	Visual inspection	N64		
			Contaminant concentration sampling	N65		
		Source Control	Visual inspection	N66		
			Contaminant concentration sampling	N67		
			Airflow and air exchange measurement	N68		

Two metrics that are more specific but that are even more difficult to actually measure in the field are the thermal conductance or resistance of opaque elements, respectively denoted by the assembly U-value (heat loss or gain per unit area and per unit temperature difference) and assembly R-value (inverse of U-value). Christian and Kosny (1995) have refined the conductance metric for wall sections using terms such as center-of-cavity (not including framing or additional elements such as doors or windows), clear-wall (including framing but no additional elements such as doors or windows), and whole-wall conductance (including framing, doors, and windows).

Windows also use the conductance metric. It is listed on window labels such as that of the National Fenestration Rating Council (NFRC). Like opaque envelope elements, it is difficult to

actually measure this metric in the field. Window radiative behavior can be described by metrics such as emittance, solar heat gain coefficient (SHGC), daylight transmittance, and UV transmittance. These radiative metrics are simpler to determine in the field.

Table 1f. Continued list of diagnostics related to indoor environmental quality metrics.

Category	Class	Metric	Diagnostic	Rating	Time, h	Cost, $
Indoor Environmental Quality (continued)	Indoor Contaminant Concentrations	Carbon Monoxide & Carbon Dioxide (CO and CO_2)	Active sampling (electrochemical cell for CO)	N69		
			Active sampling (infrared gas analyzer)	N70		
			Passive sampler	N71		
			Active sampling (grab bag and gas chromatograph)	N72		
		Nitrogen Oxides (NO_x)	Active sampling (chemiluminesence)	N73		
			Passive sampler	N74		
		Formaldehyde (HCOH)	Passive sampler	N75		
		Radon (Rn)	Active sampling (continuous radiation monitor)	N76		
			Passive sampling (alpha-track canister or electret chamber)	N77		
		Particulates and Bioaerosols	Active sampling (optical particle sampler)	N78		
			Active sampling (vacuum sample + gravimetric or microscopic)	N79		
			Passive sampling (tape extraction + count)	N80		
		VOCs	Active sampling (grab bag and gas chromatograph)	N81		

Table 1g. List of diagnostics related to control and other equipment metrics.

Category	Class	Metric	Diagnostic	Rating	Time, h	Cost, $
Controls & Other Equipment	Thermostat, Humidistat, Timers, Fan/Motor Speed, and Damper/Valve Position	Calibration, Setback/Setup, Deadband Width, and Controlled Variable Variation	Observation and monitor operation	N82		
	Plug Load	Load and Consumption	Observation and monitor operation	N83		

Subbarao et al. (1985) have attempted to combine the thermal conductance and radiative behavior of all assemblies by characterizing their impact on long-term thermal performance. They have suggested using two short-term parameters: building heat loss coefficient for conductance and equivalent clear aperture area for solar radiation. Saunders et al. (1994) defined a similar metric (building load coefficient), but included infiltration as well.

The airtightness of the building envelope elements, both at the component level and together as a system, is a general metric often described in the literature that we reviewed. In rare cases, economic factors are included with the airtightness metrics (e.g., $/$CFM_{50}$). A simple metric of interest with respect to airtightness is air barrier type and location. Terms that are more specific are airflow or air change rate at a standard pressure differential (e.g., CFM_{50}, CFM_{25}, ACH_{50}), or effective leakage area (e.g., ELA_4). In some cases, the intermediate parameters of equations used to calculate these metrics are used instead. They include terms such as the flow coefficient and pressure exponent.

Airtightness metrics are sometimes normalized by floor area and/or building height to allow comparison between buildings. An example is the specific leakage area (SLA) metric in Title 24, which is the effective leakage area normalized by conditioned floor area. Another example is the normalized leakage (NL) in ASHRAE Standard 119 (1994), which is effective leakage area normalized by conditioned floor area and by eave height relative to that of a one-story house. For energy purposes, NL is a convenient metric because it approximately represents the seasonal average air change rate due to natural infiltration alone. For an airtight one-story house, a normalized leakage of 0.1 is approximately equivalent to 2.1 ACH_{50} or an effective leakage area of 1.4 $in^2/100\ ft^2$ (SLA=1.0). An NL of 0.1 for a two-story house is approximately equivalent to 1.7 ACH_{50} or an effective leakage area of 1.2 $in^2/100\ ft^2$ (SLA=0.8). Using the same NL regardless of house height ensures that different height houses are on a level playing field in terms of energy consumption associated with infiltration. It also means that taller houses need to be more airtight. In contrast, the SLA metric allows taller houses to have more natural infiltration and use more energy compared to a one-story house.

Three fundamental metrics characterize the thermal mass of the building envelope: time constant, capacity, and availability. All are difficult to determine in the field. The time constant of the building (Sonderegger et al. 1981) represents how quickly internal temperatures within a building assembly respond to an external change in temperature or heat flux. Capacity represents the maximum amount of thermal energy that can be stored or released due to a uniform change in temperature of the building assembly. Uniform temperatures are not achieved instantaneously, which leads to thermal gradients within a building assembly. This means that only part of the assembly is thermally charged or discharged initially. Availability represents the fraction of the capacity that remains available to store or release heat at any given time.

There are several metrics for moisture damage, but the literature that we reviewed does not commonly refer to them. Simple qualitative metrics include visible wetness or degradation of interior or exterior finishes and structural components. Degradation can include staining, streaking, bacterial or fungal growth, and wood rot. More complex and quantitative terms used by researchers involved with this issue and moisture-damage susceptibility include vapor partial pressure, condensation potential, mass of condensed water, surface water activity, water intrusion rate, diffusion path length, drying potential, and moisture content. The latter metric is the one most easily quantified during a field test.

Insulation Quality Diagnostics

Visual Inspection: The literature that we reviewed described several quantitative techniques for evaluating the thermal performance of insulation systems (Wray et al. 2000). As described in Appendix C, 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 expensive equipment, 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 construction crews seal the framing and insulation from view, while it is easier to correct problems. In existing houses, it is often difficult or impossible to inspect these assemblies. Consequently, techniques that are more complex and expensive are generally required in these houses to avoid destroying the exterior or interior surfaces of the assembly. Other visual inspection steps can include checking that labels from each insulation bag are stapled in the attic. The presence of these labels helps ensure that the correct amount of insulation has been installed.

These inspections do not quantify assembly thermal resistance or conductance (R- or U-value). However, one can subsequently calculate assembly thermal performance using data from these inspections in conjunction with building plans or an assembly material audit. Well-developed commercially available software can facilitate these calculations. 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 analysis methods 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 thermography systems and scanning radiometers produce false color images of the scan on a video display for easier viewing of intensity differences. Scanning thermography 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 ($200 to $1,300). 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 provides 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 non-uniform or specular emissivities. Infrared inspection generally is not useful for quantifying assembly thermal conductance or even framing fractions (Davis Energy Group 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.

Window Diagnostics

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 ($130 to $700) 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 multi-pane glazing assembly. Simple LEDs indicate whether the glazing is clear, has high-solar-gain (low-e) coating, or has low-solar-gain (spectrally-selective low-e) coating. The spectrometer works best when used on the pane with the coating, but it cannot distinguish which pane has the coating. However, other tools that use laser reflection to measure glazing gap thickness are available for this purpose (EDTM 2000). A digital numeric display or visible laser reflections on a sliding scale indicate gap thickness and which pane has the coating. Commercially-available solar transmission meters are also available to determine window emittance class (EDTM 2000). However, they are less direct and more difficult to use than the handheld spectrometer, because they require measuring the solar irradiance with and without the glazing in the irradiance path. This can be difficult for fixed (non-opening) windows. These meters cost about $170 to $250.

Using non-contact infrared thermography 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 Diagnostics

To quantitatively evaluate the airtightness of building envelope elements, there are three diagnostic techniques. They include using a blower door, AC pressurization (Sherman and Modera 1986), or pulse pressurization (Modera et al. 1987). However, only the first technique is well developed, commercially available, and discussed here. Appendix C further describes the latter two.

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. The device determines airflow through the envelope as a function of pressure differences imposed by the blower (ASTM 1997, ASTM 1999a, CGSB 1986). Including pressure gauges, it typically costs about $1,600 to $3,500.

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, ASTM 1997). 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 (greater than two) 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 air-tightness 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 times for accurate testing. 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 41 to 95ºF (5 to 35ºC). In cold climates, this constraint severely limits times for accurate testing.

To identify envelope leak locations, several techniques are available (ASTM 1995). The most practical diagnostic is to use commercially-available smoke tubes while pressurizing or depressurizing the building using a blower door. This technique shows the location of leak entries and exits indoors or outdoors, but not the leakage paths themselves within the envelope assemblies. Smoke released near a leak is sucked into leak entries and diffused at leak exits. This technique is inexpensive and rapid, but knowledge of likely leak locations is required to minimize the search effort. Searching for leaks on the building exterior can be especially difficult or impossible due to wind effects. The acidic nature of the smoke can cause material damage or occupant irritation if used in large quantities. Smoke tubes cost about $30 to $50 per tube.

Comparisons of thermographic scan images before and after pressurizing or depressurizing the building using a blower door can highlight air leakage paths that might otherwise be confused as insulation anomalies. Sufficient time between these scans must elapse for the leaks to equilibrate to the temperature of the air passing through them. The time depends on the airflow rate through the cracks, the temperature differential, and the envelope thermal mass. Although this technique is rapid, it is expensive and subject to the limitations described in the section about using infrared thermography for inspecting opaque building envelope assemblies. Other detection methods are required as a supplement to confirm leaks located using this technique.

Envelope Moisture Diagnostics

Diagnostics to assess moisture damage are poorly developed. In particular, most diagnostics can only evaluate the presence of moisture, rather then the susceptibility to moisture damage. These diagnostics typically involve visual and electrical inspection techniques.

In some cases, researchers have used conventional or pulsed infrared thermography to carry out rapid, non-destructive, broad-area scans with the intent of locating moist areas (Marshall 1980, Knehans and Styer 1983, Vavilov et al. 1991, Grinzato et al. 1992, Bison et al. 1993, Bison et al. 1994, Wild et al. 1998, Barker 1999). However, these infrared methods still in development; require expensive cameras, high-power flashes, sophisticated analyses, and highly trained personnel; and are useful only under limited conditions. As such, infrared techniques for moisture inspection are not ready for use in residential commissioning.

There are no formal standards for assessing water damage or measuring the moisture content in building assemblies. Two inspection agencies have recently developed diagnostic protocols in an attempt to fill this void (NHCID 1998, GAHI 2000). These protocols address water damage that has occurred in southeastern US houses clad with Exterior Insulation and Finish Systems (EIFS).

The NHCID (New Hanover County Inspection Department) protocol is the most developed one available. It provides guidelines for locating and assessing moisture related damage in wood frame structures clad with drainable EIFS. It describes the use of a dielectric moisture meter for

qualitative investigation, followed by subsequent quantitative assessment of suspected wet areas with a conductance meter. It also describes locations for wall scanning and probing, including below windows, doors, flashing, penetrations, and joints. In addition, it provides a comprehensive reporting format to document measurements. This protocol contains no precision and bias specifications, but it does suggest a field method for "calibrating" a dielectric meter.

The GAHI (Georgia Association of Home Inspectors) protocol provides brief guidelines and recommendations for visually inspecting and testing houses clad with EIFS. The visual inspections focus on observing exterior water damage, as well as assessing exterior water drainage and intrusion management systems. It recommends that visual observations suggesting water entry be followed by moisture testing using a dielectric meter and then a conductance meter. It suggests conducting destructive structural investigations if moisture contents greater than 30% are measured. A related document (EIMA 2000) is largely based on the GAHI protocol. Its visual inspections focus on observing interior water damage, as well as assessing exterior water drainage and intrusion management systems. The EIMA (EIFS Industry Members Association) protocol requires only a conductance meter. It suggests conducting destructive structural investigations beginning at a lower threshold: 20%. The EIMA protocol also provides a cursory form as guidance for recording inspection data.

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, one can refer to best practices guides and lists of likely defects that may lead to future damage (Lstiburek and Carmody 1994, RDH 2000).

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. The dielectric devices cost about $300 to $6,000; the conductance devices cost about $150 to $900.

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 non-conductive 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 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. These devices are contact pressure sensitive (Margotta et al. 1984).

Penetrating conductance devices determine the moisture content of non-conductive porous building materials near their exposed surfaces. This method measures the resistance between the probes and correlates the resistance to moisture content. A disadvantage of this method is that it damages the envelope surface during probe insertion, such that surfaces often require repair after such tests, even when there are no moisture problems. 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.

Although several studies report the accuracy of these devices for use with wood products (James 1988, Warren 1994, ASTM 1998), there appear to be no published data describing their accuracy for other materials, especially when combined as building assemblies. For wood, ASTM (1998) describes conductance meter accuracy of about 7% relative error (about ± 0.5 to 2% moisture content); dielectric meter accuracy is about ± 5% moisture content. Warren (1994) notes that dielectric meters improperly weight moisture content for materials more than about 3 mm (0.125 inch) thick and are sensitive to undesirable field penetration beyond the target zone.

Simpson (1999) indicates that accuracy decreases when wood fibers are saturated (25 to 30% moisture content). Above 30%, readings are at best relative comparisons of whether the sampled material is gaining or losing moisture. These devices are susceptible to static electricity and related errors at low (less than 8%) moisture content. Conductive materials such as metal fasteners, flashing, and joints can cause falsely elevated moisture content readings.

AIR DISTRIBUTION SYSTEMS

Background

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 is due 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 ventilation. For some of these houses, this function is an integral part of the space conditioning system operation. Furthermore, the proposed ASHRAE Standard 62.2 (2002) requires 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.

Metrics

There are numerous metrics related to duct leakage and the thermal performance of residential air distribution systems, most of which have been developed over the past ten years. Metrics related directly to duct leakage include duct leakage flows (e.g., CFM_{25}, CFM_{50}), duct leakage class, and effective duct leakage area (e.g., ELA_4, ELA_{25}). These metrics can be subdivided into leakage to indoors and outdoors, as well as into return, supply, cabinet, and boot components. They can also be normalized by the airflow through the air-handler or by the conditioned floor area of the house. Other metrics include airflow through the air handler, airflow and pressure drop within a duct, power delivered to the duct system, power lost from supply ducts due to conduction and leakage, and fractional conduction loss (Walker et al. 1996).

Three metrics that are more complicated include thermal regain, delivery effectiveness, and distribution system efficiency (ASHRAE 1999). Each of these can be defined either on a design condition basis or on a seasonal basis. Thermal regain represents the fraction of heat transferred unintentionally into or out of a duct that returns to the conditioned space. Delivery effectiveness is the thermal energy transferred to or from the conditioned space divided by the thermal energy transferred at the equipment-distribution system heat exchanger. Distribution system efficiency is the energy actually consumed by the equipment connected to the distribution system divided by the energy that the equipment would consume if the distribution system was adiabatic, had no impact on equipment operation, and did not influence building loads. “Tons at the register” (Walker et al. 1998b, 1998c) is another relevant metric. It is a measure of enthalpy flow delivered intentionally at each supply grille.

Airflow and ventilation-related metrics are similarly numerous, and have been developed over a longer period (about 20 years). Many can be used at component, room, or whole-house levels. They include metrics such as duct and ventilation airflows, air exchange rates, temporal and spatial ventilation effectiveness and efficiency, and indoor-outdoor and interzonal pressure differentials. Some of these metrics can be subdivided. In particular, the temporal distribution of air within a room or entire house can be represented by metrics such as age of air, turnover time, and effective ventilation rate. Carbon dioxide (CO_2) levels indoors are sometimes used as a surrogate metric to quantify ventilation adequacy, but may be inappropriate when there are other pollutants of concern within the house. Ohnishi et al. (1998) has defined three metrics to describe whole-house ventilation performance: supply rate fulfillment, exhaust rate fulfillment, and overall ventilation rate fulfillment. An additional metric useful to discussing infiltration-based ventilation airflow potential is infiltration degree-days (IDD). Parameters used in infiltration or ventilation simulation models also represent metrics that can be used to characterize how a house will perform in terms of ventilation. Such terms include surface pressure coefficients, as well as terrain and shielding parameters, all of which are related to wind effects.

When assessing time-varying airflows and ventilation in terms of controlling indoor air quality, the quantity of interest is often the temporal average rather than the peak. Apart from duct and ventilation airflows, and indoor-outdoor and interzonal pressure differentials, perhaps the most important airflow and ventilation-related metric that can be practically determined during residential commissioning is the effective ventilation rate.

The concept of effective ventilation (Sherman and Wilson 1986, Yuill 1986, Yuill 1991) describes the proper ventilation rate averaging process. In this concept, the average (effective) rate is the steady-state one that would yield the same average contaminant concentration over the period of interest in the occupied space as does the actual sequence of time-varying discrete ventilation rates over the same period and in the same space. This effective rate is only equal to the simple arithmetic average rate when the discrete ventilation rates are constant over the period of interest and the contaminant concentration has reached its steady state value. Simple arithmetic averaging of instantaneous ventilation rates or concentrations cannot generally be used to determine these averages due to the non-linear response of indoor concentrations to the ventilation rate variations.

An important constraint in the effective ventilation concept is that the contaminant source strength F must be constant over the period of interest and must be uncorrelated with the ventilation rate. These conditions are satisfied in many residential buildings, because the emission rates of many contaminants that are controlled by whole-building ventilation vary slowly. Sherman and Wilson (1986) describe how to deal with pollutants that have step-wise constant emission rates. Pollutants such as carbon monoxide, radon, and formaldehyde, whose emission rates can be affected by ventilation, cannot use this concept and require analyses that are more complex.

For constant source strength pollutants, the relationship between effective air change rate, effective ventilation rate, volume, source strength, average concentration, and time-averaged effective turn-over time is given by*:

$$I_m = \frac{\overline{Q}}{V} = \frac{F}{V \cdot \overline{C}} = \frac{1}{\overline{\tau_e}} \qquad (1)$$

The time-averaged effective turn-over time in Equation 1 represents the characteristic time for the concentration in the occupied space to approach steady-state over the time period of interest. It can be determined from a sequence of discrete instantaneous ventilation air change rates I_i using the following (Sherman and Wilson 1986):

$$\overline{\tau_e} = \frac{1}{N}\sum_{i=1}^{N}\left(\tau_{e,i}\right) \qquad (2)$$

$$\tau_{e,i} = \frac{1 - e^{(-I_i \cdot \Delta t)}}{I_i} + \tau_{e,i-1} \cdot e^{(-I_i \cdot \Delta t)} \qquad \text{for } I_i > 0, \qquad (3)$$

$$\tau_{e,i} = \Delta t + \tau_{e,i-1} \qquad \text{for } I_i = 0 \qquad (4)$$

ASHRAE Standard 136 (ASHRAE 1993c) provides a set of factors to assist in calculating the annual effective air change rate of houses, for use in evaluating the impact of these air change rates on indoor air quality. These factors were determined using Equations 2 through 4. Metrics such as envelope airtightness (in terms of normalized leakage area as defined by ASHRAE Standard 119) and ventilation system airflows need to be determined to use Standard 136.

Several metrics represent the performance of heat recovery devices in ventilation processes. These include terms such as sensible, latent, and total energy recovery effectiveness; sensible

* Nomenclature for Equations 1 through 4 is described in the List of Symbols within the Table of Contents.

and total heat recovery efficiency; temperature ratio; ventilation reduction factor; and exhaust-air-contamination ratio. Determining these metrics requires complex tests, which are not practical during residential commissioning.

From this list of metrics, the simplest and most practical ones to determine in the course of residential commissioning are airflow through the air handler, duct pressure drop and airflow, duct leakage flows or area, and interzonal pressure differences.

Duct Leakage Diagnostics

Several quantitative diagnostics are available to uniquely determine duct leakage (Walker et al. 1998a, Walker et al. 1999, Francisco and Palmiter 2000): the duct pressurization test, the DeltaQ 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, we do not recommend it for commissioning except as a rapid screening supplement to more elaborate tests.

Researchers are in the process of improving the cost and accuracy of duct leakage testing. They are also rewriting the ASTM Standard E1554 (1994) for measuring duct leakage to include newer methods. We expect its revision will be complete in 2002. The standard (and our discussion) focuses on the existing duct pressurization test and the new DeltaQ test, 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. Appendix C describes the other duct leakage diagnostics.

Duct Pressurization Test: This test is the most common one performed on duct systems. It is analogous to airtightness testing of building envelopes in that the test measures airflows at specified pressure differences. All the supply and return grilles in a system are covered and a measured amount of air is blown into the ducts through a small fan-assisted flow meter. Resulting duct pressures indicate how leaky the ducts are. The test measures the combined size of holes in the duct system, but not the flow through them to outside at operating conditions. The test device is expensive: typical costs are about $1,500 to $2,000.

To translate from hole size to airflow, these tests require that a duct system operating pressure be assumed (often based on measured plenum and/or grille pressures). 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.

The conversion from hole size to airflow has large uncertainties for leaky duct systems, because the assumed pressure may be a poor indicator of the pressures at duct leaks, whose location is unknown. However, for verifying that ducts have little leakage, a pressurization test is useful because even large errors in estimating the pressure difference across the holes will not result in large leakage flow uncertainties. This is one reason why many utility and weatherization programs use this test as a screening tool and why codes and standards are gradually adopting it. Other reasons include:

- Robustness. The duct pressurization test has almost no restrictions on the type of system it can be used on, or the weather conditions during the test. In particular, it can be used in unfinished or finished houses. This test is 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.

- Repeatability. The combined results of several research projects (Walker et al. 1998a, 1998b) together with the field experience of other users have shown that the repeatability of duct pressurization testing is very good.
- Simplicity. It is easy to interpret the results of a duct pressurization test without having to perform many (or any – with the appropriate hardware) calculations. This allows the test crew to evaluate the ducts during the test and to immediately assess the validity of the results.
- Familiarity. Work crews that have performed envelope leakage tests are familiar with the test method for ducts, because envelope testing uses a similar apparatus and calculation methods.

There are several variations of this duct leakage test, which involve increasing time and equipment requirements (and complexity):

- Total Leakage. This is the simplest test and the most used. Both supply and return ducts are tested at the same time, so the split between supply and return leaks must be guessed. In addition, the fraction of total leakage that leaks to outside for energy losses also must be guessed.
- Leakage to outside. For these tests, the house is pressurized using another fan to the same pressure as the ducts so that any duct leakage is to outside. This test has the additional complication of requiring two fans and extra pressure measurements. In addition, it requires more time because the pressures across the ducts and the building envelope must be balanced.
- Supply/return split. To separate supply and return ducts, a physical barrier must be installed, usually inside the air handler cabinet or return plenum. The two sides of the duct system can then be tested separately to determine the supply/return split.

Because the pressurization test is usually implemented to measure the total leakage of the ducts and not just the leakage to outside, it will overestimate the leakage required for energy loss estimates. However, from a code compliance testing point of view, this error is in the right direction because it means that the true losses will be less than those indicated by the test. In other words, a system whose total leakage passes a leakage specification is guaranteed to have leakage to outside that is less than the specification.

For energy ratings of homes with leaky ducts (e.g., assessing distribution system efficiency using ASHRAE Standard 152P), the simple pressurization test can be inappropriate due to the assumptions about pressures across the duct leaks (Walker et al. 1998b, Francisco and Palmiter 1999). In these cases, other methods such as the DeltaQ test may give better results. Leaky ducts tend to produce a larger pressure signal for the DeltaQ test, which reduces its uncertainty.

One of the biggest drawbacks to the pressurization test is the requirement of covering all the grilles and attaching the flow and pressurization equipment. 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). In addition, detailed versions of the test require inserting a blockage to separate the supply and return and using a blower door to match the duct and house pressures – both of which can be time consuming. 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 any of the seals fail, the test will overestimate the duct leakage because it will include the seal leakage.

DeltaQ Test: This new 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 test gets its name from the difference in flows (the common symbol for flows being Q), hence the name DeltaQ. A unique feature of this test (compared to duct pressurization) is that it determines envelope leakage at the same time as duct leakage.

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.

A substantial advantage of the DeltaQ test is that it is cheaper than other duct leakage tests. It uses equipment (a blower door) that is widely available and that almost all people interested in duct leakage already have (e.g., weatherization program participants). This minimizes the capital cost to carry out the tests. In addition, there are no requirements for grille sealing or for separation of the supply and return systems at the air handler by a seal. Compared to the duct pressurization test, the DeltaQ test is less time-consuming (lower labor costs) and is less susceptible to leakage caused by poor sealing or seal failure during the test. However, there can be a tradeoff between increased capital costs for automating the test and the time savings resulting from the automation. Together, data acquisition systems and computers to record the data cost about $3,200 to $4,500. However, the time saving, record keeping ability, and operator error reductions resulting from automating the test outweigh the higher capital cost of this option. Without automation, pressure gauges to carry out this test cost about $450 to $750.

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 Appendix A describes, 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.

Air-Handler Airflow Diagnostics

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) and a flow plate and grid (Palmiter and Francisco 2000).

Other techniques to measure air-handler airflow include using:

- the sum of duct branch flows,

- the air temperature difference across the air-handler (Downey and Proctor 1999),
- a tracer gas (Walker et al. 1998b), or
- fan curve interpolation.

Measuring individual duct branch flows and summing them can lead to substantial errors, depending on the type of flow hood that is used. As described later in this report, 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.

Of the other techniques, the second 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). As shown in Appendix A, it is particularly problematic when used to assess airflows in systems that have inadequate refrigerant charge, because of the wide variation in air temperatures downstream of the evaporator coil.

While using a tracer gas can be very accurate, it requires expensive, delicate equipment and a well-trained technician. It is also subject to flow-nonuniformity-induced errors, which are difficult to assess in the field.

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. 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.

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. The measurement device is essentially the same as the one used in duct pressurization tests (cost is about $1,500 to $2,000).

The actual accuracy of this method is not well defined 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. However, based on field tracer gas tests (Walker et al. 1998b), we expect the accuracy of the test method is approximately ±10%. As Appendix A indicates, airflows obtained using this method in three houses also agreed very well with the measured sum of supply grille flows and supply duct leakage (within 2 to 3%). Agreement was poorer when compared to the sum of return grille flows and return duct leakage, but this may have been due to difficulties in measuring return flows. 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. In addition, when the flow plate is mounted at a filter grille, the return duct leakage needs to be added to the measured flow. The device costs about $1,100.

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 houses, differences are less than 5%. Reasons for differences are not reported, but 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 inches (75 mm) to the plate, do not adversely affect measurement accuracy.

As described in Appendix A, comparisons of field measurements that we conducted in three houses indicate a negative bias of 9 to 14% for airflows obtained using the flow plate and grid relative to fan-assisted flow meter measurements. The reason for the bias is unknown, but it is unlikely due to flow bypass because we taped the rigid plate to the air handler cabinet in each test.

Distribution System Airflow Diagnostics

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-static-tube traverse, or a flow grid. Of these, the first is consistently 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-static tube), low velocities, misaligned sampling of the air stream, fouling (flow grid), and duct leakage.

Of particular note, our laboratory and field tests indicate that conventional non-powered flow hoods are sometimes an order of magnitude less accurate than fan-assisted flow hoods: potential errors are about 20% to 30% of measured flow. As a result, these hoods can be inadequate to measure flows in residential systems. The measurement errors are likely due to recirculation regions that occur within the hood, and non-uniformity 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. It is possible to obtain reasonable results using some conventional flow hoods if the field tests are carefully done, the grilles are appropriate, and grille location does not restrict flow hood placement. Appendix A provides detailed results.

ASHRAE (1988) recommends using a pitot-static-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.

A new simple $200 device has recently become available to measure exhaust fan flows (Nelson 2001). It involves placing a gasketed box with a calibrated variable-sized orifice over the fan inlet and measuring the pressure drop across the orifice. The manufacturer reports that its accuracy is about 10% over a range of 10 to 120 cfm. However, it requires independent testing to assess its accuracy and usability.

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 feet (2 m) or more of flex duct attached to the flow hood virtually eliminates errors due to flow non-uniformities. These devices are not yet commercially available, but can be easily constructed of readily available components.

COOLING EQUIPMENT

Background

Even in new houses, cooling systems rarely perform as intended (Sherman et al. 1987). Aside from inadequate airflow across evaporator coils, refrigerant charge deficiency is 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.

Metrics

Because refrigerant has such an important impact on performance for cooling equipment that does not use a TXV for refrigerant flow control, the refrigerant mass ("charge") within the system is a metric in itself. Coil volume and refrigerant line length are related metrics, because they affect the amount of refrigerant that a system requires.

The literature refers to performance characteristics for cooling equipment in terms of capacity and efficiency. Capacity represents the ability of the cooling equipment to remove heat. Manufacturers often report it in units of tons (12,000 Btu/h) and usually referred to it in terms of the nameplate rating or the ARI rating. Sometimes, it is called the "installed" capacity. These metrics typically represent the capacity for a fixed set of indoor and outdoor operating conditions. A related metric is the required capacity that is determined using load calculations and that is used to size equipment. These capacities can represent the system as a whole or its components (e.g., evaporator, condensing unit).

Common metrics associated with the efficiency issues are the energy-efficiency ratio (EER) and the seasonal energy-efficiency ratio (SEER). EER is an instantaneous measure that represents the total cooling capacity of the cooling equipment (Btu/h) divided by the total electrical input (Watts). The electrical input includes the power supplied to the condensing unit and air-handler fan. SEER is an integrated measure that represents the total cooling capacity of the cooling

equipment (Btu/h) during its normal annual usage period divided by the total electrical input (Watt-hours) during the same period. It includes the effects of equipment cycling on capacity and power consumption. The term coefficient of performance (COP) is also a common metric that is applied to heat pumps more so than air conditioners. It is defined in the same way as the EER, but it uses common units instead and is dimensionless.

To account for equipment, installation, and operation deficiencies, Neal (1998) has proposed the use of another metric: field adjusted SEER (SEERFA). This metric represents the seasonal performance of an installed cooling system (equipment and attached ducts). System performance degradation may occur due to improper refrigerant charge, inadequate evaporator airflow, duct leakage, and equipment oversizing. Neal also describes an approximate method for quantifying SEERFA. That method uses several correction factors to adjust the "rated" SEER of the cooling equipment and extend it to encompass system performance. Neal bases the correction factors on limited data from his literature review. There has been no subsequent fieldwork to validate their use. Substantial research is required before Neal's metric and method can be broadly applied within the scope of residential commissioning. That work includes: developing a practical diagnostic that can determine absolute or fractional charge deviation; determining the variation of SEER with evaporator airflow; determining appropriate corrections to accommodate the range of airflow deviations, duct leakage, and oversizing found in the field; and determining how each of the performance degradation effects should be combined.

Of these metrics, refrigerant charge is the most practical to determine during the course of residential commissioning. Apart from simply measuring total electricity consumption over a fixed period, evaluating the other metrics in the field requires complex and time-consuming diagnostics.

Refrigerant Charge Diagnostics

Several diagnostic techniques are available to assess the amount of refrigerant charge 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 latter two tests are not standardized, but equipment manufacturers commonly specify them.

When a charging scale, refrigerant recovery unit, vacuum gauge, and vacuum pump are used (total cost of about $1,500 to $2,000), the gravimetric test can accurately determine the amount of refrigerant and non-condensable fluids in a cooling system by removing, weighing, and replacing them. However, this test 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 adequacy by determining the refrigerant 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 intent is to ensure that the refrigerant vapor 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 intent is to ensure that the refrigerant vapor is fully condensed upon leaving the condenser. Superheat tests are more important than subcooling tests, because non-TXV-controlled equipment is substantially more sensitive to typical charge deficiencies.

Consider the superheat test. 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 1 (Downey and Proctor 1999) shows such a chart, which typically relates superheat (5 to 40ºF, 3 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. Lower superheats are not listed, because they correspond to overcharging, which increases the risk of compressor flooding and associated damage.

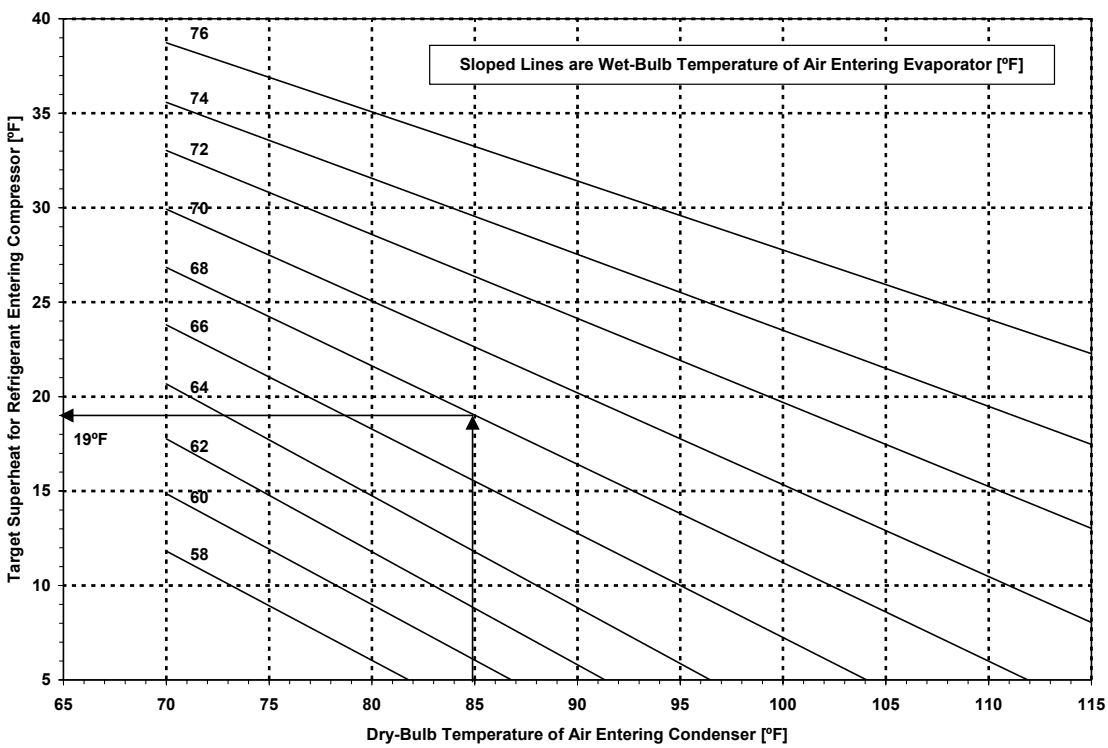

Figure 1. Refrigerant superheat charging chart.

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 test 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. To help understand this issue, consider Bakersfield, CA when the outdoor dry- and wet-bulb temperatures respectively are 104°F and 70°F (40°C and 21°C). These temperatures correspond to the 0.4% design cooling condition (ASHRAE 2001). For these conditions, the lowest return-air wet-bulb temperature for which the superheat test can be used is 66°F (19°C). If the indoor air temperature is 75°F (24°C) and the humidity ratio is the same indoors and outdoors, then the corresponding indoor (return-air) wet-bulb temperature of 61°F (16°C) is too low to use the superheat test. Testing in the spring when outdoor air dry-bulb temperatures are not too hot can circumvent this problem. Alternatively, the indoor wet-bulb temperature can be elevated artificially by overheating and humidifying the house. This latter technique requires further development to determine appropriate strategies.

The superheat test also 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.

Equipment to carry out the superheat test includes a means of measuring various temperatures and a refrigerant pressure gauge. The cost of non-automated equipment to do this is about $400 to $500.

Automated devices to carry out the superheat test, along with other fault detection diagnostics, are commercially available. However, they are expensive ($2,000 to $20,000) and require further development. Appendix A describes our laboratory and field evaluation of two such devices.

COMBUSTION APPLIANCES

Background

While poor design or installation of either the 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. Excessive depressurization of a house when exhaust devices are operating can cause some or all of these phenomena.

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 (Nagda et al. 1995). In spite of these efforts, we still lack the ability to reliably answer questions of whether backdrafting and spillage can occur, how long such events last and how frequently they occur (especially where stable backdrafting might occur), and whether the spillage gases are hazardous or toxic to occupants (Nagda 1995). However, although the frequency of spillage events might be very low, spillage directly affects the indoor environment and may pose significant health, comfort, or indoor air quality problems in some cases.

Metrics

As with cooling equipment, capacity and efficiency are common metrics for the performance of combustion appliances. The capacity metric is the nameplate output rating, but the burner "input" capacity of these appliances is also a metric. A related metric is the required capacity that is determined using load calculations and that is used to size equipment. Common metrics associated with the efficiency issues are the steady-state combustion efficiency, the annual fuel utilization efficiency (AFUE) for space heating equipment, and the Energy Factor (EF) for water heating equipment. The Energy Factor includes other water heater metrics such as standby losses, recovery efficiency, and the tank volume.

Familiar metrics for installation and operation of combustion appliances include safety issues such as clearance to combustibles, vent sizing, and outdoor airflow rates to support combustion. Performance metrics that describe the ability of an appliance to properly vent its combustion gases or conversely its potential for backdrafting and spillage of these gases into a house are less familiar. They include house depressurization or the draft (pressure differential) in the attached vent. These metrics can apply either to startup (cold flue) conditions or to steady-state operation. For the startup case, a particular metric is the cold-vent establishment pressure (CVEP), which represents the maximum indoor-outdoor pressure differential against which the hot combustion gases from the combustion appliance can establish a proper flow through the vent.

Two other important metrics involved with this issue are the concentrations of carbon monoxide (CO) and nitrogen dioxide (NO_2) in the combustion gases. If the appliance backdrafts, exposure to elevated concentrations of CO indoors can be lethal to occupants, while exposure to NO_2 can lead to chronic respiratory problems.

One other relevant metric is heat exchanger leakage, which involves the direct leakage of combustion gases into the space conditioning air flowing through the air-handling unit. This metric is more important for existing houses than for new houses. However, it may be desirable to check new equipment to detect manufacturing defects.

Combustion Appliance Diagnostics

Of the metrics listed above, the potential for appliance backdrafting and spillage is the most critical one to assess in the course of residential commissioning. Heat exchanger leakage is also an important metric to evaluate, but there is no simple and reliable diagnostic at this time. Furthermore, the norm is poorly defined and may be unreliable for defining acceptable leakage levels of combustion gas products. Apart from these metrics, visually checking clearance to combustibles, vent sizing, and combustion air intake sizes, or measuring carbon monoxide concentrations at draft hoods of unsealed appliances, evaluating the other metrics in the field requires complex and time consuming diagnostics.

Appliance Backdrafting and Spillage Diagnostics: The National Fuel Gas Code (NFPA 1999) describes a very simple test to assess appliance backdrafting and spillage. The test involves moving a lighted match or taper around the edge of the relief opening of a draft hood while the combustion appliance is operating. If the flame is drawn into the hood, it is assumed the appliance is venting correctly. If the flame is blown outward away from the hood or extinguishes, it is assumed that the appliance is backdrafting and spilling combustion gases indoors. It is important to note that this test does not require operating exhaust devices within the house. As such, the test does not specifically assess depressurization-induced backdrafting and spillage.

Several other "snapshot" style test protocols have been developed (CGSB 1995, ASTM 1999b) to indicate the potential for depressurization-induced 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.

House Depressurization Test: The house depressurization test (CGSB 1995, ASTM 1999b) involves measuring the change in indoor-outdoor pressure differentials created by operating various combinations of installed air-moving equipment (space conditioning, ventilation, fireplace, and laundry) that can depressurize the house when combustion appliances are off. Measured changes in pressure differentials due to operating the air-moving equipment are then compared with prescribed pressure limits to determine the potential for depressurization-induced backdrafting and spillage. These limits are based on field tests in several Canadian houses.

The flue or chimney must be allowed to cool to within 5 to 10ºF (3 to 6ºC) of the room air temperature after the combustion appliances are turned off and before the test begins. A blower door can be used to accelerate the cooling. Another prerequisite for the test is that the flue or chimney be checked for blockage. Qualitative diagnostics such as visual inspection (Oberholtzer 1993) and using a smoke tube, cigarette smoke, or match or lighter flame to identify the presence of a draft in the flue or chimney can be used. However, no diagnostics are currently used to quantify the restriction of a venting system. Duct leakage test diagnostics could be applied, but accessing the upper end of a flue or chimney to seal it temporarily can be difficult, potentially hazardous, and time consuming.

A disadvantage of this test is that the prescribed limits may not accurately represent the potential for backdrafting and spillage of the specific appliances in the house being tested.

Pressure gauges to carry out this test cost about $450 to $750.

Downdrafting Test: The downdrafting test (ASTM 1999b) involves conditions similar to the house depressurization test. However, there is no pressure measurement, so manometers are not required. Instead, only a simple observation (yes/no) is recorded of whether the flue or chimney had a downdraft at the time of the test. A smoke tube, cigarette smoke, match flame, or lighter flame is used to identify the occurrence of depressurization-induced downdrafting.

An advantage of this test is that it requires the least time and equipment. However, a disadvantage is that it does not represent the potential for an appliance to reverse a downdraft. For example, a weak downdraft that might be reversible is considered as much a failure as a strong irreversible downdraft.

Appliance Backdrafting Test: The appliance backdrafting test (ASTM 1999b) involves conditions similar to the house depressurization test. However, there is no pressure measurement,

so manometers are not required. Instead, it determines how long a combustion appliance takes to establish a draft after its burner is fired. A smoke tube, cigarette smoke, match flame, or lighter flame is used to identify the establishment of a draft in the flue or chimney. The time to establish a draft is then compared to a prescribed time limit (5 minutes) to determine whether any depressurization-induced backdrafting that occurs is acceptable.

A disadvantage of this test is that the prescribed time limits may not accurately represent the acceptability for backdrafting of the specific appliances in the house being tested.

CO in the combustion gas or indoor air must be monitored during this test to assess whether hazardous conditions exist. The test must be terminated if such conditions occur.

CVEP Test: The cold vent establishment pressure (CVEP) test (Koontz and Nagda 1996, Grimsrud et al. 1996, ASTM 1999b) involves similar conditions to the house depressurization test. This test also identifies the pressure limit at which each appliance establishes a draft in an initially cold flue or chimney while operating, with the house air-moving systems and other combustion appliances off. A blower door is used to vary the depressurization of the house from 15 Pa or 25 Pa (whichever will induce actual backdrafting) toward zero until a draft is established. This element of the test is repeated for each combustion appliance, with the flue or chimney being allowed to cool to near the outdoor air temperature between each pressure limit subtest. A blower door can be used to accelerate the cooling. A smoke tube, cigarette smoke, match flame, or lighter flame is used to identify the stagnation or establishment of a draft in the flue or chimney and the cessation of any backdrafting.

Like the house depressurization test, this test measures the change in indoor-outdoor pressure differentials created by operating various combinations of installed air-moving equipment (space conditioning, ventilation, fireplace, and laundry) that can depressurize the house when combustion appliances are off. These measured changes in pressure differentials due to operating the air-moving equipment are then compared with the measured CVEP limits to determine the potential for depressurization-induced backdrafting and spillage.

Grimsrud et al. 1996 indicate that two trained technicians can carry out the tests in one house over a period of 4 to 6 hours. A computerized data acquisition system that monitors the necessary pressure difference and that adjusts the blower door fan speed to maintain each desired envelope pressure difference can be used to facilitate the CVEP test, especially when determining the CVEP limits. A temperature sensor appropriately located could be used as a backdrafting indicator when a data acquisition system is used. As with the DeltaQ duct leakage test, there can be a tradeoff between increased capital costs for automating the test and the time savings resulting from the automation. Together, data acquisition systems and computers to record the data cost about $3,200 to $4,500. However, the time saving, record keeping ability, and operator error reductions resulting from automating the test outweigh the higher capital cost of this option. Without automation, pressure gauges to carry out this test cost about $450 to $750.

This test has the advantage that it does not use prescribed limits like the house depressurization test or appliance backdrafting test. Consequently, its results might more accurately represent the potential for depressurization-induced backdrafting and spillage of the specific appliances in the house being tested (Koontz and Nagda 1996).

As in the appliance backdrafting test, CO in the combustion gas or indoor air must be monitored during this test to assess whether hazardous conditions exist. The test must be terminated if such conditions occur.

Test Limitations: Due to the short-time span of all 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, even weeklong monitoring as suggested by Grimsrud and Hadlich (1995) is probably impractical during commissioning to achieve this end.

Table 2 shows a comparison of results from carrying out several of these tests in six houses (Nagda and Koontz 2000). Columns 2 through 4 show results based on detailed continuous monitoring of vent performance, where the failure criteria is having a positive pressure in the vent relative to the room containing the appliance (causes flow from the vent to the room). The house fails if either the furnace or domestic hot water (DHW) heater fail. These data constitute the "truth standard" in this comparison. Columns 5 through 7 show results obtained using the ASTM appliance backdraft test. Columns 8 through 10 compare the ASTM test results to those obtained from long-term monitoring. Column 11 shows results obtained using the CGSB house depressurization test. Column 12 compares the CGSB test results to those obtained from long-term monitoring. The check marks in columns 8 through 10 and in column 12 indicate that the ASTM or CGSB test (as listed) obtained the same result as continuous monitoring.

Table 2. Comparison of backdrafting and spillage potential test results.

	Continuous Monitoring (Positive Vent dP wrt Room)			ASTM Worst-Case Backdraft Test			ASTM Matches Continuous Monitoring?			CGSB Downdraft Test	CGSB Matches?
House	Furnace	DHW	House	Furnace	DHW	House	Furnace	DHW	House	House	House
1	Fail	Pass	Fail	Pass	Fail	Fail	False Pass	False Fail	✓	Pass	False Pass
2	Fail	Pass	Fail	Pass	Pass	Pass	False Pass	✓	False Pass	Fail	✓
3	Fail	Fail	Fail	Pass	Fail	Fail	False Pass	✓	✓	Pass	False Pass
4	Pass	Fail	Fail	Pass	Fail	Fail	✓	✓	✓	Fail	✓
5	Fail	Fail	Fail	Pass	Fail	Fail	False Pass	✓	✓	Fail	✓
6	-	Fail	Fail	-	Fail	Fail	-	✓	✓	Pass	False Pass

All these tests are problematic because they can easily result in false positive or negative test results. Wind effects, especially gusts, may be a significant cause of these problems. Further research is needed to assess the accuracy and repeatability of these tests. 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 the building industry can use them more extensively and reliably. In particular, the following nine 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. Further research is needed to assess the impact of wind effects, as well as envelope and duct leakage, on the accuracy and repeatability of duct leakage tests, including the new DeltaQ test.
4. Formal standards are needed for the calibration and use of airflow diagnostic tools, such as flow hoods with and without fan assist, fan-assisted flow meters to measure air-handler airflow, 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. Research is needed to examine the utility of temporarily elevating indoor enthalpy, in order to extend the periods when the superheat method can be used to test cooling equipment in hot, dry climates.
8. Further research is needed to assess the accuracy and repeatability of methods that determine the potential for backdrafting and combustion gas spillage.
9. A simple and reliable test for furnace heat exchanger leakage still needs to be developed. The norm for the current tracer gas test is poorly defined and may be unreliable for defining acceptable leakage levels of combustion gas products.

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APPENDIX A: LABORATORY AND FIELD STUDY RESULTS

This appendix describes several recent laboratory and field studies that LBNL staff and others have carried out at more than 100 houses. The purpose of these evaluations is to determine the accuracy and usability of existing diagnostics that we expect to include in the commissioning guide we are preparing. Because these studies precede writing the guide, they do not necessarily use the expedited commissioning techniques that we will describe in the guide.

Our efforts concentrated on evaluating diagnostics in the following four areas:

- Duct leakage (DeltaQ) tests
- Air-handler airflow tests
- Distribution system (supply and return grille) airflow tests
- Refrigerant charge tests

The majority of our effort in this project focused on detailed measurements in four California houses, over the course of one day in each house. To the extent possible, we chose specific houses to maximize the range of system types and commissioning issues studied. However, not every diagnostic was tested at each site. These studies in general were not intended to provide statistically representative samples, so it was not necessary to test houses representative of every climate zone throughout California. To the extent that it was possible to cooperate with other field projects, we augmented the number of houses in our evaluation discussions. We also used data from available literature to supplement these discussions.

The length of time we spent in each house does not represent how long it might take to commission a house, because actual commissioning may not address every facet of performance in each house. Furthermore, the time that we spent in each house was more research oriented and focused on collecting sufficient data that would enable us to evaluate specific diagnostics that might be useful in commissioning.

EVALUATION OF THE DELTAQ DUCT LEAKAGE TEST

Much of our focus in evaluating duct leakage tests was on the DeltaQ test, because it is new. In cooperation with other projects that involve developing the DeltaQ test, LBNL and Brookhaven National Laboratory (BNL) have carried out repeatability tests to estimate uncertainties in this test method. In addition, several research teams have carried out the DeltaQ test in more than 100 houses to show that it is usable in a wide range of houses and to identify limits or problems in field applications. Many of these field tests also involved duct leakage tests using other methods. The following summarizes the results of these efforts.

Repeatability Testing

To evaluate the repeatability of the DeltaQ test method, we carried out multiple DeltaQ tests of a building at LBNL (Wempen 2000). The test building is located in a coastal hillside canyon at LBNL in Berkeley, California. Canyon walls, trees, and nearby similarly-sized buildings significantly shelter the test building from direct exposure to coastal winds. The test building has a 24 ft (7.3 m) by 50 ft (15.2 m) floor plan, with the long axis aligned with the prevailing winds. Interior floor to ceiling height was 8 ft (2.4 m). There are no interior walls or partitions. Fan-assisted flow hood and tracer gas measurements indicated the air-handler airflow in this building is approximately 1,000 cfm. We tested the same envelope, air-handler, and duct system configuration 20 times over several days in mild weather with wind speeds up to 5 mph (8 km/h).

Table A1 summarizes the repeatability test results in terms of the average leakage, the standard deviation, and the 95% confidence interval (C.I.). The repeatability errors (95% C.I.) listed in Table A1 are quite small in absolute terms, but are large compared to the small average leakage flows. However, we need to consider these errors in proper perspective. In terms of the uncertainty in calculating energy losses from the duct system and in terms of testing if a system meets low leakage specifications, the uncertainty as a fraction of air-handler airflow is the most important factor. Compared to this flow, the duct leakage and uncertainty in leakage are small. In this case, the 95% confidence intervals for supply and return leakage are in the range of 0.5 to 1.0% of the fan flow. This is an excellent result. In the future, we expect to repeat these tests with greater supply and return leakage (and changed trailer envelope leakage).

Table A1. Results of LBNL DeltaQ repeatability tests.

Absolute Leakage, cfm					
Average		Standard Deviation		95% Confidence Interval	
Supply	Return	Supply	Return	Supply	Return
19	66	11	16	5	7
Fractional Leakage, % of 1,000 cfm Air-Handler Airflow					
Average		Standard Deviation		95% Confidence Interval	
Supply	Return	Supply	Return	Supply	Return
1.9	6.6	1.1	1.6	0.5	0.7

We expect that fluctuations in envelope pressure difference during the DeltaQ test (mostly due to fluctuating wind speed and direction) could lead to increased test result variations. However, our

repeatability results (shown in Figure A1) indicate that the test result variability does not increase very much with the measured envelope pressure difference variability, which is represented by the standard deviation of the envelope pressure differences that we measured with the air handler and blower door off. This is a good result, because we want the test to be relatively insensitive to these pressure fluctuations and to be repeatable over a wide range of weather conditions.

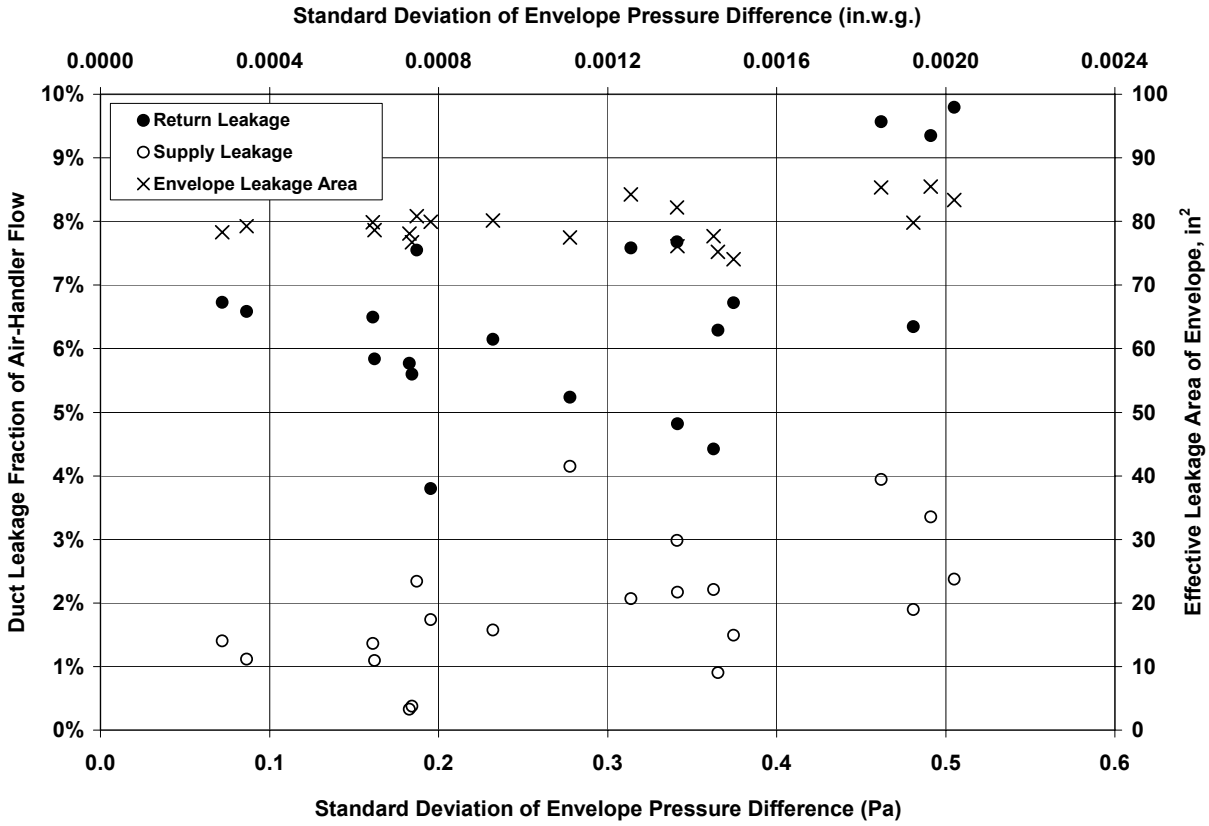

Figure A1. LBNL DeltaQ repeatability test results.

John Andrews (2000) of BNL has performed the DeltaQ test three times each in two Long Island, NY houses. For each house, Table A2 shows the average leakage and the average absolute difference from the mean for the three tests. The average differences are similar in magnitude to the LBNL tests described above, but are proportionally less as a fraction of the duct system leakage because the duct leakage was much higher in the BNL systems.

Table A2. Results of BNL DeltaQ repeatability tests.

House	Supply Leakage, cfm		Return Leakage, cfm	
	Average	Average Difference from the Mean	Average	Average Difference from the Mean
1	214	8	46	14
2	72	19	286	9

Field Experience

Initial Pilot Test: We performed the pilot test of the DeltaQ procedure in a Berkeley, California house with well-known system characteristics, where we have already made several other duct leakage measurements. For this first house, we performed the measurements manually, without computer control or data acquisition. Table A3 summarizes the test results.

Table A3. Comparison of duct leakage obtained using various test methods.

Case	Duct Leakage, cfm				
	DeltaQ	NPT	Tracer Gas	Duct Pressurization[1]	Duct Pressurization[2]
Supply	5	17	n/a	30	51
Return	181	151	160	95	116

[1]Determined using operating pressures based on *plenum pressure* measurements.

[2]Determined using operating pressures based on *pressure pan* measurements.

The agreement between the DeltaQ test, nulling pressure test (NPT), and tracer gas results indicates that the duct pressurization test is overestimating the supply leakage and underestimating the return leakage. Most of the difference is due to uncertainty in the duct pressurization test when estimating the pressures across the duct leaks.

Initial Field Evaluations: In an effort to determine the practical limits of using the DeltaQ test, several researchers from LBNL, BNL, and Davis Energy Group (DEG) have applied this test procedure to 17 other houses. In most cases, they also performed duct pressurization tests and air-handler airflow tests. BNL staff performed the DeltaQ tests manually (Andrews 2000). LBNL and DEG staff performed the DeltaQ tests using LBNL-developed automation software. Table A4 lists the air-handler airflow and DeltaQ test results for the 17 houses.

The 17 test houses cover a wide age range from new to old (zero to 100 years), a large range of sizes (up to about 3,700 ft^2), and a large range of duct system sizes (as shown by the range of air-handler airflows). The duct system materials include sheet metal, duct board, and flexible plastic. The majority of the ducts in the California and Nevada houses are located in the attic, with some systems having ducts in crawlspaces. The New York houses have the majority of their ducts located in unheated and uninsulated basements. The last four houses listed in Table A4 are the ones that we monitored in detail to evaluate various diagnostics.

Figure A2 illustrates DeltaQ and duct pressurization test results for the pilot test and for 12 of the 17 houses. It includes an equality line representing perfect agreement between tests. Comparing aggregate results, the average total leakage (supply plus return) fraction of air-handler airflow was slightly higher for the duct pressurization test (21%) than for the DeltaQ test (19%). Comparing individual tests, the average absolute difference of 7% of air-handler airflow was considerably larger.

CSUC/LBNL Field Tests: Experienced HVAC technicians and undergraduate engineering students in conjunction with California State University Chico and LBNL have recently completed field tests of over 100 more California houses, with the goal in part to assess duct leakage in systems that are between 5 and 20 years old. The field tests involve using the DeltaQ

and duct pressurization tests, and measuring air-handler airflows. The DeltaQ tests used a computer-based data acquisition and control program developed by LBNL.

Table A4. Initial field evaluations - DeltaQ test results.

House Location	Air-Handler Airflow (cfm)	Duct Leakage (cfm)		Leakage Fraction of Air-Handler Airflow	
		Supply	Return	Supply	Return
Long Island, NY	679	214	46	32%	7%
Long Island, NY	912	72	286	8%	31%
Las Vegas, NV	1,551	81	14	5%	1%
Las Vegas, NV	1,900	18	23	1%	1%
Las Vegas, NV	2,114	3	11	0%	1%
Alameda, CA	1,265	48	64	4%	5%
Folsom, CA	1,200	52	46	4%	4%
Pleasanton, CA	1,600	61	47	4%	3%
San Francisco, CA	515	58	106	11%	21%
Tracy, CA	1,782	109	61	6%	3%
Tracy, CA	1,525	70	64	5%	4%
Tracy, CA	2,494	102	53	4%	2%
Walnut Creek, CA	879	136	58	15%	7%
Larkspur, CA (Site 1)	1,216	123	205	10%	17%
Sacramento, CA (Site 2)	1,257	10	48	1%	4%
Sacramento, CA (Site 3)	1,345	19	49	1%	4%
Concord, CA (Site 4)	804	96	265	12%	33%

Our initial analyses also show that the DeltaQ test is fairly rugged. In windy conditions, indoor-outdoor pressure differences can vary widely during the test. However, these large variations do not lead to large variations in the test results. This is an important factor, because previous work by Walker et al. (1998a) showed that other test methods that use the pressures measured across the building envelope have high sensitivity to wind and envelope conditions.

The DeltaQ test does not have these sensitivities because it uses multiple pressure readings over a wide range, so that an individual poor measurement does not corrupt the entire test. Also, many of the test pressures are significantly higher than those imposed on the building by the weather, which reduces the sensitivity to weather effects. Figure A3 shows the results of a sample DeltaQ test. In Figure A3, Qs represents supply leakage, and Qr represents return leakage. LSQ refers to the least squares equation fit applied to the difference in flows (DeltaQ's) when calculating duct

leakage. To better illustrate the variation in DeltaQ flows, Figure A3 shows them multiplied by a factor of 10.

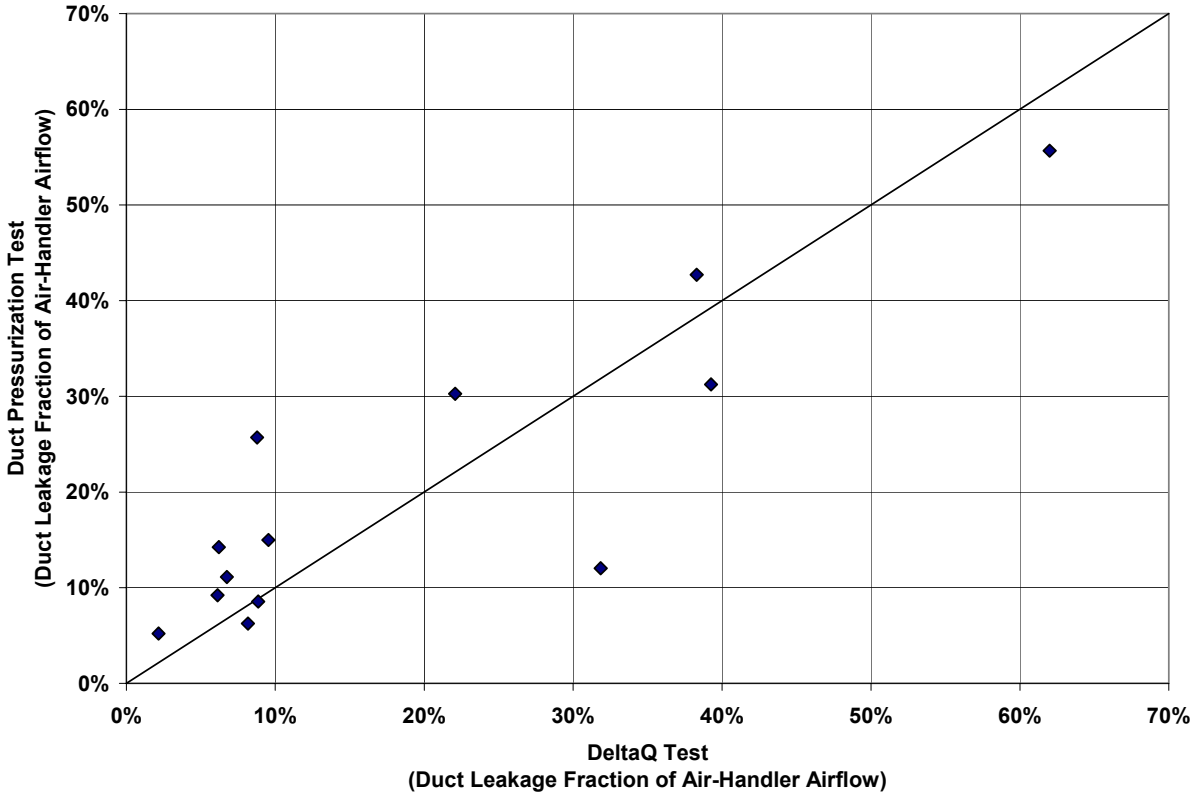

Figure A2. Comparison of duct pressurization and DeltaQ test results for total (supply plus return) duct leakage.

We have carried out related work to assess the potential for errors caused by uncertainty in the duct reference pressure that the DeltaQ test uses to calculate duct leakage. We found that even fairly large changes in duct reference pressure did not change the final duct leakage result a great deal. Even when this pressure is changed by a factor of two, the supply and return leakage only changes by about 10 to 15%.

When the duct leakage is small, the DeltaQ test can sometimes yield negative numbers for supply or return leakage. Two factors contribute to this behavior. One is that the precision of the test is limited to about 10 to 20 cfm. The other is that, at these low leakage levels, the results become more sensitive to "outliers" in the measured data. Generally, when negative numbers result from the test, this shows that the duct system is not leaky and the test result should be interpreted to mean that the leakage is less than the precision of the test procedure (i.e., less than 10 to 20 cfm). This implies that the leakage flows typically will be less than about 1% of fan flow and therefore are not significant in terms of energy losses or poor distribution. Also, any system with this little leakage will pass any of the existing (and probably future) leakage limits found in energy codes. For example, the CEC “Low-Rise Residential Alternative Calculation Method Approval Manual” (1998) specifies a 6% of fan flow limit for duct leakage. Voluntary programs such as EPA Energy Star ducts have a 10% of fan flow limit. Therefore, these precision errors are not a significant barrier to the use of the DeltaQ test.

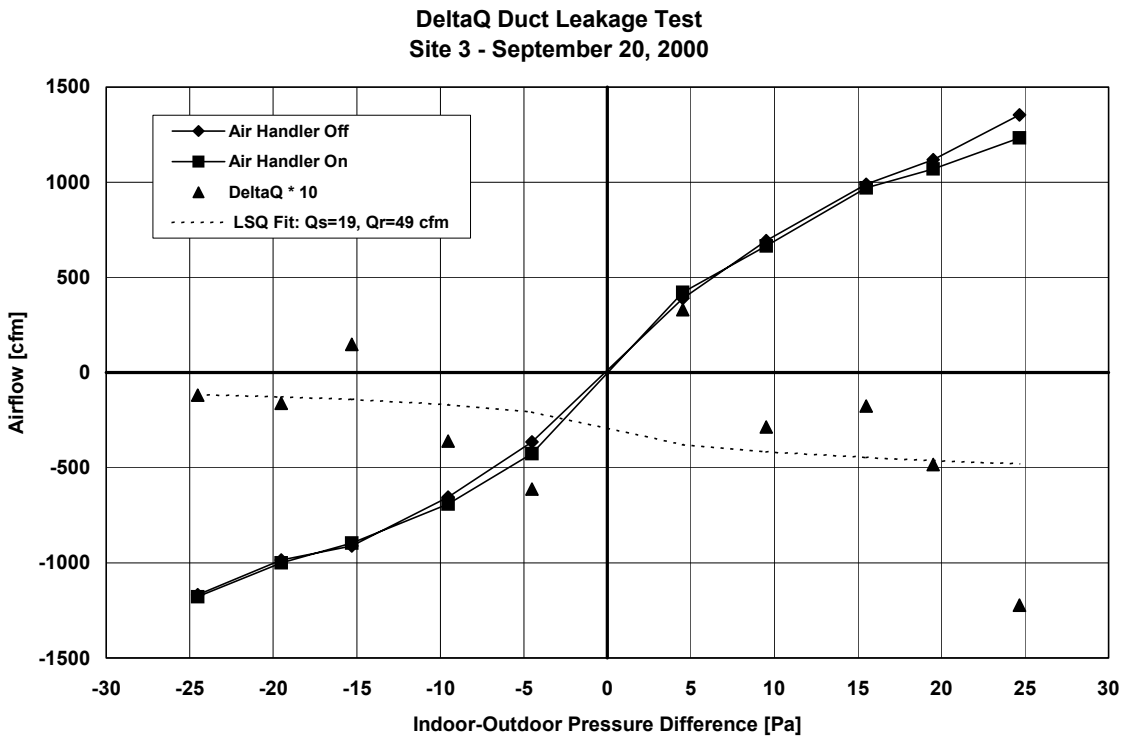

Figure A3. Sample DeltaQ test results.

Summary

Our initial analyses of duct leakage tests at over 100 houses and at our laboratory show that the DeltaQ test procedure is fairly rugged, unlike other test methods that use pressures measured across the building envelope. In windy conditions, indoor-outdoor pressure differences can vary widely during the test. However, these large variations do not lead to large variations in the test results. The test is also relatively insensitive to large changes in duct reference pressure. This is in contrast to the large leakage flow uncertainty in the duct pressurization test associated with estimating the pressures across the duct leaks.

Precision of the DeltaQ test is limited to about 10 to 20 cfm. Leakage flows less than this typically will be less than about 1% of fan flow and therefore are not significant in terms of energy losses or poor distribution.

EVALUATION OF AIR-HANDLER AIRFLOW TESTS

ACCA Manual S (1995b) describes a design procedure for estimating the air-handler airflow required for a residential cooling system at design conditions. It depends on the evaporator sensible load and on the dry-bulb air temperature drop across the evaporator. For air entering the evaporator with a dry-bulb air temperature of 75ºF and a 50% relative humidity, the procedure attempts to achieve a dry-bulb temperature of 54 to 58ºF for the air leaving the evaporator. For sensible heat ratios (SHR) in the range of 0.80 to 0.85, the resulting flows are in the range of 415 to 545 cfm/ton of total evaporator capacity (sum of sensible and latent capacities). The lower airflows correspond to lower SHRs (higher latent loads) and result in a colder evaporator and leaving air temperature. These conditions are intended to minimize fan power and achieve adequate humidity control while avoiding evaporator icing.

Manufacturers typically recommend a lower airflow range: 350 to 450 cfm per nominal ton of evaporator total capacity. The lower airflow is more appropriate for use in humid climates. Using the dry-bulb temperatures described above for air entering and leaving the evaporator (with 54ºF as a minimum), an airflow of 350 cfm/ton corresponds to an SHR of 0.67. The airflow target introduced in the AB970 2001 revisions to Title 24 is in the lower half of the manufacturer range: 385 cfm/ton (Wilcox et al. 2001).

Often, installed equipment does not meet any of the targets described above. For example, Blasnik et al. (1996) tested 28 systems and found that more than 50% had flows below 350 cfm/ton. The average system had 86% of the manufacturer's recommended airflow (standard deviation of 16%). The worst system had as little as 57% of the manufacturer's recommended airflow. Seven systems had flows that were at or above the manufacturers recommended flow. A common reason for low airflow was an undersized, restrictive flex duct system.

Manufacturers recommend corrective action when airflows are below 350 cfm/ton, because airflows this low can cause evaporator icing. Ice on the evaporator insulates it and increases system flow resistance, which reduces air-handler airflow. The resulting reduction in heat transfer from the air to the refrigerant can cause liquid refrigerant to enter the compressor and damage it.

Too low an airflow also reduces total and sensible capacity, and reduces efficiency. However, latent capacity increases as airflow decreases (ACCA 1995b). This occurs because sensible capacity decreases faster than total capacity. Rodriguez (1995) tested the effect of reduced airflow on two 3.5-ton heat pumps. One heat pump had a reciprocating compressor and a short-tube-orifice expansion device; the other had a scroll compressor and a TXV. Figure A4 shows the impact of reduced airflow on equipment performance in terms of total capacity and energy efficiency ratio (EER). For the short-tube-orifice-controlled heat pump, these data indicate that at a 14% reduction in flow (e.g., to 344 cfm/ton from 400 cfm/ton), total capacity is reduced 7% and EER is reduced 6%. For the TXV-controlled heat pump, the reductions in capacity and EER are less (only about 2% at the same airflow reduction).

Several diagnostic tools and techniques are available to measure air-handler airflow. Two of the most promising tools include a fan-assisted flow meter (Walker et al. 1999), and a flow plate and grid (Palmiter and Francisco 2000). Both are commercially available. The following describes our field studies to evaluate these two methods, along with three other methods that one might consider.

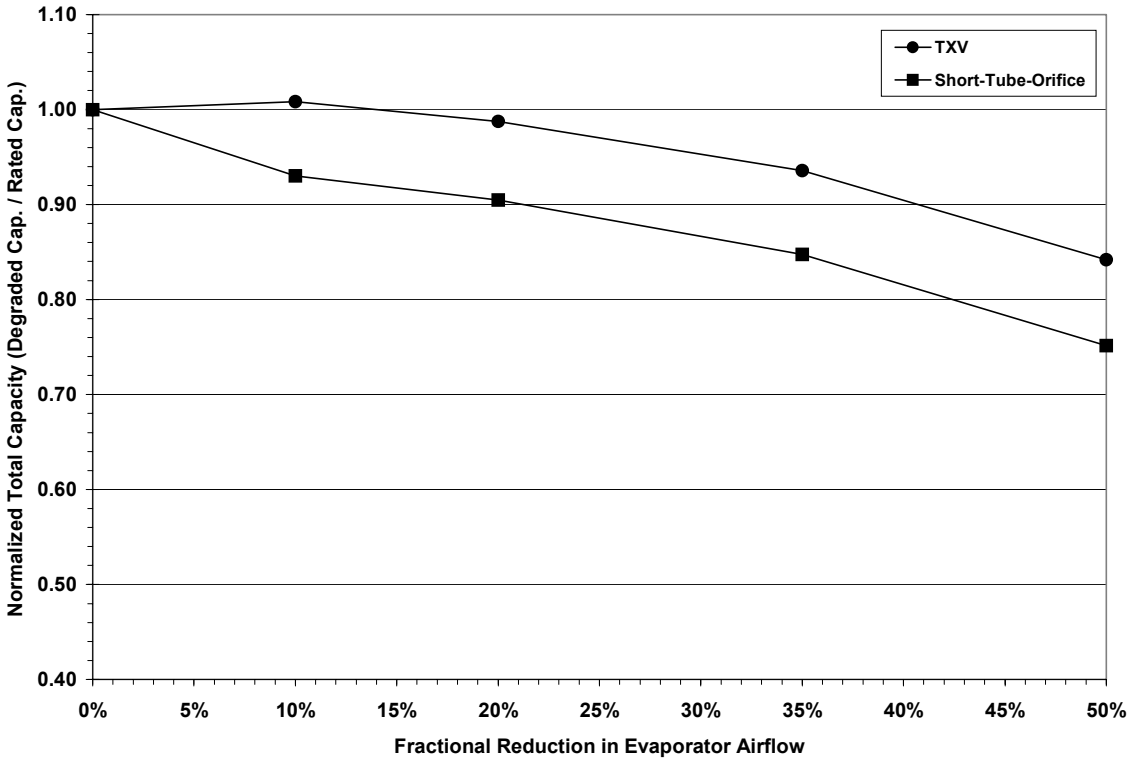

Figure A4a. Effects of reduced airflow on heat pump capacity (Rodriguez et al. 1995).

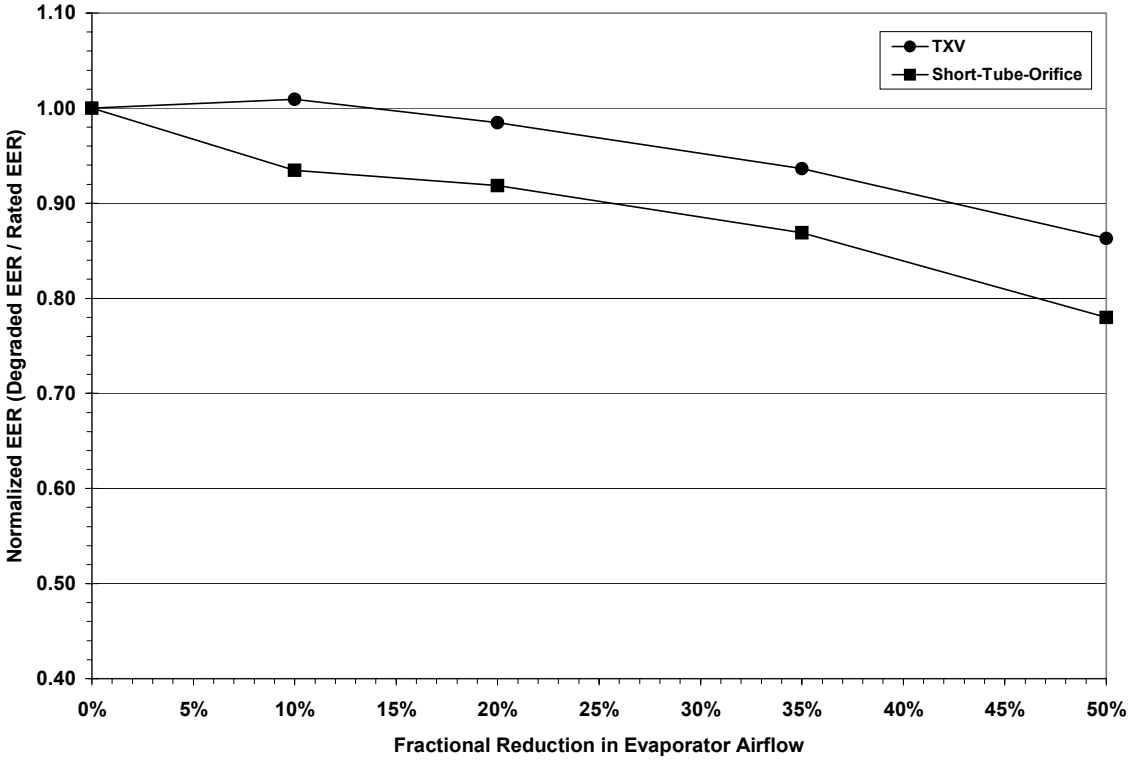

Figure A4b. Effects of reduced airflow on heat pump EER (Rodriguez et al. 1995).

Methods Evaluated

Fan-Assisted Flow Meter: This device uses a calibrated flow meter combined with a fan to determine air-handler airflow. It is essentially the same device as the one used in duct pressurization tests. There are two possible test configurations: attached to the air-handler cabinet at its access door, or attached at a return grille if the return ducting is well sealed. If the return duct is leaky, then its leakage needs to be added to the measured flow. Attaching the device is time-consuming. If the device is connected to the air-handler cabinet, additional time is required to seal off the return upstream of the air handler.

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.

For our evaluations, we attached the fan-assisted flow meter to the air-handler cabinet, to avoid having to include the duct leakage in our measurement.

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. During a test, it 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 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.

Other Techniques: In addition to the two methods described above, we evaluated three other methods:

- the sum of duct branch flows,
- the dry-bulb temperature drop of air entering and leaving the evaporator in cooling mode or temperature rise of air entering and leaving the furnace heat exchanger in heating mode (Downey and Proctor 1999), and
- a tracer gas (Walker et al. 1998b).

Measuring individual duct branch flows and summing them can lead to substantial errors, depending on the type of flow hood that is used. As described elsewhere in this report, 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. The uncertainty in the larger duct flows will govern the uncertainty in the total flow. If an accurate flow hood (such as a fan-assisted one) is used, and there is an accurate estimate of duct leakage, then this method can be an acceptable means of measuring air-handler airflow.

Of the other two techniques, the second is prone to heating mode 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). However, because of its simplicity, this technique has been introduced as a test method in Title 24 (Wilcox et al. 2001). The test does not actually determine the airflow rate. Instead, it is intended to indicate whether the airflow is adequate

(using a target based on 385 cfm/ton). It specifies a target temperature difference as a function of the dry-bulb and wet-bulb temperatures of the air entering the evaporator. Airflow is considered adequate if the measured temperature difference is within 3ºF of the target. If it is above the target upper bound, then the airflow is too low. If it is below the target lower bound, then the evaporator capacity is too low (or less likely, the airflow is too high).

While using a tracer gas can be very accurate, it requires expensive, delicate equipment and a well-trained technician. It is also subject to flow-nonuniformity-induced mixing errors, which are difficult to assess in the field.

We considered one other method but excluded it from our field evaluation: fan curve interpolation. This method 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.

Field Study One

Our evaluations of techniques to measure air-handler airflow began a few years ago with a field study in five new houses located in California and one new house in Texas (Walker et al. 1998b). All the houses except one have split-system central air conditioners and are heated by natural gas. The Texas house has a heat pump with electric strip heat.

In our tests, we used one or more of three different techniques in each house:

- directly measuring the air-handler airflow using a tracer gas,
- directly measuring the air-handler airflow using a fan-assisted flow meter attached to the air handler cabinet, and
- indirectly determining the air-handler airflow as the sum of supply duct flows (measured using a fan-assisted flow hood) and supply duct total leakage (estimated using duct pressurization techniques).

Not all tests were carried out in every house. The tests that were carried out in a house were done at least twice. The various cases included flows "as found"; flows with different duct leakage; and, in one case, flows with different cooling equipment. In all, this resulted in 14 sets of measurements. Figure A5 shows the results of our tests. The notation for the cases in Figure A5 is house number and then case number.

There was generally good agreement between the three test methods. Using the tracer gas test results as a benchmark, the fan-assisted flow meter results on average were within 11% (200 cfm); the sum of supplies plus duct leakage on average were within 10% (150 cfm).

In our flow hood evaluations, we found that a fan-assisted flow meter coupled to a flow hood is an accurate device for measuring supply and return airflows (relative absolute error of 2%). Clearly, this accuracy does not necessarily represent that of the fan-assisted flow meter applied to measuring air-handler airflow. The latter accuracy is not well defined 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.

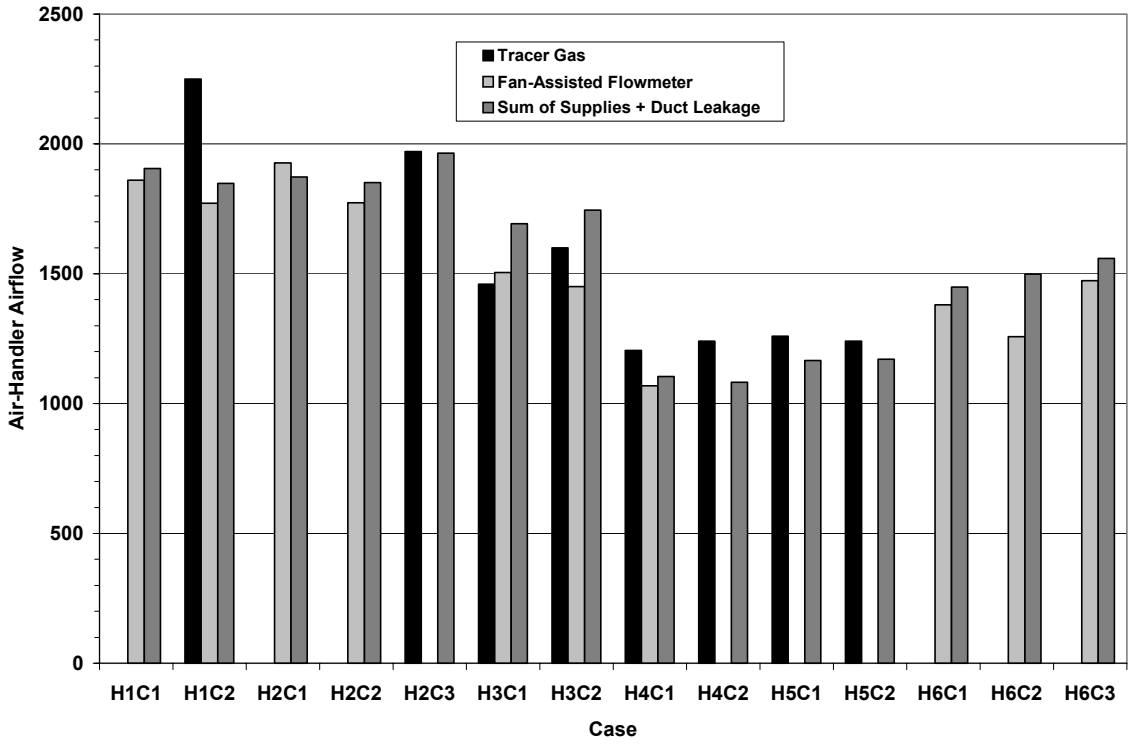

Figure A5. Comparison of air-handler airflow measurements for six houses.

Field Study Two

In September 2000, we carried out another field study to compare methods of measuring air-handler airflow. This study focused on two methods: the flow plate and grid, which is new, and the prototype non-powered Hood 8, which is part of an automated diagnostics package that includes Method 2 from our evaluation of refrigerant charge assessment tools.

Our evaluations in this field study included four California houses: two new ones and two older ones. All the houses have split-system central air conditioners and are heated by natural gas.

In these tests, we used two different techniques in each house:

- directly measuring the air-handler airflow using a fan-assisted flow meter attached to the air handler cabinet, and
- indirectly determining the air-handler airflow as the sum of supply duct flows (measured using our fan-assisted Hood 10 and the prototype non-powered Hood 8) and supply duct leakage to outside (measured using the DeltaQ test).

Results: Figure A6 shows the results of our tests. The duct leakages shown in Figure A6 are from DeltaQ test measurements of leakage to outdoors. Due to time limitations, we did not use the duct pressurization test to measure total leakage. However, in the two older houses (Houses 1 and 4), the ducts were located in a well-vented crawlspace and garage respectively. The ducts of the other two houses were located in well-vented attics. Consequently, we believe that the duct leakage measured by the DeltaQ test in each of these houses is a good approximation of total duct leakage.

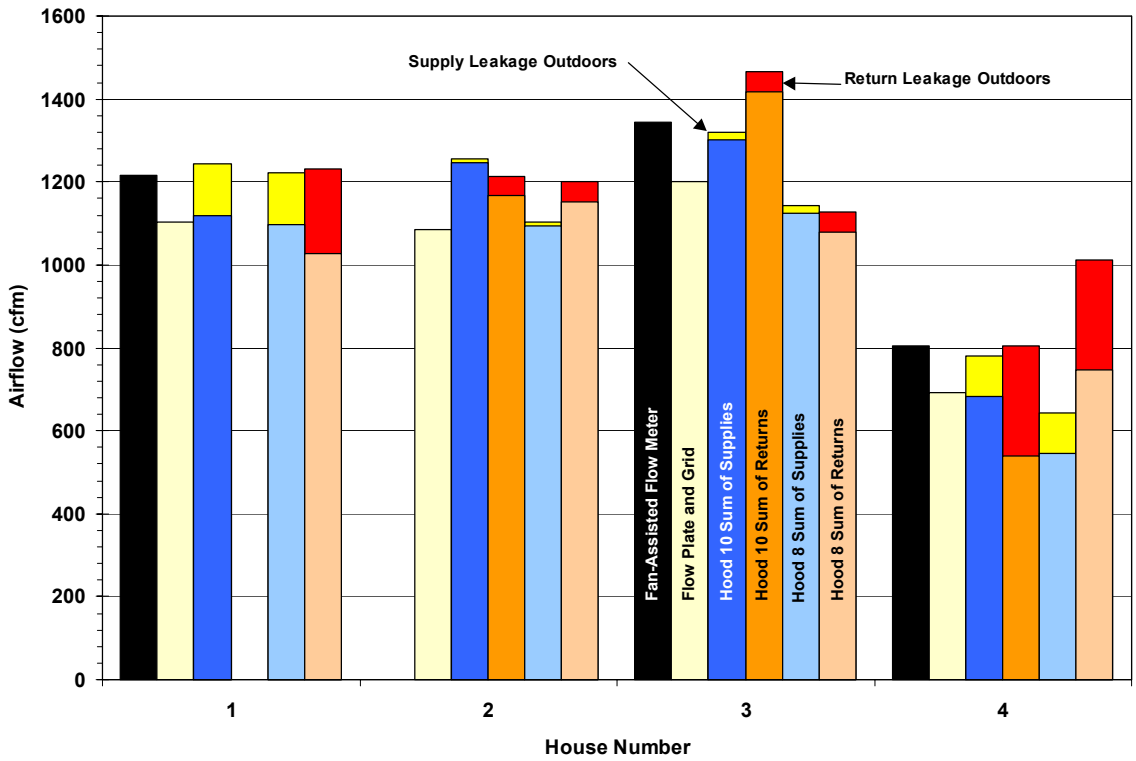

Figure A6. Comparison of air-handler airflow measurements for four houses.

The "Hood 10 Sum of Returns" (fan-assisted flow hood) datum is missing in Figure A6 for the return flow of House 1. We did not use that hood to measure one return grille flow in House 1, because there was a leak on the other side of the wall from indoors to the grille boot. That leak drew air from a corner of a cabinet toe-kick, such that the flow could not be captured without great difficulty. This leak could not be measured by Hood 8 either, but the technician using that device reported the results as if all flows had been measured. Comparing results, it appears the leak may have been small and we should have measured the grille flow anyway.

The fan-assisted flow meter datum is also missing in Figure A6 for House 2. There were two problems with the measurement. One, the technician measuring this flow did not recognize that the attic was not directly connected to the house through the ceiling access hatch. Instead, that hatch led from the garage to the attic. As a result, air supplied to the air handler cabinet did not come from inside the house as it should and the test is invalid. We attempted to correct this error by applying pressure corrections to account for the inadvertent pressurization of the house by the supply duct flows. However, even with this correction, the flow was about 40% low. We suspect that the return plenum seal that was used in this test may have failed, because it was extremely difficult to install and the house pressure increase would also have tended to force it open. A failed seal means that some flow would bypass the flow meter without being measured. To prevent large measurement errors with this technique, care is necessary to ensure that the return is properly sealed.

Comparison of Results: The airflows obtained using the fan-assisted flow meter in three houses agreed within 2 to 3% of the measured sum of supply grille flows (fan-assisted Hood 10) and supply duct leakage (DeltaQ). Agreement was poorer when compared to the sum of return grille

flows (Hood 10) and return duct leakage (DeltaQ), but this may have been due to difficulties in measuring return flows, as we describe later in our flow hood evaluations (some of the returns were too large to be measured all at once with the flow hood).

Airflow measurements using the flow plate and grid show a negative bias of 9 to 14% relative to fan-assisted flow meter measurements. The reason for the bias is unknown, but it is unlikely due to flow bypass because we taped the rigid plate to the air handler cabinet in each test. We did not expect to find such a consistent bias, but it is within the measurement deviations reported by Palmiter and Francisco (2000).

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 houses, differences are less than 5%. Reasons for differences are not reported, but 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 inches (75 mm) to the plate, do not adversely affect measurement accuracy.

Unfortunately, the diagnostic package that includes the prototype non-powered Hood 8 does not include a distinct protocol such as the DeltaQ test or duct pressurization test to measure duct leakage. As a result, this package does not offer a reliable means of determining air-handler airflow. In particular, Table A5 shows that the air-handler airflow measurements obtained using Hood 8 differed by as much as 30% from those obtained using the fan-assisted flow hood (and flow meter). This is true even when duct leakage is included. This was expected, given the inaccuracy of Hood 8 (RMS errors of about 21% for supply flows and 33% for return flows, based on our laboratory tests). Improving the accuracy of this hood and including duct leakage will enable the diagnostic package to provide better estimates of air-handler airflow.

Table A5. Fractional errors in air-handler airflow measurements, Hood 8 versus fan-assisted Hood 10, with and without duct leakage effects.

Site	Hood 8 Fractional Error			
	Sum of Supplies	Sum of Returns	Sum of Supplies plus Duct Leakage	Sum of Returns plus Duct Leakage
1	-12%	-17%	-2%	-1%
2	-13%	-8%	-12%	-4%
3	-15%	-18%	-13%	-15%
4	-30%	-4%	-18%	30%

Assessing the Temperature Drop Method: During our tests of the four houses, we also collected continuous return and supply plenum temperature data for use in evaluating refrigerant charge diagnostics. These data are also useful to examine the temperature drop method of assessing air-handler airflow adequacy that is now included in Title 24. Figure A7 shows these data.

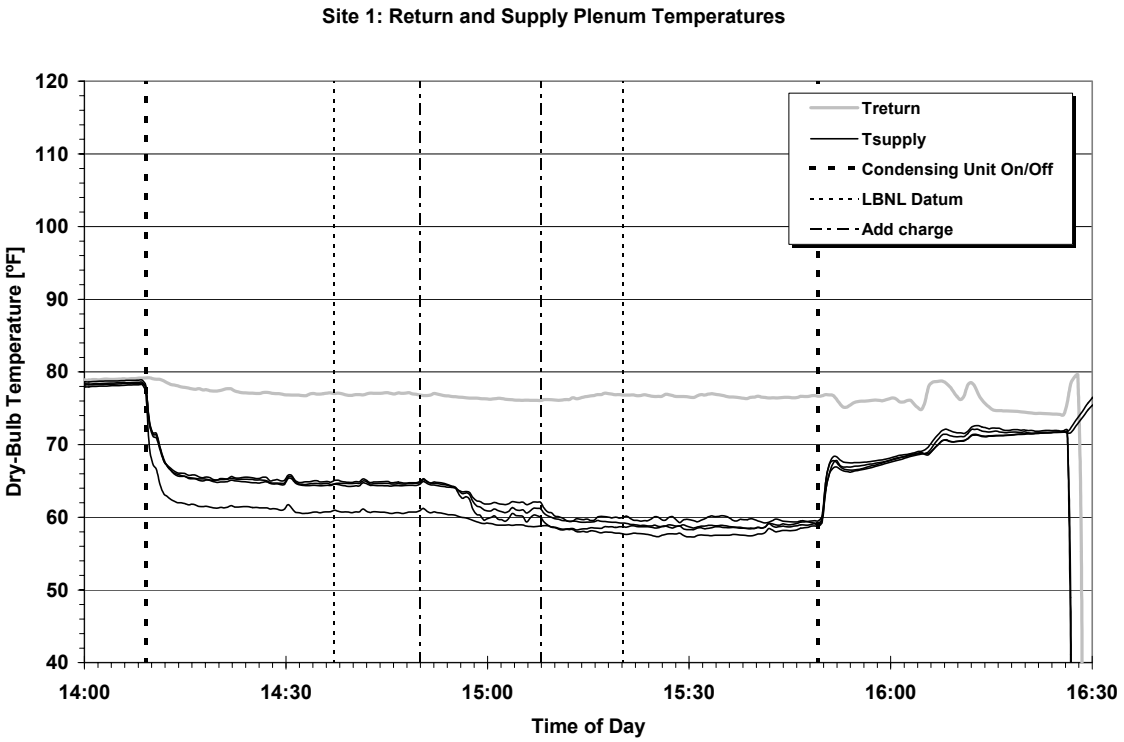

Figure A7a. Plenum temperature variations – Site 1.

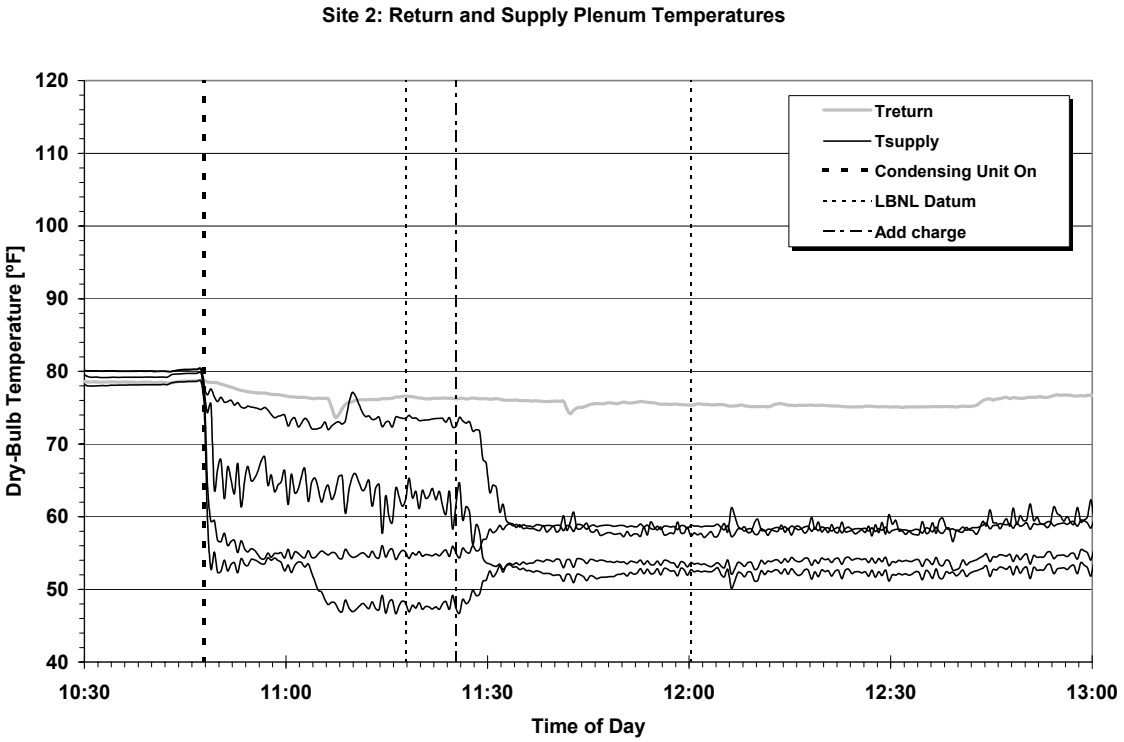

Figure A7b. Plenum temperature variations – Site 2.

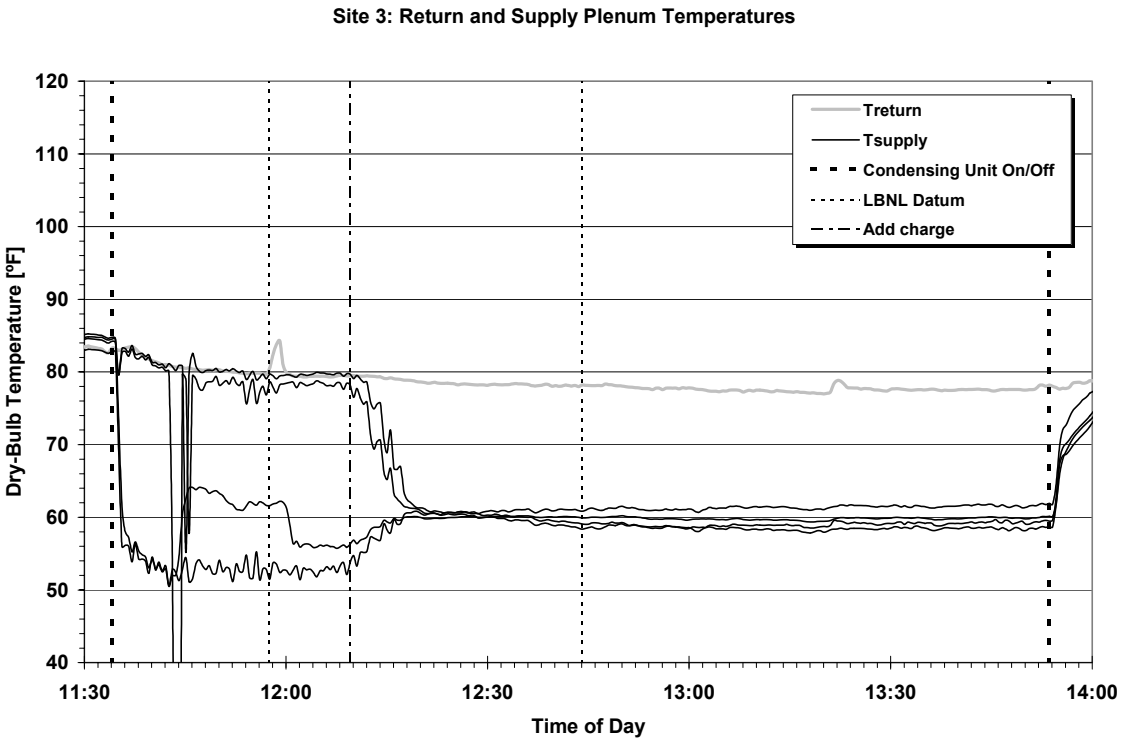

Figure A7c. Plenum temperature variations – Site 3.

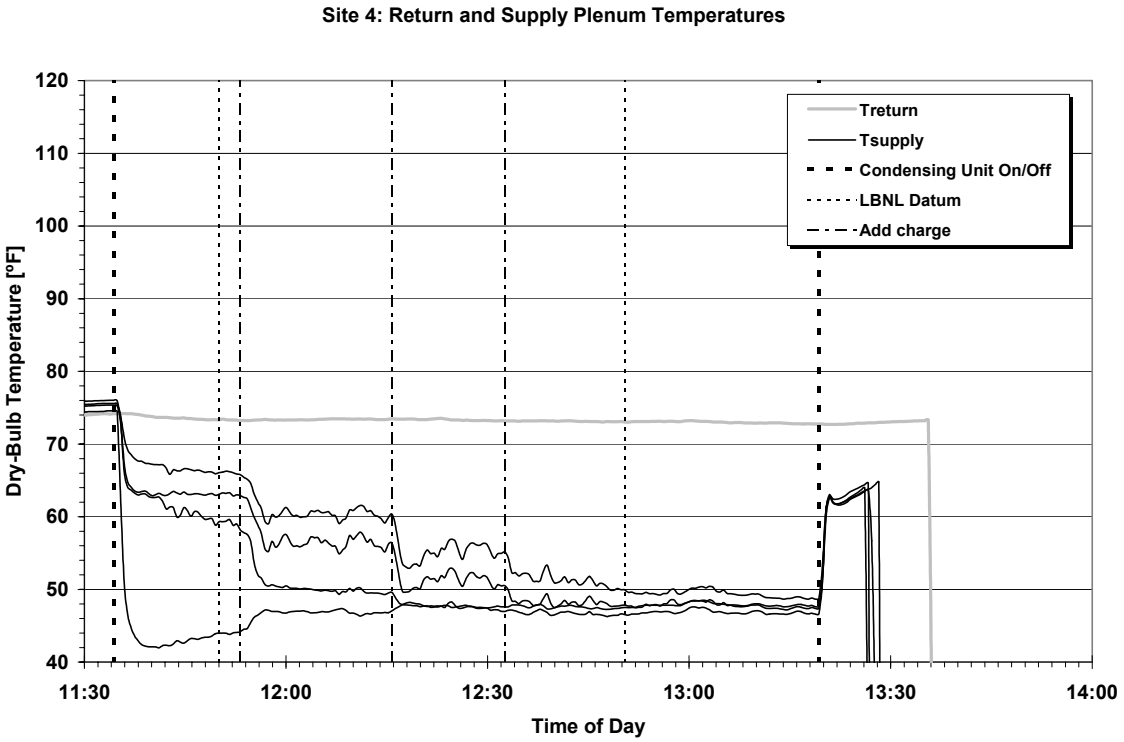

Figure A7d. Plenum temperature variations – Site 4.

We measured return air temperatures upstream of the air-handler fan, as near the transverse center of the return plenum as was possible. The supply air temperatures were measured downstream of the evaporator at approximately the center of each transverse quadrant of the supply plenum. This latter measurement differs from the Title 24 protocol, which requires that the air temperature be measured at the transverse center of the supply plenum, which can be difficult to achieve in a large plenum and may be of questionable value, as discussed below.

Figure A7 shows that supply plenum temperature is highly variable spatially and extremely sensitive to charge (all four cooling systems were substantially undercharged). Table A6 summarizes the results of these measurements at the "LBNL Datum" times shown in Figure A7 with the system "as found" and after charge was corrected. Before charge was added, the supply temperatures vary quadrant to quadrant by as much as 30ºF. After charge was added, these variations drop to about 3 to 6ºF. However, Figure A7 shows that there are still some occurrences of as much as 10ºF even after charge is corrected (Site 2).

Table A6a. Measured supply plenum dry-bulb air temperatures for airflow adequacy assessment.

Site	Condition	Supply Plenum Minimum [ºF]	Supply Plenum Maximum [ºF]
1	As Found	61	65
	Post-Charging	58	60
2	As Found	48	74
	Post-Charging	53	59
3	As Found	51	80
	Post-Charging	58	61
4	As Found	44	66
	Post-Charging	44	50

Table A6 also summarizes the results of the proposed airflow adequacy tests, along with normalized airflows for comparison. Those airflows are based on air-handler airflow measurements using Hood 7 (including duct leakage) and on the nominal total capacity of the evaporator when available. For the two older houses (Sites 1 and 4), no evaporator capacity data were available. In these cases, we have used the rated capacity of the condensing unit.

A comparison between the diagnoses of the proposed test and the normalized airflows shows that the proposed test does not always work. Only Site 1 has adequate airflow, assuming the target is 385 cfm/ton. If we consider only the "as found" cases, we see that the test can provide almost any answer, because of the large differences in supply plenum temperatures. This indicates the test should not be used until charge is corrected.

If we now consider only the "post-charging" cases, the test reliably diagnoses the correct flow condition in two of the four cases: Site 1, which has adequate airflow, and Site 4, which has very low airflow (42% less than the assumed target of 385 cfm/ton). Unfortunately, the test missed the

two cases where the airflow is significantly low (18% low at Site 2, 14% low at Site 3); these airflow deficiencies are sufficient to cause substantial losses in cooling capacity and efficiency. This finding is consistent with results from independent field tests of 13,000 cooling systems: when tests more accurate than the temperature drop method were used, they indicated that 70% of the systems tested had inadequate airflow, whereas the temperature drop method was only able to identify 21% of the systems as having low airflow (Proctor 2002).

Table A6b. Return plenum air temperatures and temperature difference targets for airflow adequacy assessment.

Site	Condition	Return Dry-Bulb Temperature [ºF]	Return Wet-Bulb Temperature [ºF]	Temperature Difference Target [ºF]
1	As Found	77	65	18.3
	Post-Charging	77	65	18.3
2	As Found	77	62	20.4
	Post-Charging	75	61	21.0
3	As Found	81	66	19.6
	Post-Charging	78	64	19.5
4	As Found	73	61	18.8
	Post-Charging	73	60	19.4

Table A6c. Measured temperature difference deviations from targets and diagnoses for airflow adequacy assessment.

Site	Condition	Minimum Deviation [ºF]	Maximum Deviation [ºF]	Diagnoses -3 < Deviation < +3: OK > +3: Low Airflow < -3: Low Capacity	Normalized Airflow (cfm/ton)
1	As Found	-2.3	-6.3	OK / Low Capacity	414
	Post-Charging	0.7	-1.3	OK / OK	
2	As Found	8.6	-17.4	Low Flow / Low Capacity	314
	Post-Charging	1.0	-5.0	OK / Low Capacity	
3	As Found	10.4	-18.6	Low Flow / Low Capacity	330
	Post-Charging	0.5	-2.5	OK	
4	As Found	10.2	-11.8	Low Flow / Low Capacity	222
	Post-Charging	6.6	3.6	Low Flow / Low Flow	

Summary

Data from our field tests indicate that both a fan-assisted flow meter and a fan-assisted flow hood are borderline acceptable devices for determining air-handler airflow. The accuracy of these measurements is likely about ±10%. The latter method requires an accurate measurement of duct leakage. Methods that are more accurate (±5%) would be preferable for assessing airflow through an evaporator equipped with a fixed-orifice refrigerant control, given the significant impact of air-handler airflow on cooling performance with this type of control.

Based on data reported in the literature, the flow plate and grid appears to be an accurate device for determining air-handler airflow. However, we observed a consistent negative bias near 10% compared to the fan-assisted devices that we evaluated. We suggest that the calibration of this device be assessed further in the laboratory.

One of the non-powered flow hoods that we evaluated (Hood 8) was a prototype. At this time, it is not a reliable means of determining air-handler airflow. Improving the accuracy of this hood and including duct leakage will enable the diagnostic package that includes it to provide better estimates of air-handler airflow. Because of our tests, we understand that the manufacturer of the hood is already trying to improve its accuracy.

The temperature drop method of assessing air-handler airflow adequacy, which is contained in Title 24, may be able to find the worst cases of low airflow, but is unreliable for identifying airflow inadequacies in many systems. It seems unlikely that this test can be improved, because of the large spatial variations in temperature that can occur in supply plenums, even after refrigerant charge problems are corrected.

A new air-handler airflow measurement standard needs development to address the use of fan-assisted flow meters and the flow plate and grid in field applications. This standard should cover the most common air-handler and duct system configurations found in residential systems. Further work is needed to develop a prototype for this standard test procedure.

EVALUATION OF DISTRIBUTION SYSTEM AIRFLOW TESTS

For many years, the HVAC industry has used flow hoods to measure grille airflows in non-residential buildings, usually as part of a testing and balancing procedure; residential HVAC systems very rarely have been tested (usually by the research community). Now, utility programs, weatherization programs, and codes and standards such as California's Title 24 are beginning to consider the need to commission residential HVAC systems. Such efforts could include using flow hoods to determine if individual rooms are getting correct airflow, and to estimate total air handler flow and duct air leakage.

Flow hoods have two basic parts: a flow capture device and a measurement device. The flow capture device is usually a fabric hood mounted over a rigid frame (often collapsible for storage and transportation). It directs the airflow over a sensing element in the measurement device. The hood has a larger open end, usually sized to fit a standard square commercial grille of 610 mm × 610 mm (24×24 inches); many manufacturers also offer other hood sizes. Flow measurement techniques differ between manufacturers and include pressure difference, thermo-anemometry, plate deflection, and spinning propellers. Most flow hoods can measure flows in either direction (for supply and return grilles). Some hoods have a system of user operable openings and flaps that reduce backpressures at higher flows.

A few studies have evaluated flow hood measurement uncertainty in commercial applications (Choat 1999); they found that flow hoods are poor at measuring commercial grille flows. However, there are no published studies about uncertainty associated with using flow hoods to measure residential grille airflows. Our paper discusses residential applications of flow hoods and the accuracy requirements in each case. It then discusses our laboratory tests and field study of several flow hoods, which show that some commercially available hoods can be inadequate for measuring flows in residential systems, and that powered flow hoods equipped with measurement devices that are insensitive to grille airflow patterns give reliable and consistent results.

Residential Applications for Flow Hoods and Accuracy Requirements

Flow hoods have several residential applications that may require different levels of accuracy in order to be acceptable. Applications can be split into two subsets: those based on individual grille flows, and those based on the total of all supply or return grille flows.

Subset 1, Individual Grille Flows: Measurements of individual grille flows can be used to identify parts of a system with large leaks (e.g., disconnected ducts), to determine flow imbalance between different spaces in a building, and, when combined with temperature and humidity measurements, to determine if enough heating or cooling is delivered by a grille to the space it serves. For identifying large leaks or disconnected ducts, the airflow changes are large and the accuracy of the measurement is not critical: being within ±50% of the correct flow is reasonable. Similarly, imbalances in residential airflows between different spaces in a building are only critical at higher flow rates and an accuracy of ±25% is probably reasonable.

The accuracy requirement related to providing enough heating or cooling airflow to a space for occupant comfort depends on how well the space, the rest of the building, and outside are thermally connected. For most typical residential rooms, there is little thermal resistance to other parts of the building; this reduces the sensitivity of room temperature to deviations in individual supply grille airflows. A simple steady-state heat balance for a room with an insulated exterior wall containing a window and uninsulated partitions for its other surfaces shows that a

reasonable limit is to have supply grille airflows within ±20% of their design specification to keep the room temperature within approximately ±1°C (2°F) of the adjoining room temperatures. Therefore, the accuracy of the flow measurement device needs to be better than this ±20% requirement. It is important to note that the sensitivity depends on building loads and therefore climate. The larger the load, the more precisely one needs to know the grille flow in order to maintain reasonable temperature limits. In addition, if transient performance is an issue (how fast a particular room is heated or cooled by the system), then the supply grille airflows need to be better defined.

Subset 2, Total Supply or Return Flows: One can sum individual grille measurements to find the total supply or return airflow, which in turn can be used to estimate air handler flow (if leakage is well known), duct leakage to outside (if air handler flow and leak location are well known), and supply/return imbalances (e.g., determining the degree of house depressurization in backdrafting investigations). From a residential commissioning perspective, the key uses are determining the air handler flow and duct leakage, because residences are generally not deliberately pressurized or depressurized.

For air handler flows, the desire to have the correct air handler flow is most critical for cooling systems, because inadequate air handler flows can reduce cooling capacity and efficiency, and can sometimes lead to coil icing. The effects of air handler flow become significant if the flow is about 15% lower than desired. For example, Rodriguez (1995) found an 8% reduction in equipment efficiency for a 15% flow reduction. If the grille flow measurements are to be used to estimate the effect of air handler flow on equipment performance and a reasonable limit for changing the equipment performance is about 5%, then the total of all grille flows needs to have an accuracy better than about ±10%.

The requirements are more restrictive for using the results to calculate duct leakage. The current low leakage limits for the whole duct system are between 6% (CEC 1998) and 10% (State of Oregon and proposed EPA Energy Star ducts). Because these limits include both supply and return leaks, and because the supply and return grille flows are determined separately, the measurement technique needs to determine leakage flows on the order of 3% to 5% of air handler flow (assuming leakage flows are split evenly between supply and return). If duct leakage testing needs to verify these low leakage levels or provide reasonable estimates of the energy penalty of leakier ducts, then the duct leakage measurement accuracy needs to be better than ±3%. Assuming there is no uncertainty in the air handler flow measurement, this implies that the total of all supply or return grille flows needs to have an accuracy better than ±3%. Note that this implies an uncertainty almost the same as the measurement when verifying low leakage ducts and it would be preferable to have a much tighter specification in this case (about ±1% of air handler flow). In addition, this does not address the uncertainty in measuring air handler flow or in estimating what fraction of the total leakage (the difference between air handler and grille flow) is to outside (as required for energy loss calculations).

Table A7 summarizes the accuracy criteria for using flow hoods in residential applications, in order of increasing accuracy requirements.

Table A7. Summary of accuracy requirements for residential flow hood applications.

Application	Required Minimum Accuracy
Identifying large leaks/disconnected ducts	±50%
Identifying room to room pressure imbalances	±25%
Ensuring room load and comfort requirements are met	±20%
Determining air handler flow for cooling equipment performance estimation	±10%
Determining duct leakage	±3%

Experimental Assessment of Accuracy

Measuring residential airflows with a flow hood developed for commercial systems is a challenge for the following four key reasons:

1. Residential supply grille airflows are typically much lower than non-residential ones. Usually, residential flows range from 25 to 120 L/s (53 to 250 cfm), with many in the lower half of this range and some substantially lower: some small interior bathrooms have design flows in the 5 L/s (10 cfm) range. For comparison, commercial system flows typically exceed 120 L/s (250 cfm). Manufacturers of commercially available hoods indicate their equipment is capable of measuring the lower flows; however, they provide no data to support using their measurement techniques for these flows.
2. Residential grilles do not have diffusers that make the flow spatially homogeneous. For supply grilles in particular, the vanes that direct the flow in a particular direction to control the throw of air from the grille into the room lead to highly non-uniform flows entering the flow hood.
3. Residential supply grilles are often physically smaller than those used in commercial systems. A typical residential supply grille is 150 mm × 300 mm (6 × 12 inches) rather than the 610 mm (24 inch) square grille used in commercial systems. This size difference introduces measurement errors, because the flow is non-uniform over the inlet of the flow hood.
4. Some residential systems have single return grilles that are closer to commercial grilles in terms of size and airflow; however, they often have dimensions larger than the 610 mm (24 inch) square standard flow hood opening. In these cases, it is necessary to combine several individual measurements over the face of the grille. There are substantial potential errors with this technique. For example, some flow hoods add resistance at the grille (insertion loss). This increases the airflow that bypasses the flow hood when it only covers part of the grille. As a result, the airflow measured by the flow hood is too low.

To determine the potential magnitude of errors associated with using flow hoods to measure flows at residential grilles, we conducted detailed laboratory tests on five hoods specifically intended for residential systems. These five hoods were comprised of two “standard” hoods from major manufacturers, one “prototype” hood that is currently being developed, one propeller hood, and a state-of-the-art “active” hood. We also performed a field test using eight hoods in a single house. Of these eight, two were for residential use, four were primarily for commercial

use, and the remaining two were active flow hoods. Only the propeller hood and our active flow hood were common to both laboratory and field evaluations, because the flow hoods that we tested belonged to other organizations and we were restricted to the ones available to us at the time of testing. Characteristics of these hoods are described in the following section of this paper.

Our laboratory tests systematically varied potential sources of uncertainty and compared the flow hoods (numbered 6 though 10) to a very accurate standard. These tests evaluate the factory calibration and the sensitivity of the results to changes in entering flow pattern (which can be thought of as the robustness of the measurement technique/device); they do not evaluate insertion loss effects. In the field study, the flow hoods were used in one house with nine supply grilles and a single return. Hoods numbered 1 through 5 and 9 through 11 were used on the supply grilles; Hoods numbered 2 through 5, and 10, were used on the return grilles. Due to limited airflow capacity, not all of the available flow hoods could measure return flows.

Flow Hoods Tested: Hoods 1 through 7 are **standard** flow hoods from three manufacturers; Hoods 2, 6, and 7 were specifically developed for measuring residential flows. The standard hoods measure flow across a flow element within the throat of the hood. The element samples the flow at several fixed locations and combines the samples together in a manifold that contains a thermo-anemometer or that is connected to a pressure transducer. With fixed sampling locations, it is possible that non-uniform flows will not be sampled with sufficient spatial resolution, or that incorrect weighting might be applied to some samples.

Hood 8 is a **prototype** flow hood that uses a flow capture device like a “standard” flow hood, but uses a proprietary flow sampling and sensing technology. This hood is still under development and is not generally available.

Although Hood 9 (**propeller** flow hood) is no longer in production, some residential airflow practitioners still use it. This hood is intended for the smaller grilles and flows in residential systems. The sensing element is a freely spinning propeller, whose speed indicates the flow through the hood. A possible advantage of this hood is that it samples the whole flow (the propeller tip clearance to the flow capture housing is very small). However, it does not eliminate problems of non-uniform flow, because of inertial effects of the propeller and non-linear interactions between local airflow velocity and the rotational force applied to the propeller. In addition, it is possible that swirl in the flow will cause the propeller to spin either too fast or too slow, thus biasing the measurements.

Hoods 10 and 11 are **active** flow hoods (also known as fan-assisted or powered flow hoods), which were developed for research use to reduce the effects of backpressure on flow measurement. For a flow capture device, these hoods use a fabric capture hood from a standard flow hood (Hood 10) or a cardboard box (Hood 11). The outlet of the capture device connects to a calibrated fan and flow meter through a length of flex duct and a flow straightener. By adjusting fan speed until there is no pressure difference between the room and hood interior, one can compensate for the flow resistance of the capture hood, flexible duct, and flow meter. This pressure balancing ensures that placing the flow hood over the grille does not reduce the grille flow and minimizes the effects of air leakage between the flow hood edges and the surfaces they are pressed against.

Laboratory Test Apparatus: Figure A8 shows a schematic of our laboratory test apparatus. It represents a “single branch” system in which all flow passes through the reference nozzle and the

flow hood. The reference nozzle combines a flow straightener, a nozzle, and a pitot-averaging-array to form a flow meter that is less sensitive to flow asymmetry than other flow meters. It has an accuracy of ±0.5% of the flow reading. We used an adjustable fan to produce a range of typical residential grille flows through the apparatus: 25 to 120 L/s (53 to 250 cfm) for supplies and up to 1,000 L/s (2,000 cfm) for returns. Figure A8 shows the apparatus configured for supply flows; we reversed the nozzle and fan for return flows.

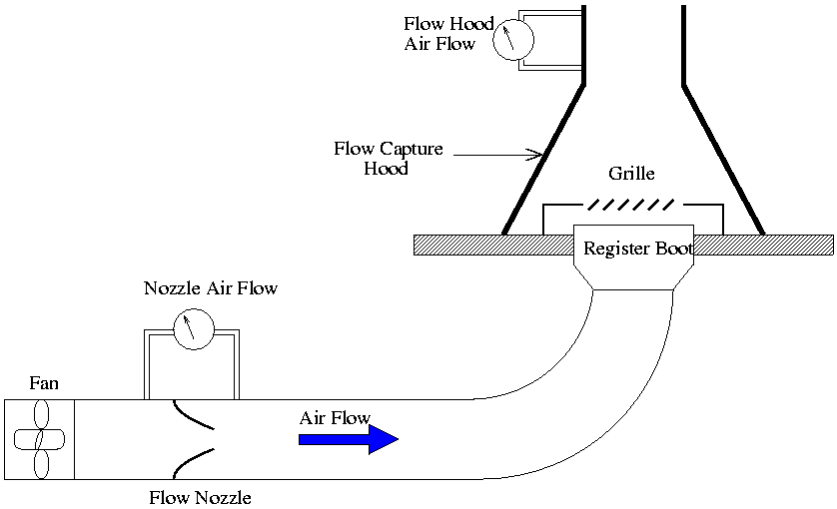

Figure A8. Laboratory apparatus configured for supply flows.

We changed the flow pattern entering the hoods by varying hood lateral placement relative to the grille (center, corner, and center edge), and by using different grille styles (one-way and four-way throws), different grille damper settings, and different boot types. To examine grille-induced swirl effects, we used two different four-way grilles with vanes in opposite directions. We positioned the dampers at a "full open" setting and, for the one-way throw grille, also with the damper blades partially closed (parallel with the outlet vanes). The rectangular boots had different entry conditions: from the long side or from the short side.

Test Results: Figures A9 through A13 show detailed results from our laboratory tests for the different test configurations. The legend differentiates between test configurations. Center/Edge/Corner refers to the location of the hood relative to the grille. The term "w/damper" means that the damper in the grille was partially closed. Lastly, the CW/CCW designation refers to the use of a four-way throw grille that introduces swirl in either the Clock-Wise (CW) or Counter-Clock-Wise (CCW) sense.

Table A8 summarizes our laboratory test results. The fractional errors listed here are the average of the individual fractional errors for each measurement and not the average error divided by the average flow rate. The average error is an estimate of the bias in the flow hood. The RMS errors do not let positive and negative errors cancel out and are a better indicator of the uncertainty in an individual grille measurement.

Tables A9 and A10 summarize the field test results relative to the reference active flow hood for supply and return flows respectively. Walker et al. (2001) describe our test results in more detail.

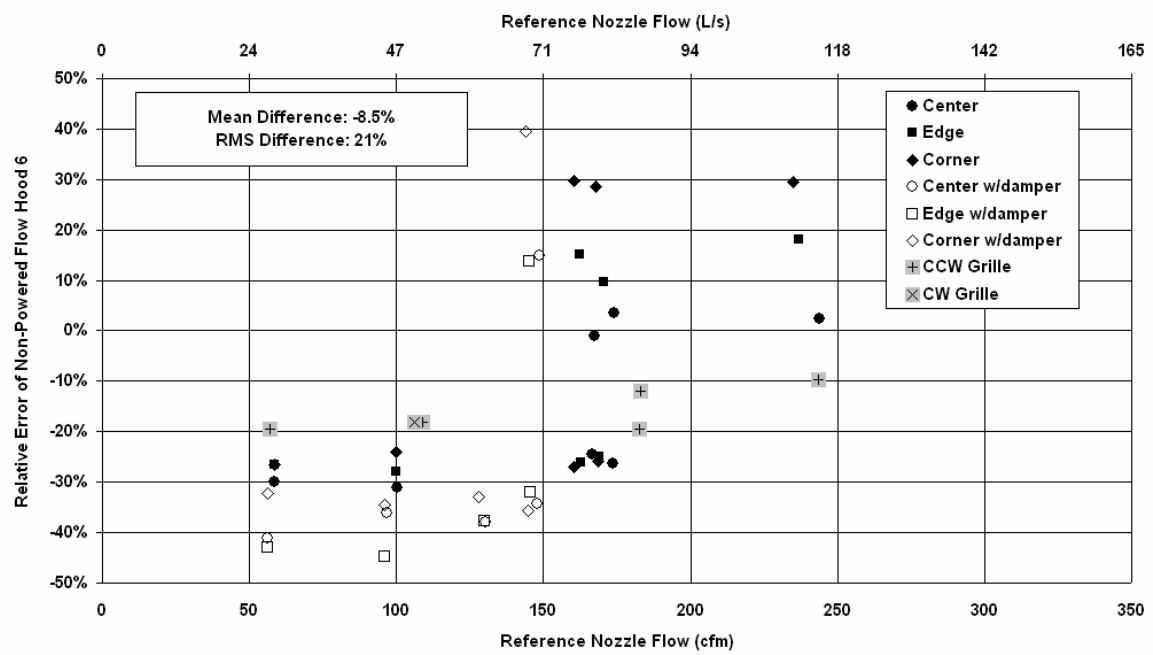

Figure A9. Laboratory results for Standard Hood 6.

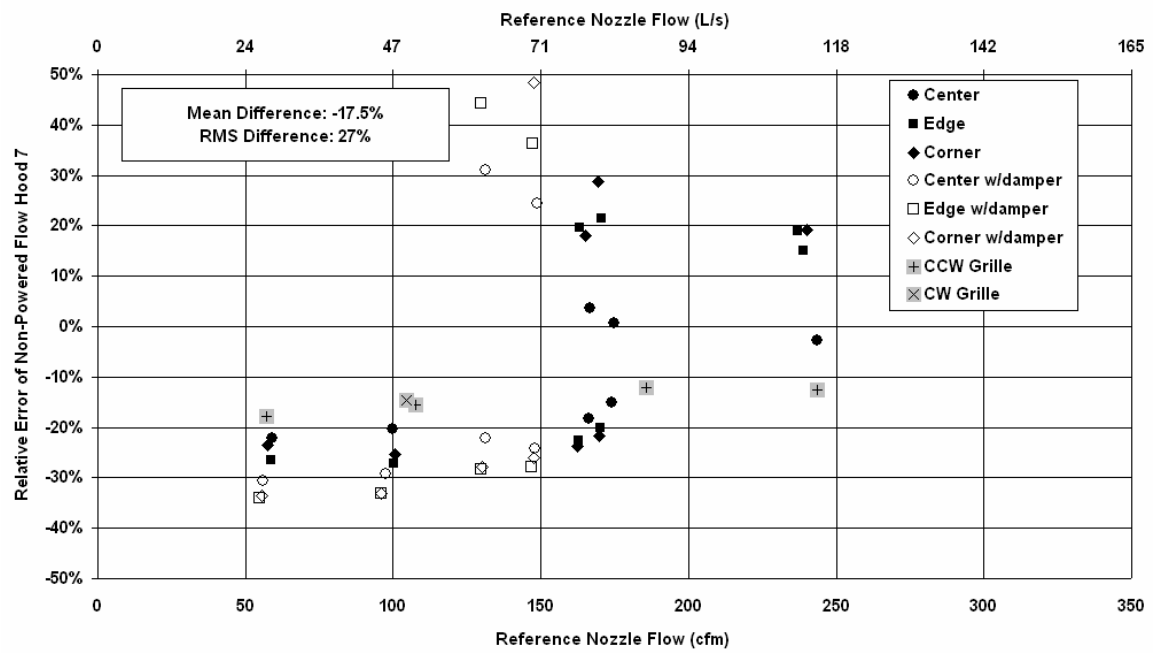

Figure A10. Laboratory results for Standard Hood 7.

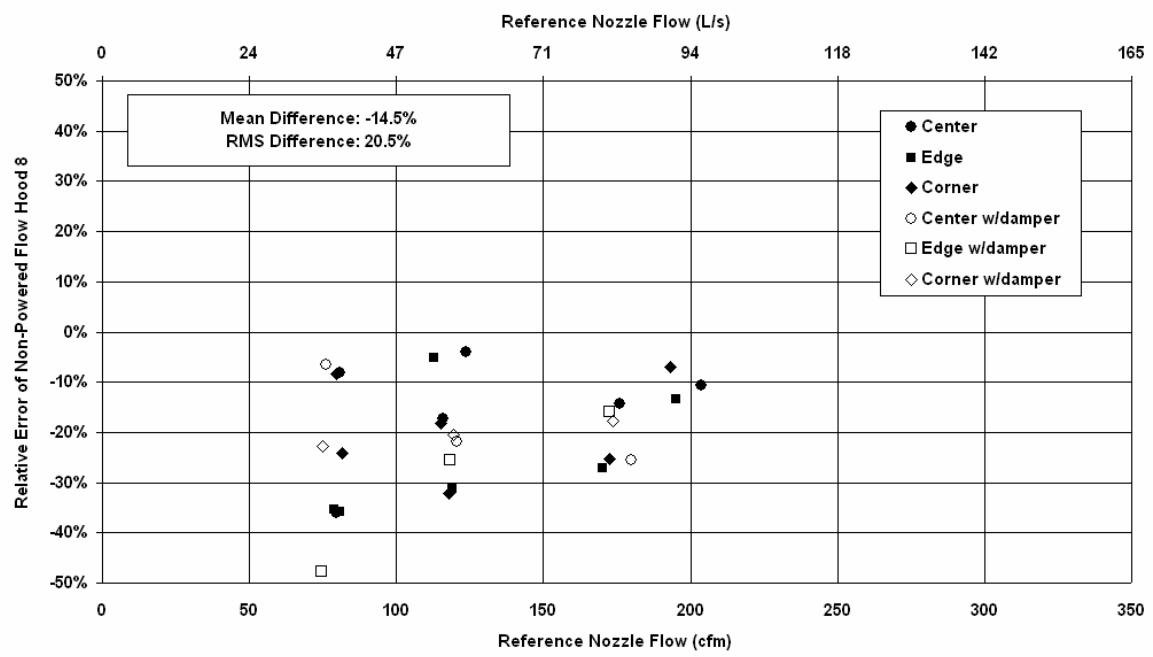

Figure A11. Laboratory results for Prototype Hood 8.

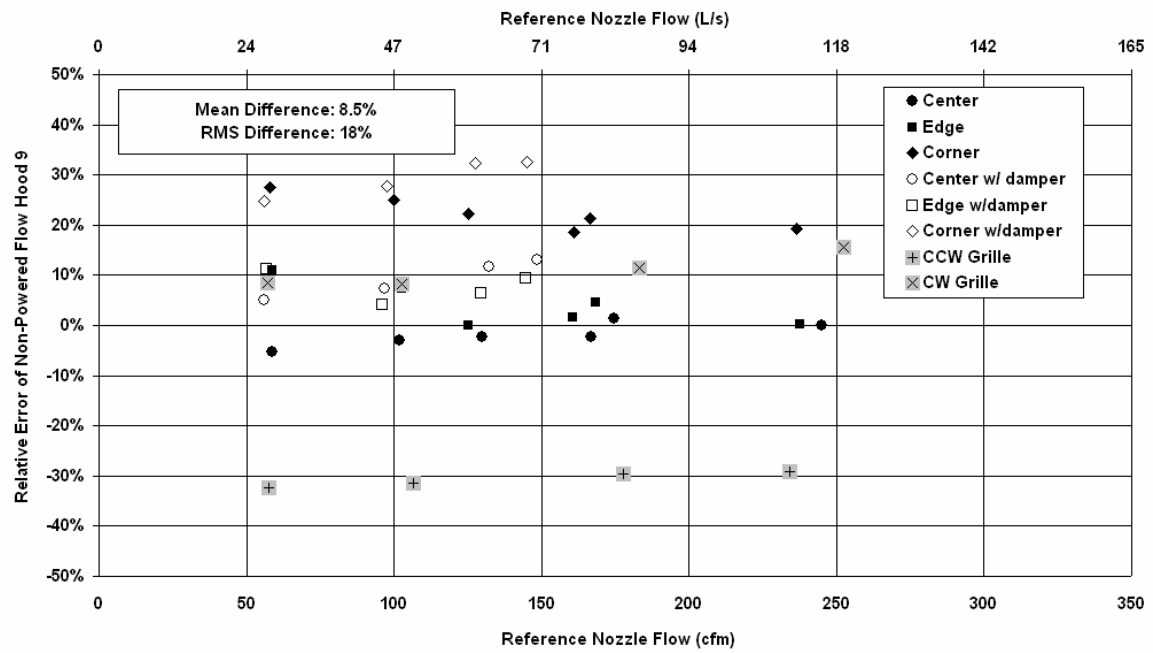

Figure A12. Laboratory results for Propeller Hood 9.

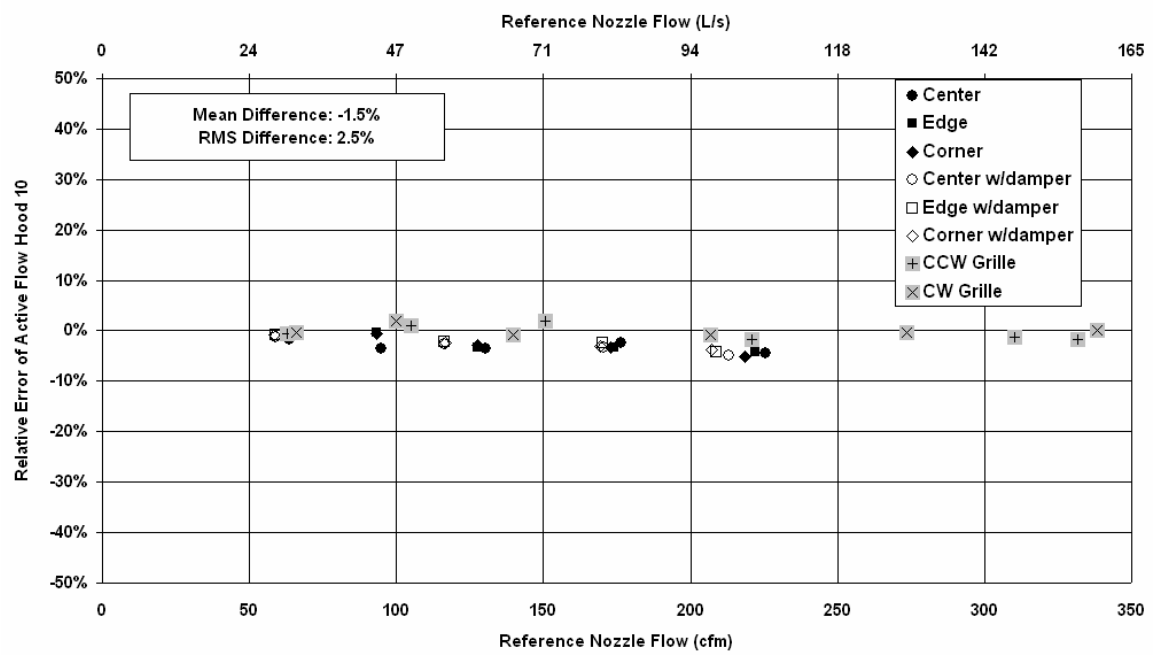

Figure A13. Laboratory results for Active Hood 10.

Table A8. Summary of laboratory test results: Supply and return flows.

Hood ID	Hood Type	Average Difference	RMS Difference	Number of Tests
		Supply Flows		
6	Standard	-8.5% (-8 cfm)	21% (28 cfm)	90
7	Standard	-17.5% (-19 cfm)	27% (36 cfm)	74
8	Prototype	-14.5% (-18 cfm)	20.5% (25 cfm)	43
9	Propeller	8.5% (10 cfm)	18% (25 cfm)	75
10	Active	-1.5% (-3 cfm)	2.5% (5 cfm)	87
		Return Flows		
8	Prototype	33% (488 cfm)	33% (511 cfm)	3
10	Active	2.5% (25 cfm)	3.5% (38 cfm)	9

Table A9. Summary of field test results: Nine supply flows.

Hood ID	Hood Type	Difference Relative to Active Hood 10	
		Sum of all grille flows	RMS for individual grilles
1	Standard	-1% (-9 cfm)	8% (8 cfm)
2	Standard	3% (31 cfm)	10% (14 cfm)
3	Standard	7% (78 cfm)	15% (12 cfm)
4	Standard	48% (519 cfm)	58% (65 cfm)
5	Standard	45% (484 cfm)	56% (61 cfm)
9	Propeller	-1% (-7 cfm)	8% (6 cfm)
11	Active	-1% (-10 cfm)	6% (4 cfm)

Table A10. Summary of field test results: One return flow.

Hood ID	Hood Type	Difference Relative to Active Hood 10
2	Standard	-17% (-177 cfm)
3	Standard	-4% (-42 cfm)
4	Standard	-1% (-9 cfm)
5	Standard	2% (18 cfm)

Key Findings

Our laboratory test results for the reference active flow hood (Hood 10, summarized in Table A8 and shown in Figure A13) show it is clearly better than the non-powered flow hoods: all its results fall in a narrow band (RMS error of only 2.5%, 5 cfm), with a small negative bias (-1.5%, -3 cfm). A comparison of these results to the criteria presented in Table A7 shows that this hood can be used in all applications.

Table A8 indicates that the non-powered flow hoods we tested in the laboratory (Hoods 6 through 9) do not necessarily meet the accuracy criteria for many residential applications. RMS errors are in the 20% to 30% range, which is much larger than the 10% or better accuracies that are required for most distribution system diagnostics. In particular, the measurement accuracy is poor for individual grilles, as well as over the sum of many grilles. This means that these hoods can be inadequate for use in estimating duct leakage and air handler flow, and for assessing individual grille flows for room load and comfort. However, most of the flow hoods can be used in applications that require less accuracy (finding big leaks/disconnected ducts and estimating room-to-room pressure imbalances). The provision made by some manufacturers to change the flow resistance of the flow meter by opening or closing vents did not offer any advantages in improved accuracy.

Flow hood errors shown in Figures A9 through A12 are mostly due to non-uniformity of incoming flow from typical residential grilles. The non-uniformity has two sources: the duct system itself (including the grille) and the opening of the flow hoods being larger than the grilles.

The duct system contributions include the effects of the flow pattern generated by the grille, the changes in flow pattern because of the use of grille dampers, swirl in the flow (either generated by the grille or upstream ducts), and the boot entry type. Because grille area is only a fraction of the total entry area of the flow hood, this guarantees non-uniform flow entering the flow hood; it also allows flexibility in the flow hood positioning over the grille. Positioning of the flow hood over the grille was found to be critical: the flow hood needs to be centered for best results. Because the results are sensitive to positioning (errors as much as ±40% due to poor centering), this is a key issue in the field application of flow hoods. In field applications, our experience indicates that the user often has little choice over flow hood placement, because grilles are located near the intersection of walls, floors, and ceilings (or other obstructions); the ability to center the hood is probably limited more by these physical constraints than by visual acuity.

Figure A12 shows that the propeller flow hood (Hood 9) has considerable variation with inlet flow conditions. It is sensitive to swirl in the entering flow, to location of the hood over the grille, and to damper position. CW swirl is in the same direction as propeller rotation and results in the propeller spinning too fast, and produces an average 11% over estimate of flow. Conversely, CCW swirl acts in opposition to propeller rotation, and produces an average 30% under estimate of flow. Even though this flow hood has a small range of positioning movement, it is still sensitive to positioning over the grille. Flow hood position relative to the grille changes the relative error by about 25%, with corner placement giving the greatest sensitivity. The effects of damper position are also significant for Hood 9: compared to the results with the damper fully open, the dampered results are 11% higher on average and have about three times the RMS error. In field applications where occupants have set dampers to control airflow (and do not want them changed), this means that the flow hood errors could change from grille to grille.

Because our laboratory tests and field experience have demonstrated the accuracy of active flow hoods and their insensitivity to non-uniform flows, we used the active Hood 10 as the **reference** flow hood for our field studies. The field test results in Tables A9 and A10 show that some flow hoods gave acceptable results and others did not. For example, differences for the sum of all supply grille flows were less than 10% compared to the active reference (Hood 10) for five of the tested hoods (Hoods 1, 2, 3, 9, and 11). However, Hoods 4 and 5 gave supply flows that are much too high for most applications (these were two identical flow hoods from the same manufacturer). The results for Hoods 1, 9, and 11 indicate that they are acceptable for all the potential grille flow tests outlined in Table A7. The return flow uncertainty for Hood 2 (-17%, -177 cfm) and the individual grille uncertainties for Hood 3 indicated by its RMS error (15%, 12 cfm) mean that these two hoods are acceptable for all the potential grille flow tests outlined in Table A7, except for determining air handler flow and duct leakage.

The findings based on our field tests apply only to the tested system; we expect that the errors reported for these field tests are lower than those from a typical HVAC diagnostic application. Experienced researchers conducted all the field tests on a system with grilles that were well placed, had fully open dampers, and did not introduce swirl or other extreme flow non-uniformities. They took as much time as necessary to achieve the best possible results for each flow hood (e.g., taking particular care to center the flow hoods). A field test survey involving more houses and typical flow hood users is needed to estimate the error distribution related to system type and hood usage.

Calibration versus Application

As with other instrumentation, flow hoods are susceptible to large errors in field applications that are not apparent in manufacturers' accuracy specifications. Flow hoods are calibrated in a fixed position with uniform flow, resulting in typical accuracy specifications of about ±3%. Instruction manuals for flow hoods often warn of the possibility of errors due to airflow patterns from grilles differing from those during calibration (e.g. Alnor 1998). However, no estimates of the related error are given. Our laboratory and field tests show that the change in airflow pattern between calibration and application creates large flow measurement errors.

ASHRAE Standard 111 (ASHRAE 1988) also discusses flow hood accuracy issues. For example, Section 8.6.4.4 states: " System Effects: Perhaps the most important result of these tests has been to demonstrate that errors as great as 15% to 30% may be caused by neglecting the effect of approach conditions." This agrees closely with our laboratory test results. ASHRAE Standard 111 also indicates in Section 8.6.5 that one should "…consider most diffuser measurement as not reliable for certifiable accuracy". Current testing and balancing reporting procedures do not emphasize these issues.

Manufacturer's instructions and ASHRAE Standard 111 discuss the use of pitot-static-tube traverses to field calibrate the flow hood to account for the problems discussed above. However, this is not a practical solution in residential systems because:

- there will rarely be duct access so that a traverse can be performed,
- ducts are often made from flexible plastic duct that cannot be used for pitot-static tube insertion and mounting (unlike sheet metal ducts),
- almost no duct system has a long enough uninterrupted flow to meet the requirements for an accurate pitot-static-tube traverse, and
- most ducts are unique (in terms of fittings, length, and layout) and a traverse would be required for every grille, thus obviating the need for a flow hood.

Summary

Of the flow hoods that we tested in the laboratory (i.e., ones that are reasonably available), active flow hoods are the most reliable and consistent for measuring distribution system airflows if the measurements are to be used in estimating duct leakage, air handler flow, and individual grille flows for room load and comfort. This does not mean that active hoods are the only ones that can work. There is no fundamental problem with passive hoods, and our field test results showed that some passive hoods can obtain good results when they are used with appropriate care on the right set of grille types and locations. Laboratory and field tests of a wider range of flow hoods should be pursued, in addition to evaluating improvements for residential flow hoods. Because the active flow hood is the most accurate, it can be used as a reference in field evaluations of other hoods.

A new flow hood measurement standard should be developed to address how flow hoods are operated in the field. This standard should have some standard grille sizes, types, and placements that would cover most common geometries found in residential systems. The laboratory tests we used are a prototype for this standard test procedure. Possible agencies for development of this standard are ASHRAE and ASTM.

EVALUATION OF REFRIGERANT CHARGE DIAGNOSTICS

Based on tests of more than 4000 residential cooling systems in California, it is clear that many systems have incorrect refrigerant charge levels (Proctor 2000). Data from these tests indicate that about 34% are undercharged, 28% are overcharged, and only 38% have correct charge. In the past, data from Blasnik et al. (1996) and Proctor (1997, 1998) have indicated that an undercharge of 15% is common.

Both undercharge and overcharge can reduce cooling equipment longevity, capacity, and efficiency. For example, laboratory test data for capillary-tube-controlled equipment (Farzad and O'Neal 1988) indicate that an undercharge of 15% will reduce cooling equipment total capacity by 8 to 22% and its energy efficiency ratio (EER) by 4 to 16%. An overcharge of 10% will reduce capacity by 1 to 9% and EER by 4 to 11%. Figures A14 and A15 show the capacity degradation of a 3 ton split-system air conditioner versus charge for various outdoor temperatures. These two figures indicate that TXV-controlled equipment is much less sensitive to deviations from the correct charge (Farzad and O'Neal 1989). Their work showed a similar pattern for EER degradation.

Laboratory test data indicate that some short-tube-orifice-controlled equipment behaves more like TXV-controlled equipment (O'Neal et al. 1989), while others behave like capillary-tube-controlled equipment (Rodriguez 1995). Additional research with a larger sample of short-tube-orifice-controlled cooling equipment is needed to clarify how the performance of equipment like this depends on charge.

Several diagnostics are available to assess the correct amount of refrigerant charge in a system, but only the superheat and subcooling tests are practical, well developed, and reliable (when properly done). Superheat tests are for capillary-tube-controlled equipment; subcooling tests are for TXV-controlled equipment. The common assumption is that superheat tests are also appropriate for short-tube-orifice-controlled equipment. Neither test is standardized, but equipment manufacturers commonly specify them. However, many service technicians do not use the tests, primarily because of the time it takes to do them, but also because they do not have necessary equipment or appropriate indoor and outdoor conditions for the test.

Superheat Test Methods Evaluated

Carrying out superheat tests on systems with a capillary tube or short-tube orifice is more important than subcooling tests on TXV equipped systems, because a TXV tends to mitigate charge deficiency effects. Consequently, we focused our evaluation on three state-of-the art methods that may facilitate superheat tests on residential cooling systems. Each method involves different hardware, software, and measurements. All three methods, which we broadly characterize as "Superheat Calculation Methods", make the superheat test easier. Table A11 characterizes the methods, as well as our data collection truth standard (Reference). Although the methods include other tests (e.g., Method 3 also assesses air-handler airflow), our evaluation only focuses on the ability of the methods to assess refrigerant charge.

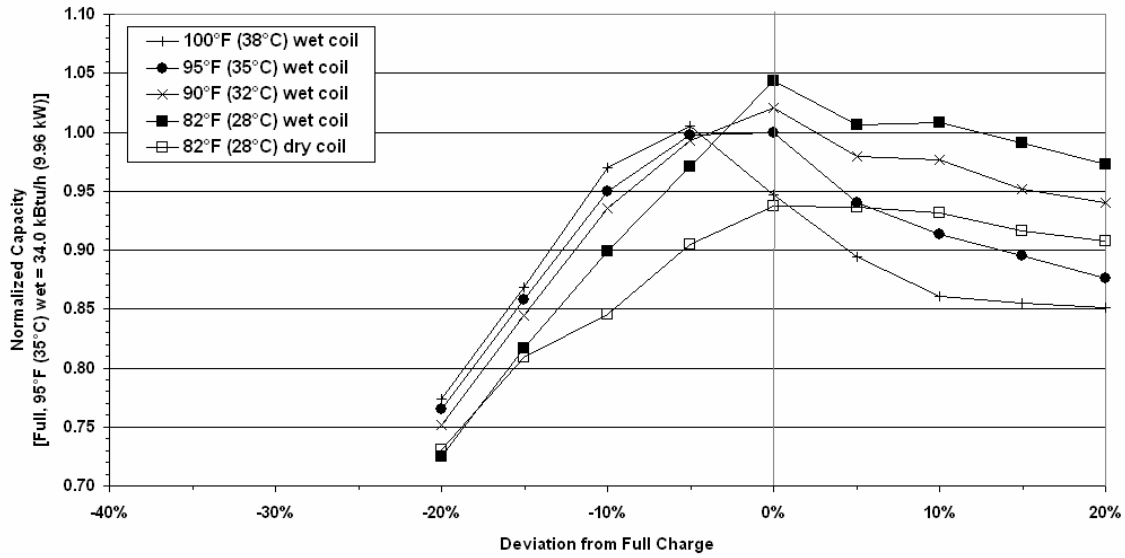

Figure A14. Total capacity variation – Capillary tube (Farzad and O'Neal 1988).

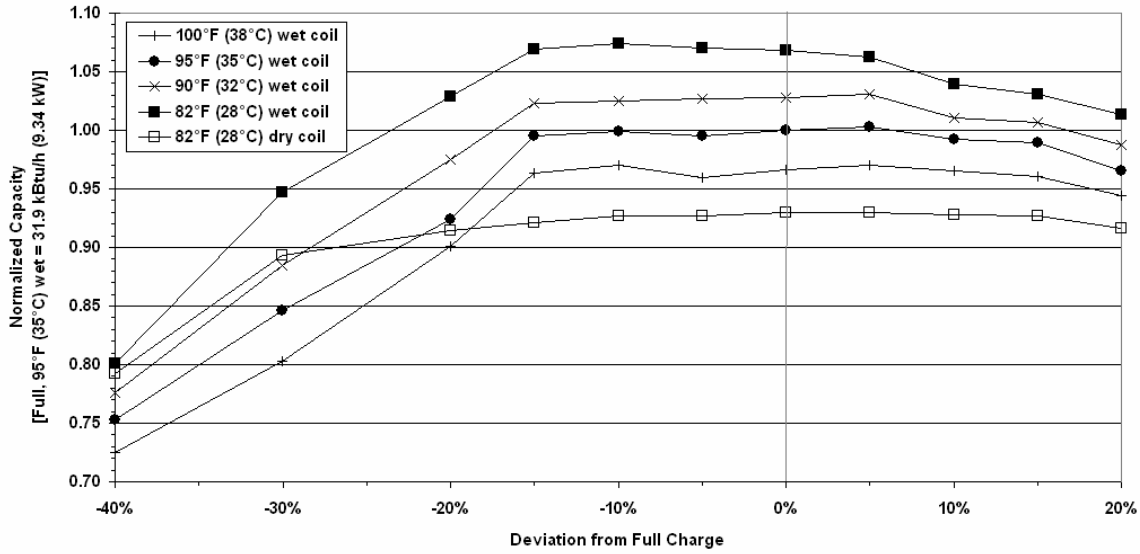

Figure A15. Total capacity variation – TXV (Farzad and O'Neal 1989).

Table A11. Superheat test methods evaluated.

Method	Description
Reference	Uses Method 3 software (see below) with continuously monitored data collected using a research-grade data acquisition system. This method is our "Truth Standard" for purposes of comparison.
1	Personal Digital Assistant (PDA) with attached refrigerant pressure transducers and temperature sensors, which is intended for use on light-commercial buildings. PDA also runs software that provides diagnoses in the field. The data can be uploaded later from the PDA to a web site that provides a more detailed analysis.
2	Data collection system including pressure transducers, temperature and humidity sensors, software, and computer that collects data for superheat test and then provides recommended action to technician. Currently designed for use by an authorized crew who carries out the test, provides diagnoses to a contractor, and then verifies the efficacy of any work that is performed.
3	Software program that requires the technician to enter single point data from refrigerant manifold gauges and temperature sensors into a computer, which then provides diagnoses based on measured and target superheat comparison. To avoid computer use in the field, the contractor also has the option of providing input data by telephone to a remote operator, who then enters it into the software and relays diagnoses back to the technician.

Our goal in the evaluations was to assess the accuracy of these methods and to ascertain whether they are useful for residential commissioning. The central questions we are attempting to answer with this work are:

- What technologies are available to make a superheat test easier?
- How do these technologies work?
- How accurate are they, and how accurate do they need to be to accurately assess charge?

There are three caveats regarding our evaluation:

1. Our evaluation explored the strengths and limitations of the methods that we tested rather than testing them on a statistically significant number of homes. In particular, we only tested cooling equipment in four houses (two new ones and two older ones), all with short-tube-orifice controls.
2. Although we ostensibly compare different methods that might facilitate the superheat test, we could not always do an "apples-to-apples" comparison. The different methods all use different input data and different algorithms. These algorithms are either proprietary or were not accessible to us. Consequently, our results describe differences between the different methods and we state when the quantities being compared are not effectively the same.
3. As a reference standard, we used the superheat test even though it is prone to measurement error, can be time consuming, and the indoor and outdoor conditions that govern its use are limited. In particular, our evaluations used continuously monitored data that we collected and output from the software of Method 3 based on these data. We chose that method because it is the most fully developed product that we considered and because it has an extensive history of field tests. We also chose it because we did not have time or resources to do gravimetric tests, the preferred truth standard. A gravimetric analysis is useful for a wider range of conditions and is potentially more accurate. That method involves removing all of

the refrigerant in a system, drawing a vacuum and leak testing the system, and then adding the manufacturer's recommended amount of refrigerant for the compressor, coils, and installed "line set" (refrigerant line length). However, the gravimetric test requires a matched indoor coil and outdoor unit, as well as a good measurement of the line set. Further drawbacks are the time and skill that it takes to do a gravimetric test, which is more complex than a superheat test.

What is the Superheat Test?

To understand our evaluations, it is important to understand the basic theory of the superheat test. Superheat is a thermodynamic metric, defined as the temperature rise above the vapor saturation temperature (i.e., the temperature at which all the liquid in a mixture is evaporated for a given pressure). For typical suction line pressures of 40 to 100 psig (276 to 690 kPa) found in R-22 systems, the vapor saturation temperature will range from 17 to 59ºF (-8 to 15°C). Refrigerant pressure gauges commonly have a concentric scale to conveniently indicate the vapor saturation temperature that corresponds to the measured pressure for a given refrigerant.

For a superheat test of a cooling system, the actual superheat at operating conditions is determined by measuring the temperature and pressure of the refrigerant in the suction line, just before the refrigerant enters the compressor. The actual superheat is the difference between the suction line refrigerant temperature and the vapor saturation temperature at the measured pressure. The deviation of this superheat value from a target superheat is an indicator of whether the amount of refrigerant charge in the air conditioner is correct when it operates at design conditions. Note that the surface temperature of the suction line rather than the refrigerant temperature itself is measured in practice. This difference is a potential source of error in the test, as discussed later when we review our field test results.

Equipment manufacturers use laboratory tests to determine target superheat values as a function of the return air wet-bulb temperature entering the evaporator and of the outdoor air dry-bulb temperature entering the condenser. Those temperatures act as surrogate metrics to characterize two variables that affect the refrigerant evaporation rate in the evaporator: the cooling load on the evaporator and the heat rejection rate of the condensing unit. These data are typically available in a table or in a chart. In a superheat test, the technician measures the two air temperatures that we describe above and then obtains the corresponding target superheat from the table or chart.

If the measured superheat value is too low compared to the target superheat, there will be too much charge in the system at design operating conditions. In addition to energy and capacity impacts, there is a chance that liquid refrigerant will not completely evaporate at these conditions and could slug the compressor. If the measured superheat value is too large compared to the target superheat, there will be too little charge in the system at design operating conditions. In addition to energy and capacity impacts that are more serious than in the overcharge case, the suction line pressure and corresponding saturation temperature of the refrigerant will be very low. This can lead to ice formation on the evaporator, which can restrict heat transfer, increase airflow resistance, and reduce air-handler airflow. This will further reduce air conditioner performance and can shorten compressor life.

Test Houses and Cooling Equipment

We used each of the methods to test four separate California houses, which are cooled by split-system central air conditioners equipped with short-tube-orifice metering devices and R-22

refrigerant. The rated capacity of all the tested air conditioners is 3 to 4 tons. Table A12 summarizes relevant house and equipment characteristics.

Table A12. Test house and cooling equipment characteristics.

Site	House Location	Cooling Equipment Age [Years]	Condensing Unit Rated Capacity [Tons (kW)]	Evaporator Rated Capacity [Tons (kW)]
A	Larkspur, CA	17	3 (11)	Unknown
B	Sacramento, CA	< 1	3.5 (12)	4 (14)
C	Sacramento, CA	< 1	3 (11)	4 (14)
D	Concord, CA	> 15[1]	3.5 (12)	Unknown

[1]Estimated. The house was about 25 years old and was occupied by the current owner 4 years ago. The system is very old and decrepit.

We conducted superheat tests in the "as found" condition and then repeated them each time after we added or removed refrigerant charge. However, we only report the measurements for the "as found" condition and the final "post-charging" condition. At each house, we operated the equipment for at least 15 minutes initially and after each charge change to allow system conditions to stabilize before conducting a superheat test.

Field Test Results

The following describes our field test results, compares the data that are required to determine the actual and target superheat values, and compares diagnoses generated by the various methods. In many cases, some of the field data are missing. Most of the time, one should interpret this as a failure of a product or operator error, indicated by "NA" in the tables. There are a couple of exceptions, indicated with "-" in the tables: we did not use Method 3 at Site D because the technician was unavailable. Additionally, Method 1 does not measure the return plenum wet-bulb temperature or use it in its analysis. We discuss the details and implications of intentional and unintentional missing data more fully throughout the following sections.

Determining the Target Superheat: An important part of conducting the superheat test is determining the target superheat. Methods 2 and 3 use a chart for this purpose, similar to the manufacturers chart described earlier. To use the chart, Method 3 requires measuring the dry-bulb temperature of the air entering the condenser and the wet-bulb temperature of the air entering the evaporator from the return plenum. It seems that Method 2 may use additional calculations (discussed in further detail later). Method 1 does not measure either of these temperatures. The manufacturer reports that this method uses a proprietary superheat chart, which ascertains the loads on the coils through some other algorithm. That method requires measuring the ambient temperature at the PDA, which is likely theorized to be close to the condenser entering temperature, because the short length of the device's refrigerant hoses requires it to be located near the condenser. It is not clear what Method 1 uses in place of the return plenum wet-bulb temperature, because it has no temperature or humidity sensors inside the house or ducts.

For each site, Table A13 lists the measured air temperature entering the condenser and the return plenum wet-bulb temperature for the "as found" and "post-charging" conditions.

With the Reference results as a benchmark, it is clear that Method 1 sometimes measures a different temperature than the condenser entering temperature, even when its temperature sensor is no more than 6 feet away from the condensing unit. For example, in the Site D post-charging case, it measures a temperature that is approximately 16°F (9°C) too high. Since it is not clear how the Method 1 algorithm works, it is not clear how this difference might affect the method's analysis. However, it seems likely that any attempt to use this temperature to determine the load on the condenser might lead to significant errors.

Table A13a. Measured parameters for determining "as found" target superheat.

Method	Condenser Air Entering Temperature [°F (°C)]				Return Plenum Wet-Bulb Temperature [°F (°C)]			
	Site A	Site B	Site C	Site D	Site A	Site B	Site C	Site D
Ref.	96[1] (36)	85 (29)	89 (32)	76 (24)	65 (18)	62 (17)	66 (19)	62 (17)
1	105 (41)	88 (31)	87 (31)	85 (29)	-	-	-	-
2[2]	108 (42)	85 (29)	91 (33)	73 (23)	66 (19)	61 (16)	65 (18)	61 (16)
3	100 (38)	85 (29)	NA[3]	-	67 (19)	63 (17)	NA[3]	-

[1]This value is incorrect – it is the ambient air temperature. The temperature probes measuring condenser entering air temperature failed for this test.

[2]Method 2 measures the humidity and temperature at the return grille(s). The number reported here is the average return grille wet-bulb temperature and not the return plenum wet-bulb temperature.

[3]Either operator error or a computer error caused the Method 3 data to be missing for Site C as found.

Table A13b. Measured parameters for determining "post charging" target superheat.

Method	Condenser Air Entering Temperature [°F (°C)]				Return Plenum Wet-Bulb Temperature [°F (°C)]			
	Site A	Site B	Site C	Site D	Site A	Site B	Site C	Site D
Ref.	100[1](38)	88 (31)	92 (33)	78 (26)	66 (19)	61 (16)	64 (18)	60 (16)
1	98 (37)	89 (32)	92 (33)	94 (34)	-	-	-	-
2[2]	105 (41)	92 (33)	NA[3]	77 (25)	65 (18)	60 (16)	NA[3]	60 (16)
3	101 (38)	NA[4]	92 (33)	-	66 (19)	NA[4]	65 (18)	-

[1]This value is incorrect – it is the ambient air temperature. The temperature probes measuring condenser entering air temperature failed for this test.

[2]Method 2 measures the humidity and temperature at the return grille(s). The number reported here is the average return grille wet-bulb temperature and not the return plenum wet-bulb temperature.

[3]A computer error caused the Method 2 data to be missing for Site C post-charging.

[4]Either operator error or a computer error caused the Method 3 data to be missing for Site B post-charging.

With the exception of Method 1 at Site D, all methods do a reasonable job measuring the condenser air entering temperature. However, there are still substantial differences in some cases (up to 4°F (2°C), Site B post-charging). Also, there is a noticeable deviation between methods at

Site A. That deviation is difficult to analyze because the Reference condenser entering temperature sensor failed at this site. The other deviations do not exceed 2°F (1°C).

The other measurement necessary to determine the target superheat is the wet-bulb temperature of air entering or that will enter the evaporator. There are major differences between methods in how they measure this quantity:

- Reference uses a thermistor and a relative humidity (RH) sensor in the return plenum.
- Method 1 does not measure this parameter.
- Method 2 uses the average of all RH and temperature measurements at the return grilles.
- Method 3 uses a thermocouple surrounded by a wet cotton sleeve in the return plenum.

Method 2 does not account for the effects of duct leakage, because it measures the temperature at the return grille instead of within the plenum. In systems with substantial return duct leakage such as Sites A and D (17 and 33% respectively), we expect Method 2 will measure a lower wet-bulb temperature, which will result in a target superheat that is lower than it should be. However, there is very little difference in the wet bulb temperatures, no matter what measurement methodology is used. Part of this is because Sites A and D have most of their ducts in a crawlspace and garage respectively, which are buffer spaces with similar temperature and humidity conditions as the house. If the ducts had been located in a hot attic, one would expect a substantial effect. In any case, from this small sample, there seems to be no effective difference between the various measurement techniques for this quantity.

Determining the Actual Superheat: There is much more consistency with how the three methods measure parameters that determine the actual superheat value. To establish the actual superheat, each method measures the temperature of the suction line near the service port at the compressor and the pressure in the suction line at this service port. The suction line pressure is then converted to a vapor saturation temperature using a standard vapor saturation temperature chart. The difference between the suction line and vapor saturation temperatures is the actual superheat. Table A14 lists the measured suction line pressures and Table A15 lists the associated saturation temperatures and the measured suction line temperature.

Several patterns are clear from these data. Differences in suction line pressures (up to 6 psig, 41 kPa, or 11%) are sometimes greater than we expect based on the accuracy that is achievable for the types of gauges used. This means that vapor saturation temperatures will also be noticeably different. In the case of the largest pressure difference (Site C as found), there is a corresponding 5°F (3°C) difference in calculated vapor saturation temperatures, which will contribute to a 5°F (3°C) difference in actual superheat. Method 3 uses 5°F (3°C) as the expected accuracy of measurement of actual superheat.

To determine if the variation in pressures between different methods was due to gauge accuracy, we checked the calibration of the pressure gauges and transducers using a Heise pressure gauge (accuracy ± 0.6 psig (4 kPa)) and helium gas at various pressures. There were very small differences of 1 to 4 psig (7 to 27 kPa) between the gauges at typical suction pressures. The larger errors occurred with the Method 2 pressure transducer. The gauges and transducer used in the reference as well as Methods 1 and 3 had errors less than 2 psig (13 kPa), with 1 psig (7 kPa) errors being most common. All gauges exhibited a negative bias.

Table A14a. Measured pressures for determining "as found" actual superheat.

Method	Suction Line Pressure [psig (kPa)]			
	Site A	Site B	Site C	Site D
Ref.	59 (410)	58 (400)	57 (390)	45 (310)
1	63 (430)	63 (430)	51 (350)	49 (340)
2	62 (430)	58 (400)	-56[1]	45 (310)
3	62 (430)	63 (430)	NA[2]	-

[1]This value is erroneous and was traced to a computer error in Method 2.

[2]Either operator error or a computer error caused the Method 3 data to be missing for Site C as found.

Table A14b. Measured pressures for determining "post-charging" actual superheat.

Method	Suction Line Pressure [psig (kPa)]			
	Site A	Site B	Site C	Site D
Ref.	67 (460)	70 (480)	78 (540)	64 (440)
1	69 (480)	70 (480)	78 (540)	66 (460)
2	69 (480)	67 (460)	NA[1]	64 (440)
3	68 (470)	NA[2]	78 (540)	-

[1]A computer error caused the Method 2 data to be missing for Site C post-charging.

[2]Either operator error or a computer error caused the Method 3 data to be missing for Site B post-charging.

Given the consistency of pressure gauges during calibration, we do not know why there are pressure differences between methods in the "as found" cases. We hypothesize that measurements at slightly different times under changing operating conditions might be the cause of these pressure differences. Unfortunately, we did not continuously monitor refrigerant pressure. However, periodic fluctuations in suction and liquid line temperatures during the tests seem to provide evidence in support of our hypothesis.

In particular, at Site C post-charging, we observed pulsating variations in suction line temperature with an amplitude of as much as 4°F (2°C) with a period of about 2 to 3 minutes peak to peak (see Figure A16). This does not mean that the vapor saturation temperatures (and therefore pressures) varied as much, but it does indicate that they would be varying. One might ask then, if pressures are varying, why are the pressures measured by each method after charge correction identical (Table A15b), and why is there almost no variation over time in suction line temperature before charge correction.

Table A15a. Measured temperatures for determining "as found" actual superheat.

Method	Vapor Saturation Temperature [°F (°C)]				Suction Line Temperature [°F (°C)]			
	Site A	Site B	Site C	Site D	Site A	Site B	Site C	Site D
Ref.	34 (1)	32 (0)	32 (0)	22 (-6)	73 (23)	79 (26)	84 (29)	68 (20)
1	36 (2)	36 (2)	27 (-3)	25 (-4)	74 (23)	76 (24)	84 (29)	68 (20)
2	35 (2)	32 (0)	-28[1]	22 (-6)	65 (18)	77 (25)	87 (31)	68 (20)
3	37 (3)	35 (2)	NA[2]	-	75 (24)	76 (24)	NA[2]	-

[1]This value is erroneous and was traced to a computer error in Method 2.

[2]Either operator error or a computer error caused the Method 3 data to be missing for Site C as found.

Table A15b. Measured temperatures for determining "post-charging" actual superheat.

Method	Vapor Saturation Temperature [°F (°C)]				Suction Line Temperature [°F (°C)]			
	Site A	Site B	Site C	Site D	Site A	Site B	Site C	Site D
Ref.	39 (4)	40 (4)	47 (8)	36 (2)	47 (8)	45 (7)	56 (13)	46 (8)
1	40 (4)	41 (5)	46 (8)	39 (4)	48 (9)	48 (9)	59 (15)	46 (8)
2	39 (4)	39 (4)	NA[1]	37 (3)	43 (6)	44 (7)	NA[1]	45 (7)
3	40 (4)	NA[2]	47 (8)	-	48 (9)	NA[2]	56 (13)	-

[1]NA = Not Available. A computer error caused the Method 2 data to be missing for Site C post-charging.

[2]Either operator error or a computer error caused the Method 3 data to be missing for Site B post-charging.

Regarding the variability in the pressure signal, the agreement between methods might simply be fortuitous, such that the measurements happened to occur at times when the pressures matched. Regarding the relatively constant as-found suction pressure, a possible explanation is that the small temperature differences between the refrigerant vapor and outdoors associated with the undercharge found at this site caused poor heat transfer in the suction line. This tends to mask the effect of pressure fluctuations on suction line temperature. This effect is not masked for the liquid line, because there are substantial temperature differences between the subcooled liquid refrigerant and outdoors. In addition, the heat transfer effectiveness from the subcooled refrigerant to the liquid line tubing wall is greater than that for the superheated refrigerant vapor to the suction line, because of the higher specific heat of the liquid.

The suction line temperatures in Table A15 show about the same amount of variation as the vapor saturation temperatures, but in a different pattern. Unlike the pressure measurements on which the latter temperatures are based, each method uses a different device to measure the suction line temperature and it is a much more complex parameter to measure.

- Reference uses a thermistor that is cable-tied to the suction line and insulated.
- Method 1 uses a large proprietary temperature sensor with an elastic clamping mechanism.
- Method 2 uses an RTD sensor that is cable-tied to the suction line and insulated.
- Method 3 uses a thermocouple that is taped to the suction line and insulated.

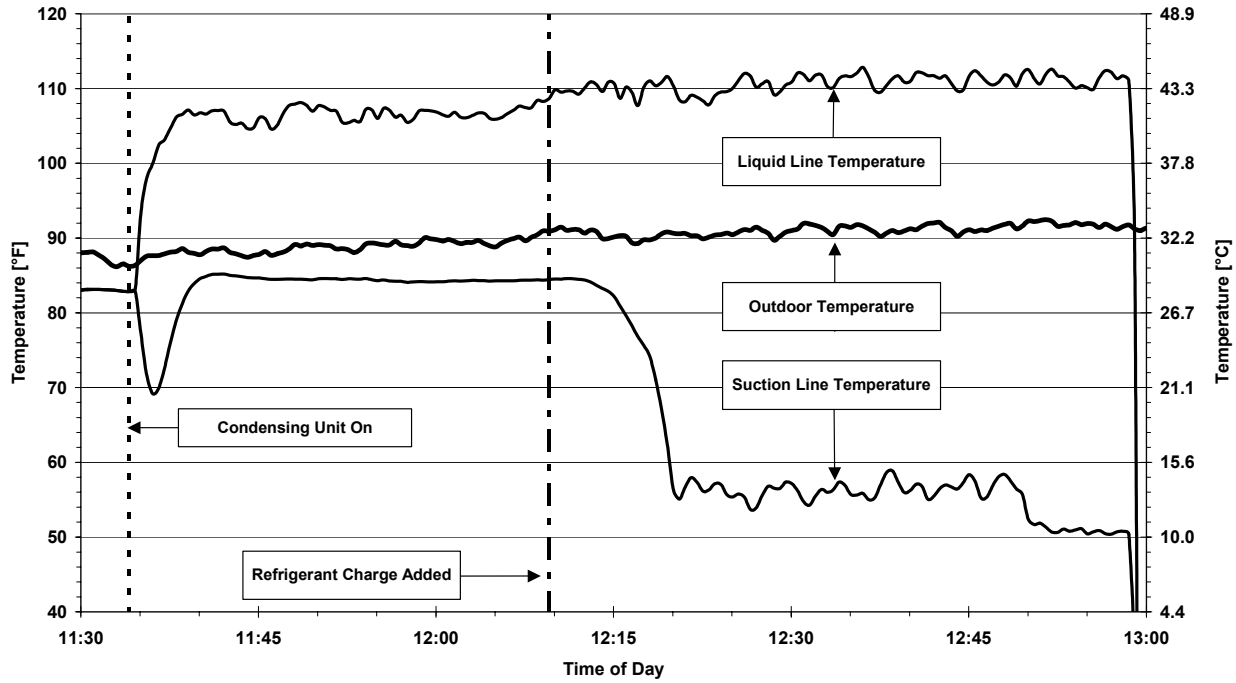

Figure A16. Site C field data.

The actual quantity needed is the temperature of the refrigerant inside the copper refrigerant line. However, this quantity is not measurable directly, so all methods measure the outside wall temperature of the copper tubing, assuming that the turbulence in the refrigerant and the high conductivity of the copper will transfer heat well from the refrigerant to the external sensor. Three heat transfer issues complicate this type of measurement:

- One issue is adequate contact between the sensor and the wall of the copper tube. All of the devices have some sort of clamping system to assure a close fit, but local variations in the copper surface as well as dirt accumulation or oxidation on the surface can add a contact resistance. This resistance leads to a higher temperature reading for the suction line than might otherwise occur. For some of the houses, we used heat sink compound with the Reference sensors. We found in the field, as well as in subsequent laboratory tests, that heat sink compound improved the temperature reading, but not significantly. Cleaning the heat sink compound off the lines after the test to avoid leaving an unsightly mess is time consuming. As a result, we do not recommend using heat sink compound for the superheat test.
- A more significant issue is whether the sensor is insulated. In particular, the Method 1 sensor has a high profile that makes insulating it difficult, but it already had a large plastic housing that provided some amount of insulation.
- Thermal mass of the temperature sensors is also an issue. Although all of the air conditioning systems operated for at least 15 minutes before each test (a requirement of the Method 3 software), we expect that the pressure and temperature of the refrigerant was still changing slightly even during the test (see Figure A16 for an example of this phenomena). Some of the temperature sensors, particularly the Method 1 sensor, had a very large mass. Such sensors

have a slower response to temperature changes than a smaller sensor (e.g., the thermocouple used for Method 3).

Target and Actual Superheat with Deviation above Target: Combined, the results from the preceding sections determine the target superheat, the actual superheat, and the deviation from the target superheat (Actual – Target). These results appear in Tables A16 and A17. Method 1 results are excluded from Tables A16a and A16b because this method does not provide a target superheat.

Table A16a. "As found" target and actual superheats.

Method	Target Superheat [°F (°C)]				Actual Superheat [°F (°C)]			
	Site A	Site B	Site C	Site D	Site A	Site B	Site C	Site D
Ref.	8 (4)	9 (5)	11 (6)	14 (8)	39 (22)	47 (26)	52 (29)	46 (26)
1[1]	-	-	-	-	38 (21)	40 (22)	57 (32)	43 (24)
2	5 (3)	7 (4)	9 (5)	11 (6)	30 (17)	45 (25)	115[2]	47 (26)
3	10 (6)	11 (6)	NA[3]	-	38 (21)	41 (23)	NA[3]	-

[1]Method 1 does not calculate a target superheat

[2]This value is erroneous and was traced to a computer error.

[3]Either operator error or a computer error caused the Method 3 data to be missing for Site C as found.

Table A16b. "Post charging" target and actual superheats.

Method	Target Superheat [°F (°C)]				Actual Superheat [°F (°C)]			
	Site A	Site B	Site C	Site D	Site A	Site B	Site C	Site D
Ref.	8 (4)	5 (3)	10 (6)	10 (6)	8 (4)	5 (3)	9 (5)	10 (6)
1[1]	-	-	-	-	8 (4)	7 (4)	13 (7)	8 (4)
2	5 (3)	5 (3)	NA[2]	10 (6)	4 (2)	7 (4)	NA[2]	8 (4)
3	7 (4)	NA[3]	10 (6)	-	8 (4)	NA[3]	9 (5)	-

[1]Method 1 does not calculate a target superheat

[2]A computer error prevented the Method 2 from saving the data for Site C post-charging.

[3]Either operator error or a computer error caused the Method 3 data to be missing for Site B post-charging.

Discussion

Based on our results, we recommend that Method 1 not be used for superheat tests of residential cooling systems at this time. One reason is that Method 1 does not report a target superheat. Instead, it reports a qualitative text string related to charge deviation: high, low, or acceptable (denoted as Hi, Lo, or Ok, with a modifying plus or minus sign to indicate whether it is a little bit high or low), or N/A, which means that the input data that Method 1 uses to calculate the target are outside an acceptable range. For this reason, the superheat target values exclude Method 1.

Table A17a. "As found" deviation above target superheat.

Method	Deviation above Target Superheat [°F (°C)]			
	Site A	Site B	Site C	Site D
Ref.	31 (21)	38 (21)	41 (23)	32 (18)
1[1]	N/A	Hi++	N/A	N/A
2	25 (14)	38 (21)	106[2]	36 (20)
3	28 (16)	30 (17)	NA[3]	-

[1]Key to Method 1 results: N/A means Not Applicable/Out of Range, Hi++ means very high

[2]This value is erroneous and was traced to a computer error.

[3]Either operator error or a computer error caused the Method 3 data to be missing for Site C as found.

Table A17b. "Post charging" deviation above target superheat.

Method	Deviation above Target Superheat [°F (°C)]			
	Site A	Site B	Site C	Site D
Ref.	0 (0)	0 (0)	-1 (-1)	0 (0)
1[1]	Ok-	Lo	Lo	Ok-
2	-1 (-1)	2 (1)	NA[1]	-2 (-1)
3	1 (1)	NA[2]	-1 (-1)	-

[1]Key to Method 1 results: OK- means the reading is fine, but a little low, Lo means that the reading is low.

[2]A computer error prevented the Method 2 data from being saved for Site C post-charging.

[3]Either operator error or a computer error caused the Method 3 data to be missing for Site B post-charging.

The use of text strings is not a problem by itself. However, for three of the four "as found" cases, Method 1 listed N/A in response to its actual superheat test, even though the systems (including the two brand new ones) were substantially undercharged. Furthermore, it reported other problems to be more important than the undercharge, so it did not give a complete diagnosis. This indicates that Method 1, when configured as when we tested, has very limited utility for assessing the refrigerant level in residential cooling systems. It is important to note that our analysis is limited to assessing charge levels. Method 1 might be very useful at locating important problems with air conditioning systems, but, without a measured entering wet bulb temperature, it does not seem appropriate for the specific problem of diagnosing refrigerant charge problems.

A more troubling problem with Method 1 is that its web data analysis sometimes differs from the PDA field analysis or its diagnoses are wrong. For example, all the cases that the PDA listed as N/A in the field were later diagnosed as undercharged by the web data analysis. Furthermore, at Sites B and C post-charging, Method 1 indicated the charge level was "Lo", which is contrary to the correctly charged condition indicated by the other methods. Having a technician obtain a

diagnosis in the field, repair the equipment according to that diagnosis, and then find out later that there was a different diagnosis that may eliminate the need for the repair or worse, indicate that the repair should not have been performed, is a severe shortcoming. The "mutating" diagnosis problem is probably easy to rectify by better coordinating the diagnoses of the PDA software and the web site. However, the incorrect indication of charge level may be more difficult to rectify. Until these problems are solved, the method is unreliable for assessing charge levels in residential cooling systems.

Regarding Methods 2 and 3, uncertainties in the measurements lead to variations in target superheat, actual superheat, and superheat deviation between methods. These variations are as much as 5°F (3°C) for target superheat (Site A as found), 9°F (5°C) for actual superheat (Site A as found), and 8°F (4°C) for superheat deviation (Site B as found). As a comparison, laboratory test data from Farzad and O'Neal (1988) for capillary-tube-controlled equipment indicate a 10ºF (6ºC) error in superheat deviation can result in a charge assessment difference of about 5 to 9%, depending on outdoor temperature.

In spite of these variations, Methods 2 and 3 agree on their diagnoses and should result in similar actions to correct charge deficiencies. As a result, the variations described above may seem less significant. However, at all four sites in this study, the air conditioners were so undercharged (about 15 to 30%) that even the smallest "as found" deviation (25°F (14°C) for Method 2 at Site A) indicates a substantial problem, and the agreement in diagnoses should be expected. This raises a question of whether the methods would perform as well for air conditioners that were better charged. Examining the post-charging cases in Table A17b offers a partial answer. Where comparisons are possible, the post-charging superheat deviations never differ by more than 2°F (1°C), which suggests that Methods 2 and 3 will produce very similar results for correctly charged systems.

Charge Effects on Equipment Performance: Table A18 shows the "as found" and "post-charging" total cooling capacities, energy efficiency ratios (EER), and power consumption that we measured or calculated, as well as the fractional changes in these parameters due to charging. A small amount of the changes in power draw, capacity, and EER can be attributed to small changes that occurred in ambient and outdoor temperatures between the "as found" and "post charging" conditions. Tables A13a and A13b list those temperatures.

The fractional charge increases listed in Table A18 are based on the total amount added divided by the factory charge listed by the manufacturer on the equipment rating plate. At Site D, this rating was not available. Service technicians should record on the rating plate the actual amount of charge that they have installed. Many rating plates have space explicitly available for this purpose. However, our field experience indicates that this is rarely done.

The capacities, efficiencies, and power draws in Table A18 are based on detailed measurements of air-handler airflow, supply and return temperatures and humidity, and power consumption made as part of the Reference measurements. We did not measure power consumption at Site D, because we could not safely connect our current and voltage sensors to the cooling equipment. As a result, we could not assess efficiency changes at Site D.

Table A18. Summary of cooling equipment performance.

		Site A	Site B	Site C	Site D
Charge Added [oz (kg)]		15 (0.2)	11 (0.3)	20.5 (0.6)	19 (0.5)
Fraction of Total		17%	13%	33%	Unknown
Air-Handler Airflow [cfm (L/s)]		1,240 (587)	1,260 (593)	1,320 (623)	780 (368)
Capacity	"As Found" [tons (kW)]	2.1 (7.4)	2.2 (7.7)	2.4 (8.4)	1.7 (6.0)
	"Post Charging" [tons (kW)]	2.8 (9.8)	2.6 (9.1)	3.3 (12)	2.3 (8.1)
	Fractional Improvement	33%	18%	38%	35%
EER	"As Found" [Btu/Wh]	5.2	7.0	8.8	N/A
	"Post Charging" [Btu/Wh]	6.2	7.5	10.6	N/A
	Fractional Improvement	19%	7%	20%	N/A
Total Power Draw Increase [Btu/h (W)]		1,840 (538)	965 (283)	1,495 (438)	N/A
Fractional Increase		11%	7%	13%	N/A

As expected, properly charging the cooling equipment significantly improved performance in terms of increasing capacity and efficiency. After charging, total cooling capacity improved by 18 to 38% and EER improved by 7 to 20%. Power consumption increased substantially after charging (increases of 280 to 540 W, or 7 to 13%). While this might seem to be a cause for concern to utilities in terms of peak electrical load, it is important to recognize that the increased capacity resulting from proper charging means that typically oversized cooling equipment is less likely to operate at its full-load. Proper charging thus increases the diversity of the aggregate air-conditioning-related load when the performance of many houses is considered together, which effectively reduces the utility peak.

An interesting result from this research is that two of these systems (Site C and Site D) were so undercharged that their vapor saturation temperatures were below 32°F (0°C). This temperature approximates the evaporator surface temperature. As a result, the evaporators iced up during the "as found" tests. We expect this greatly limited the airflow through the systems. Had we measured the airflows while the coils were iced up and included that effect in our capacity calculations, the "as found" capacities for Sites C and D would be even lower than those reported in Table A18. The systems in Sites B, C, and, particularly, D were already prone to icing even with proper charge due to their low airflow (314, 330, and 222 cfm/ton respectively).

Summary

The importance of refrigerant charge to residential cooling performance is clear, as is the need to use a superheat test. Methods 2 and 3 correctly assess refrigerant charge levels. At this time, Method 1 seems inappropriate for assessing refrigerant charge levels of residential cooling equipment. Note that the reference method is too complicated and time intensive for a service technician to consider it as a practical alternative. However, this is not really a consideration, because it is intended only for research use.

There are problems with all of the methods, such as lost data for Methods 2 and 3, and some problems with deviations in pressure and temperature measurements. In the short term, diligence

on the part of the service technician and the use of well-developed, reliable automation techniques seem to be the best solutions to these problems.

To address the significant performance degradation associated with refrigerant charge, we recommend that the building industry develop a standard method or methods to assess refrigerant charge. The results of this project suggest that the challenge will be to design a robust tool that works in most field conditions, rather than to measure the required quantities accurately enough. In particular, research is needed to develop a method of assessing refrigerant charge in cool weather. The utility of temporarily elevating indoor enthalpy also needs to be examined to extend the periods when the superheat method can be used to test cooling equipment in hot, dry climates. Ultimately, the performance of residential air conditioning systems would be dramatically improved by the development, application, and contractor training of a standard methodology to conduct refrigerant charge testing.

APPENDIX B: FOOTNOTES TO DIAGNOSTICS OVERVIEW

Table 1a: Footnotes

Case	Advantages	Disadvantages
Y01	Well developed, simple, rapid, inexpensive	Visual aspect is qualitative, less useful for unexposed areas of existing buildings
Y02	Well developed, inexpensive, integrated temperature measurement	Poorly-defined viewing area, time consuming, same problems as infrared thermography
Y03	Well developed, shows wide-area temperature variation	Expensive; uncertainty due to surrounding radiative and convective environment, unknown surface emissivity, moisture
N01	Well developed, simple, inexpensive, quantitative	Time consuming, less useful for unexposed areas of existing buildings
N02	Naturally- or artificially-driven portable conductance measurement	Research tool, time consuming, complex analysis, small homogeneous section without airflows
N03	Naturally-driven conductance measurement	Many transducers, temperature limitations, possible surface damage, same problems as ETTU
N04	Well developed, large non-homogeneous section with airflows	Research tool, expensive, time consuming, non-portable
N05	Overall envelope conductance including air intrusion and infiltration effects	Time consuming, cannot separate component conductances
N06	Well developed, integrated section conductivity	Research tool, expensive, time consuming, non-portable, small homogeneous section without airflows
N07	Well developed, integrated section conductivity	Research tool, expensive, time consuming, non-portable, small homogeneous section without airflows
Y04	Simple, rapid	Does not quantify emittance, interference by wide gaps & some glazing types, spectrometer requires commercialization
Y05	Well developed, simple, rapid, inexpensive	None identified
Y06	Well developed, simple, rapid, inexpensive	None identified
Y07	Well developed, simple, rapid	Accuracy affected by wind gusts
N08	Well developed, more rapid than multipoint blower door	No accuracy check, accuracy affected by wind gusts
N09	Well developed, reduces wind effects on leakage measurement	Expensive, complex analysis, time-consuming, not easily portable or commercially-available
N10	Potentially rapid	Complex analysis, not well-developed or commercially available, unknown accuracy
Y08	Well developed, rapid, inexpensive	Does not quantify leakage velocity or internal path location, smoke can cause irritation and material damage
Y09	Rapid, can locate internal leakage paths	Same problems as infrared thermography for opaque assembly deficiencies
N11	Quantifies component leakage	Poor leak location resolution, time consuming, uncertainty may exceed component leakage, possible surface damage
N12	Quantifies leakage velocity	Time consuming, expensive
N13	Rapid; no envelope pressure changes, so less affected by wind	Expensive and delicate equipment
N14	Rapid, inexpensive	Poor magnitude sensitivity, especially for exfiltrating leaks
Y10	Rapid, inexpensive	Qualitative, less useful for new buildings, cannot inspect closed assembly cavities without damage
Y11	Well developed, rapid, inexpensive, no damage, wide area	Qualitative, material dependence, limited scan depth, existing buildings only
Y12	Well developed, quantitative, inexpensive, accurate	Point-by-point, time consuming, surface damage, material dependence, existing buildings only
N15	Inexpensive	Qualitative, time consuming, small area, possible surface damage, existing buildings only
N16	Wide-area	Not well-developed, qualitative, same problems as infrared thermography for opaque assembly deficiencies, existing buildings only

Table 1b: Footnotes

Y13	Well developed, simple, inexpensive, usable for unfinished houses, low wind sensitivity	Time consuming, potential for grille and supply-return seal integrity failure, duct pressure uncertainties
Y14	Simple, rapid, inexpensive, no sealing required, also measures envelope leakage	New test (requires further evaluation), wind gust uncertainty, usable only for finished houses
N17	Well developed, inexpensive	Complex, time consuming, usable only for finished house with single return, wind gust uncertainty
N18	Inexpensive, usable with multiple returns	Complex, time consuming, usable only for finished houses, wind gust uncertainty, new test
N19	Well developed, simple, rapid	Qualitative, unreliable
Y15	Well developed, simple, inexpensive	Time consuming, sometimes requires sealing supply from return
Y16	Rapid, simple, inexpensive	New device (requires further evaluation)
N20	Well developed, simple, inexpensive	Time consuming, needs correction for duct leakage, depends on type of flow hood used
N21	Well developed, simple, rapid, inexpensive	Airflow mixing problems, radiant temperature errors, refrigerant charge dependency
N22	Simple	Time consuming, expensive elaborate fragile equipment, airflow mixing problems
N23	Simple, rapid, inexpensive	Unreliable, performance data unavailable or inappropriate for fan as installed
Y17	Simple, rapid, inexpensive, no backpressure, no seal, complete flow capture	Well developed but not commercially available
N24	Well developed, simple, rapid, inexpensive, complete flow capture	Uncertainty due to backpressure, seal leakage, metering element fouling, and recirculation
N25	Well developed, simple, rapid, inexpensive, no backpressure, no seal, complete flow	Uncertainty due to unknown effective area, flow direction, and inertial effects
N26	Well developed, simple, rapid, inexpensive	Requires in-situ calibration, subject to fouling, permanent fixture, uncertainty due to duct leakage downstream
N27	Well developed, simple, rapid, inexpensive	Poor or no access to duct, uncertainty due to duct leakage downstream, flow area, and insertion depth
N28	Well developed, simple, inexpensive, no backpressure, complete flow capture	Time consuming, timing and bag volume uncertainties
N29	Well developed	Time consuming, same problems as duct leakage, air-handler airflow, and duct airflow diagnostics
N30	Well developed	In-situ analysis expensive (elaborate fragile equipment), laboratory analysis less expensive, room mixing problems, weather dependent

Table 1c: Footnotes

Case	Advantages	Disadvantages
N31	Well-developed	Expensive, time consuming (new devices to reduce time require further evaluation), sensor location uncertainties
N32	Potentially simple test	Not well-developed, time consuming, unknown accuracy
Y18	Well developed, rapid, inexpensive	Cool and hot dry weather limitations, requires measuring several parameters
Y19	Well developed, simple, inexpensive, no weather limitation, accurate for matched coils	Time consuming, poorly defined norm for mismatched coils
N33	Simple, inexpensive	Qualitative, unreliable, cannot be used to detect overcharging, not usually available on residential systems
N34	Simple, inexpensive	Qualitative, unreliable, dry weather limitation, cannot be used to detect overcharging
N35	Quantitative	Not well developed, unknown repeatability, complex
N36	Rapid, simple, quantitative	Expensive, measure several parameters, new device (requires further evaluation)

Table 1d: Footnotes

Y20	Well developed, simple, rapid, inexpensive, quantitative	Some components inaccessible without disassembling building
Y21	Simple, rapid, inexpensive	Affected by wind gusts, prescribed limits may not represent installed equipment
Y22	Simple, rapid, inexpensive	Affected by wind gusts, prescribed limits may not represent installed equipment
Y23	Simple, rapid, inexpensive	Affected by wind gusts, prescribed limits may not represent installed equipment, CO hazard
Y24	Simple, inexpensive, determines equipment limits	Time consuming, affected by wind gusts, CO hazard
N37	Inexpensive, determines actual performance over time	Complex, time consuming, no norm
N38	Well developed, simple, rapid, inexpensive	Short-term test, lack of established protocols
N39	Well developed, inexpensive, addresses long-term flows	Complex, time consuming to determine pressure limits, lack of established protocols
N40	Well developed, inexpensive, addresses long-term flows	Complex, time consuming to determine pressure limits, some duct pressure loss data not available
N41	Well developed, inexpensive	Same problems as duct airflow diagnostics
N42	Well developed, inexpensive	Same problems as duct airflow diagnostics
N43	Inexpensive	Qualitative, some regions of heat exchanger inaccessible
N44	Inexpensive	Qualitative, no norm
N45	Well developed, simple, rapid, inexpensive	Hazardous (requires license to open gas line)
N46	Well developed, simple, inexpensive	Time consuming, high-limit switch can prevent steady-state operation
N47	Well developed, inexpensive	Time consuming, same problems as air-handler airflow diagnostics, high-limit switch can prevent steady-state operation
N48	Well developed, simple, inexpensive	Time consuming, high-limit switch can prevent steady-state operation
N49	Well developed, simple, rapid, inexpensive	Qualitative, not reliable indicator for burner adjustment
N50	Well developed, inexpensive	Complex, time consuming, high-limit switch can prevent steady-state operation, poor regional norms
N51	Well developed, inexpensive	Complex, time consuming
N52	Well developed, inexpensive	Complex, time consuming, difficult to use in occupied house, poor norm

Table 1e: Footnotes

Case	Advantages	Disadvantages
N53	Well developed, simple, inexpensive	Spot measurement (requires sensors in multiple locations)
N54	Wide area view	Not well developed, complex, time consuming, same problems as infrared thermography for opaque assembly deficiencies
N55	Well developed, simple, rapid, inexpensive	Not for dry locations (<20% RH), requires frequent calibration & constant water supply, no datalogging capability
N56	Well developed, simple, rapid, inexpensive, no water supply required	Not for use in humid locations (>95% RH), requires frequent calibration
N57	Well developed, rapid, requires only infrequent calibration, no water supply required	Expensive, delicate, requires regular cleaning
N58	Well developed, simple, rapid, quick response, omnidirectional	Expensive, delicate, subject to fouling, spot measurement (requires sensors in multiple locations)
N59	Well developed, inexpensive, omnidirectional	Time consuming, slow response, no datalogging capability, spot measurement (requires sensors in multiple locations)
N60	Well developed, inexpensive	Very slow response, can't detect low flows, directional
N61	Well developed, better approximation of human body convective/radiative response	Expensive, directional
N62	Well developed, inexpensive, omnidirectional	Poor approximation of human body convective/radiative response
N63	Well developed	Expensive, directional, poor approximation of human body convective/radiative response
N64	Well developed, simple, rapid, inexpensive	Qualitative, cannot detect some sources
N65	Well developed, rapid, quantitive, detects selected sources	Complex relation between concentration and source strength, expensive for some contaminants
N66	Well developed, simple, rapid, inexpensive	Qualitative, cannot detect some sources
N67	Well developed, rapid, quantitive, detects selected sources	Complex relation between concentration and source strength, expensive for some contaminants
N68	Well developed	Same problems as duct airflow and air exchange diagnostics, does not address source strength or contaminant concentrations

Table 1f: Footnotes

N69	Well developed, simple, inexpensive, short-term response, in-situ analysis	Does not address exposure, requires frequent calibration
N70	Well developed, simple, short-term response, in-situ analysis	Expensive, does not address exposure, requires frequent calibration
N71	Well developed, simple, no calibration required, addresses exposure	Averaging loses critical peaks, pre/post test contamination, laboratory analysis
N72	Well developed, simple, no calibration required	Obscures critical peaks, does not address exposure, laboratory analysis
N73	Well developed	Expensive, does not address exposure, requires frequent calibration, poor indicator of average levels
N74	Well developed, simple, inexpensive, measures long-term exposure	Pre/post test contamination, laboratory analysis
N75	Well developed, simple, inexpensive, measures long-term exposure	Pre/post test contamination, laboratory analysis
N76	Well developed	Expensive, does not address exposure, requires frequent calibration, poor indicator of average levels
N77	Well developed, simple, inexpensive, measures longer-term average	Pre/post test contamination, laboratory analysis, does not address exposure
N78	Well developed, in-situ analysis	Expensive, does not address exposure or particle/bioaerosol type, particle concentration norm poorly defined
N79	Well developed, determines particle/bioaerosol type	Expensive, requires laboratory analysis, does not address exposure, particle concentration norm poorly defined
N80	Well developed, inexpensive	Requires laboratory analysis, does not address exposure, particle concentration norm poorly defined
N81	Well developed	Complex, expensive delicate equipment, requires species identification (total concentration (TVOC) norm poorly defined)

Table 1g: Footnotes

N82	Simple, rapid, inexpensive	Qualitative, not well developed, monitoring can be time consuming
N83	Simple, inexpensive	Qualitative, not well developed, plug load measurement can be time consuming

APPENDIX C: DISCUSSION OF EXCLUDED DIAGNOSTICS

Components and systems in a house that need commissioning include building envelopes, air distribution systems, cooling equipment, heat pumps, combustion appliances, controls, and other electrical appliances. Tables 1a through 1g in the main body of this report provide an overview of metrics and 107 diagnostics that we have considered in this project for residential commissioning. Indexed footnotes to the tables (Appendix B) summarize the advantages and disadvantages of each diagnostic. Our discussion here in Appendix C describes 83 of the diagnostics that we have examined, but have excluded because they are not ready or are inappropriate for residential commissioning.

BUILDING ENVELOPE

Envelope Assembly Deficiencies

Insulation Sampling: Extracting samples of insulation to assess the installed density of blown insulation in walls or ceilings is a well-developed, simple, inexpensive, and quantitative technique. However, it is time consuming and is not useable when insulation is unexposed. Extraction is done using a 6- to 12-inch (150 to 300 mm) diameter and up to about 2 feet (0.6 m) deep "cookie cutter". Procedurally, three samples are extracted from three or four cavities (nine to 12 samples in total). Samples must be allowed to air dry if insulation is blown in wet to reduce settling, such as stabilized blown cellulose insulation and blown-in-blanket fiberglass insulation used in walls. The drying requires several days. If the moisture content of the insulation as installed is of interest, the sample can be weighed to determine the difference in extraction weight and sample weight (NAHB 1997). The density of the dry sample is based on its dry weight divided by its volume. This metric can then compared to manufacturer's specifications. This technique cannot be easily used on foam-in-place (low- or medium-density polyurethane) installations, because removed insulation is difficult to replace.

Infrared Thermography: Field use of infrared thermography to evaluate insulation homogeneity (ASTM 1990) is limited and may not be repeatable for several reasons. These include:

- Ambient temperature can affect both the performance of the thermographic equipment and the amount of infrared radiation emanating from the surface of the subject. At very high or very low outdoor temperatures, when maximum indoor-outdoor temperature differences occur and an infrared detection system would be most useful, these systems become less stable. Low indoor-outdoor temperature differences do not provide images with high enough contrast to reliably detect building envelope deficiencies. Indoor-outdoor temperature differences should be at least 18ºF (10ºC) for at least 4 hours before scanning to allow detection of discernable differences.
- Changes in surface temperatures due to solar radiation can obscure thermal patterns that result from the transfer of heat through the building envelope due to indoor-outdoor air temperature differences. Exterior scans should be conducted at night. Interior scans can be conducted at night or on heavily overcast days.
- Objects exposed to solar radiation will store heat and then release it for some time after the surface no longer is in direct view of the sun. Time must be allowed for the stored heat to dissipate before starting the scan. The length of time depends on the object's thermal mass and on the temperature difference between the surface and its environment. Wood frame

walls with wood or aluminum siding may require as little as 2 hours to release stored heat; heavier construction with brick may require more than 6 hours.

- Wind-driven airflows along exterior surfaces, as well as interior surface airflows (caused by differences in surface temperature and room air temperature or by HVAC air distribution), can cause serious distortion of surface temperature patterns. Wind speed should be no more than 15 mph (24 km/h) to minimize their effect on the scan.
- Scanning is subject to complex interactions caused by differential heating or cooling rates of dry and wet areas. Dry areas will cool or warm faster due to lower thermal mass. However, dry areas will also be less conductive. As a result, it is difficult to resolve insulation anomalies from moisture differences. It is particularly difficult to use this technique on roofs, because standing water, roof repairs, and exhaust discharges can mask anomalies below.
- To determine temperature from a scan, the user must describe the emissivity of the scanned surface in a long-wave range (usually 8 to 12 μm). Estimating emissivity is difficult: oxidation, deposition of dust, rainwater, or other foreign matter, as well as surface temperature changes, can alter the surface and its emissivity. Low-emissivity surfaces do not provide good contrast.
- Scan distortions can occur due to the angle of viewing by the infrared camera, its distance from the scanned surface, and on the nature of the surface material, which may radiate specularly (differently in different directions). Although the exterior of walls can simply be viewed from the ground, viewing roofs is more complex. To view roofs at a perpendicular angle, mobile elevated platforms or aerial equipment (e.g., helicopter) must be used (Burch 1980). Due to the cost of that equipment, roof scans for an individual building tend to be impractical. Interior scans in existing occupied houses can be difficult due to the placement of furniture near walls.

Envelope Assembly Thermal Conductance

ETTU: The Envelope Thermal Test Unit (ETTU) is a field diagnostic tool (Sonderegger et al. 1981) based on the guarded hot box concept. This portable research device (not commercially available) can be used to determine the thermal conductance of an envelope section. The device uses two flexible blankets aligned with each other, with one on each side of the 2-foot (0.6 m) square test section. Each blanket contains two layers of heaters separated by a central low-thermal-mass insulating layer. Each blanket also contains several surface thermistors and heat flux sensors (thermistor pairs, each separated by a polystyrene slab that has a known thermal conductance). The blankets have a guard (insulated) perimeter region to reduce edge effects on the measurement section.

This method differs from a conventional hot box, which measures heat flows in response to preset steady-state temperatures. ETTU instead measures the temperature response of the envelope section to known heat flows. ETTU can determine the steady-state and dynamic response of an envelope section based on natural thermal driving forces or by cycling its heaters in dynamic tests using pink noise forcing functions (signal with continuous frequency spectrum and equal power in each octave or decade, which provides amplitude weighting toward the low-frequencies) with a semi-diurnal fundamental frequency. Most of the development work to date has focused on the response to artificial forcing functions. However, the artificial forcing has been found to create lateral conduction effects that are not easily analyzed (Modera et al. 1984).

Furthermore, air circulation within envelope cavities was also found to be problematic with this device.

An ETTU test does not require that the envelope section reach thermal equilibrium to determine thermal conductance, because complex frequency analyses (using Fourier transforms) are used in the analyses of test data. The average thermal conductance of an envelope test section can be calculated from either the steady-state or dynamic data. However, the device cannot determine the thermal conductance of or deficiencies in separate envelope elements within a test section. ETTU can also determine the time constant for an envelope section, which is a metric for thermal mass.

If this tool is to be used, it must be developed further to deal with lateral conduction and internal air circulation before being commercialized. In addition, the test must be made simpler and less time consuming (a typical test may take one to two days).

Heat Flux Transducer: Heat flux transducers can be used to determine a representative average thermal conductance for an envelope section with negligible lateral conduction (e.g., without wood framing members). As a result, this simple test can be applied to some opaque envelope assemblies, but is not applicable to windows, due to their three-dimensional heat transfer behavior, particularly in the edge of glass regions and in the frame. For use on opaque assemblies, some knowledge about the construction of the assembly must be available to avoid placing the sensor in an area of three-dimensional heat transfer (e.g., near thermal bridges such as wood framing components).

To calculate thermal conductance, the temperature on the envelope face of each transducer or the air temperature near each heat flux transducer must also be measured. Several transducers and sensors should be mounted over the area of the envelope section, because residential building envelopes typically have non-uniform heat flow. These devices need to be located over insulation cavities, but not over framing members.

A disadvantage of the test is that appropriately locating heat flux transducers and temperature sensors requires considerable experience and expertise. Infrared thermography and building plans are useful for determining appropriate locations for these devices (areas of average or extreme heat flow, areas where large surfaces have similar heat flow, and areas of one-dimensional heat flow). Further disadvantages of the test are that mounting individual heat flux transducers and temperature sensors is time consuming and their fastening to the envelope can cause surface damage.

Bias errors that are difficult to quantify can occur due to lateral conductive heat flow, air leakage, and air intrusion in envelope components, due to contact resistance, and due to the influence of heat flux transducers on surface characteristics. Pastes or gels can be used on transducers to reduce the contact resistance. Changes in surface characteristics can include additional thermal resistance due to the sensor, as well as mismatches in convective heat transfer coefficients and in emissivity. Coatings may need to be applied to the transducers so they better represent the characteristics of the envelope section being tested.

Instantaneous measurements using heat flux transducers cannot be used to determine the thermal conductance of an envelope section. Instead, recording equipment such as a data acquisition system must be used. In addition, without elaborate frequency analysis of the heat flux and temperature data, long time periods (several days) are required to obtain average thermal conductance based on average temperature differences and average heat fluxes, especially with

low temperature differences and high thermal mass or large diurnal temperature swings. Natural temperature differences may be too low at some periods of the year to provide a reliable measurement in less than a week for massive walls.

Hot Box: Hot box devices are research tools primarily intended for use in a laboratory on large (e.g., 8 ft by 8 ft, 2 m by 2 m) non-homogeneous envelope sections. These devices determine assembly thermal conductance under controlled steady-state air temperature, air velocity, and radiation conditions. They cannot determine the conductance of individual assembly elements, unless the elements are mounted within a subassembly of known thermal conductance (e.g., a window mounted in a well-characterized wall section).

A hot box is comprised of a metering chamber on one side of the test section and a climate chamber on the other side. The chambers are large, heavily insulated, and open on one side. A temperature-controlled guard chamber around the metering chamber is sometimes used to limit heat transfer across the metering chamber surfaces.

A computerized data acquisition system controls the environmental chamber and metering chamber guard region to maintain a steady temperature difference across the test section for a long enough period of time that the heat flux across the section is constant. To achieve thermal equilibrium, the test duration may be hours or days. The heat flux across the test section is determined by the heat input to or extraction rate from the metering chamber, which is required to maintain constant conditions. Cyclic operating conditions can also be used to determine the dynamic response of the envelope section. This device can create air velocities that are characteristic of natural or forced airflows parallel or perpendicular to envelope surfaces.

Bias errors can occur due to unmeasured lateral heat (flanking) losses at test section intersections with the chambers. Two- or three-dimensional thermal modeling of this region can be used to estimate the magnitude of the error.

Hot boxes are expensive, not portable, and not commercially available.

Whole-Building Tests: Janssen and Rasmussen (1985) developed a complex technique for determining the thermal conductance of the entire envelope. It relies upon temperature decay and rise during one- to two-hour-long furnace off and on periods respectively and the elimination of infiltration effects. Those effects are removed using infiltration diagnostics during the temperature decay and rise periods and using subsequent calculations.

Sandberg and Jahnsson (1995) describe a technique similar to that of Janssen and Rasmussen, but that does not involve furnace cycling. Instead, it characterizes the total heat loss rate of a house as it is normally operated by its occupants. Actual indoor-outdoor temperature differences and energy consumption are measured. Average heat loss per unit temperature difference is calculated from these data.

Saunders et al. (1994) also describe a related technique that is based on coheating. That technique involves maintaining constant indoor air temperatures using electric heaters and continuously measuring the input power for the heaters. Unlike Sandberg and Jahnsson, Saunders et al. remove infiltration effects. As a result, their technique separates out thermal conductance and is more useful for describing heat transfer characteristics at times other than just during the test.

The whole-building thermal conductance tests can be used as an overall compliance check. However, all of these tests are time consuming and require the use of computerized data

acquisition systems in conjunction with short-term monitoring. These tests require significant further development to make them practical for use in residential commissioning.

Envelope Material Thermal Conductivity

Guarded hot plates and heat flow meters are research tools primarily intended for use in a laboratory to measure the thermal conductivity of building materials. These devices are expensive, not portable, and not commercially available. The heat flow meter is less expensive than the guarded hot plate.

Guarded Hot Plate: A guarded hot plate has two isothermal cold plates at similar temperatures that are separated from a central isothermal hot plate by homogeneous test specimens. Non-homogeneous test specimens cannot be tested, because isothermal plate temperatures cannot be maintained with these specimen types. The edges of the plates and specimens are guarded from the surroundings by insulation. The entire apparatus is typically located in a controlled environmental chamber. A computerized data acquisition system controls the environmental chamber and plates to maintain a steady temperature difference across the specimens for a long enough period of time that the heat flux across the specimens is constant. To achieve thermal equilibrium, the test duration may be hours or days. Heat flux across the test specimens is based on measuring the heat input to the hot plate and heat extraction from the cold plates.

Heat Flow Meter: A heat flow meter is a comparative tool that is calibrated using specimens of known thermal conductivity. It provides more rapid determinations of thermal conductivity than a guarded hot plate, because it is a simpler device and does not need a surrounding controlled climate chamber.

The device has an isothermal cold plate that is separated from an isothermal hot plate by one or two homogeneous test specimens and one or two heat flux transducers. With one specimen, the heat flux transducers may be located on one or both plates adjacent to the test specimen. With two specimens, one heat flux transducer is located between the test specimens. Non-homogeneous test specimens cannot be tested, because isothermal plate temperatures cannot be maintained with these specimen types. The edges of the plates and specimens are guarded from the surroundings by insulation or guard heaters. In some cases, the entire apparatus is also located in a controlled environmental chamber. However, such a chamber is not necessary. A computerized data acquisition system controls the environmental chamber and plates to maintain a steady temperature difference across the specimens for a long enough period of time that the heat flux across the specimens is constant. To achieve thermal equilibrium, the test duration may be one or more hours, instead of days.

Envelope Airtightness

Interzonal and Series Leakage: Two or more blower doors operated simultaneously (one for pressure variation and flow measurement and the others as balancing fans) and/or varying the size of leakage openings can be used to determine interzonal leakage, such as between living spaces and the attic or between adjoining dwellings.

In terms of series leakage and air barrier location, blower doors in conjunction with spot pressure differential measurements can also be used to establish the boundaries of the pressure envelope within the envelope assemblies (Fitzgerald et al. 1994, Cummings 1998).

Interzonal and series leakage tests are time consuming and tend to be used in research applications. There are no standard protocols for their use.

AC Pressurization: The AC pressurization method of assessing envelope airtightness uses a piston assembly mounted in a door or window opening to alternately force air into and out of a building (Sherman and Modera 1986). The device is a research tool and is not commercially available.

Piston movement varies the effective volume of the building. The device creates small (less than 4 Pa) pressure differentials typical of those driving infiltration in buildings. To determine the envelope airtightness, analyses compare the pressure response of the building to piston movement, with corrections for compressibility of the air and structural flexing due to oscillating pressure changes.

Synchronous detection (comparison of building pressure frequency response only at the driving frequency of piston) has the advantage that it reduces the interference from wind effects. As a result, this test is more accurate than using a blower door. However, compared to using a blower door, AC pressurization requires equipment that is more elaborate and less portable and analyses that are more sophisticated. It is also more time consuming than a blower door test.

Pulse Pressurization: The pulse pressurization method (Modera et al. 1987) uses a rapid release of air from a container (e.g., compressed air tank) located within the building to create a pressure pulse. The associated pressure response of the building is monitored using a microphone and spectrum analyzer that includes a data acquisition system. Subsequent analyses then compare this response to the pressure pulse to determine envelope airtightness.

The method is not well developed and is not commercially available. Preliminary tests have been carried out by LBNL to evaluate this method, but no field protocol exists. The accuracy of the method is unknown. A disadvantage of this method is that it requires equipment that is more elaborate and analyses that are more sophisticated than those associated with a blower door test. However, it is potentially less time consuming than a blower door test.

Leakage Site Detection: Smoke bombs can be used to locate leaks more rapidly than smoke tubes. However, they are more expensive than smoke tubes and the amount of smoke released must be carefully controlled to avoid difficulties in visualizing leaks, surface contamination, and triggering smoke alarms. The smoke must also be mixed so it is near leak entries and exits. Tracer gases can be used as an alternative to smoke. This more complex technique requires that the indoor air be seeded first before using an active tracer gas detector outdoors, which is expensive and fragile. This technique has all the problems described later in this appendix on using a tracer gas to determine air exchange rates, plus those described above when using smoke.

The most time consuming technique is to mask off regions of the building envelope that are suspected of containing leaks. Differences in airtightness determined using blower door tests can then indicate the magnitude of the leakage. A disadvantage of the test is that small differences between blower door tests might result from test uncertainty rather than the presence of leaks. Another disadvantage is that the technique only indicates that a region is leaky, but does not provide specific information on leak location unless small regions are masked off. Furthermore, in some cases, sealants used in masking off the envelope may cause material damage. A related technique is on-site sealing of leaks, which has the advantages of no material damage and the improvement of the building envelope.

Another method is to use a hot-wire anemometer while pressurizing or depressurizing the building using a blower door. The anemometer has the added advantage that it can quantify leakage velocities, which can be used to indicate the size of a leak. This technique however

requires that the anemometer be held still for each measurement to avoid confusing anemometer motion with the presence of a leak. As a result, this technique is more time consuming. It also requires more elaborate and expensive equipment, which may not be justifiable by the ability to quantify leakage velocity. As with the smoke and tracer methods, a limitation is that knowledge of likely leak locations is required to minimize the search effort.

Acoustic techniques can also be used to locate leaks. A commercially-available sound detection device such as an ultrasonic probe can be moved over the exterior surface while an associated sound generator placed indoors generates a signal of suitable frequency and amplitude. The generated signal should not be at a frequency that is obscured by ambient noise. The positions of the generator and probe can be reversed to locate interior leak entries and exits. This technique has the advantage that it is rapid, does not require envelope pressurization or depressurization, and is less affected by wind. However, it requires expensive and delicate equipment. As with smoke and tracer methods, a limitation is that knowledge of likely leak locations is required to minimize the search effort.

Draft sensation is a rapid, inexpensive technique to locate leaks, but it has poor magnitude sensitivity, especially for exfiltrating leaks.

Envelope Moisture

Surface Analysis using Impermeable or Absorbent Materials: Impermeable or absorbent materials can be used in qualitative comparative tests when evaluating envelope moisture problems (Lichtman et al. 1999). The “mat” test involves sealing an impermeable material such as polyethylene sheeting over a suspect surface. After a short period has elapsed (e.g., one day), the surface of the impermeable material is inspected for signs of wetness.

A more quantitative test uses a vapor emission and absorption method. A small airtight pre-weighed container containing absorbent material is sealed to the suspect surface. After about 60-72 hours, the container is weighed again. The weight change of the container (compared to the pre-test weight) indicates the amount of absorbed moisture.

Both tests are time consuming, but can be good indicators of high moisture content that warrants further investigation with a subsurface resistance probe. The most suitable use of these tests is to compare measurements from one region to another (e.g., a suspected wet region to a known dry region of similar material).

AIR DISTRIBUTION SYSTEMS

Duct Leakage

House Pressure Test: The house pressure test (HPT) (Walker et al. 1998a) measures the pressure changes across the building envelope and duct system due to air handler operation. It uses the house envelope as a flow meter and therefore requires envelope leakage to be measured also. Test time can be shortened if envelope leakage is not measured, but this reduces the accuracy, depending on how well the envelope leakage can be estimated.

This test is complex. It involves many pressure difference measurements, such as that between the supply and indoors when one supply grille is blocked using a pressure pan and that between the return and indoors across the filter at the return grille (or halfway between the return grille and plenum with the filter removed if the filter is not at the grille). Several configurations are used in the test (return open, supply open, air handler on and off; return open, supply blocked, air handler on; return blocked partially to achieve at least a 100 Pa pressure difference or fully

blocked, supply open, air handler on and off; and return blocked, supply blocked, air handler on). In each of these six cases, the pressure difference between the attic and indoors is measured ten times, and measurements are carried out with the air handler off and then on (60 attic-indoor pressure measurements). Averages of these attic-indoor pressure differentials are then used in subsequent calculations. Returns are blocked to avoid a problem: a balanced supply and return duct leakage will appear to be airtight, because the house pressure will not change when the air handler is turned on or off (supply leaks depressurize a house, whereas return leaks pressurize a house). A blocked return has no effect on an airtight system, but unbalances the supply and return leaks in a leaky system.

Most studies have found the accuracy of this test to be too poor for the results to be used in energy analyses (Walker et al. 1998a, Andrews et al. 1998, Francisco and Palmiter 1997). A major problem with this test is that it is sensitive to wind pressure fluctuations across the building envelope. These fluctuations are the same magnitude as the small pressures measured during the test and can violate assumptions used in the calculation procedure. In addition, test sensitivity is strongly dependent on envelope leakage.

The house pressure test should only be used on airtight houses (relative to outdoors and to the attic). A working definition of airtightness is that changes in the attic-indoor pressure difference should be more than 0.5 Pa between air handler "on" and "off" modes (with or without return sealed). In leaky houses, the test repeatability is poor, because the test precision is very sensitive to pressure measurement accuracy (uncertainties of even 0.1 Pa across ceiling can cause large fractional errors in calculated duct leakage). This uncertainty is due to using the difference between two ceiling pressure differences measured under different conditions, with a difference that is close to the instrument measurement resolution.

Another constraint on the use of the house pressure test is that it should only be used if the standard deviation of each group of 10 attic-indoor pressure differences is less than the differences between the means of each group. This check is an indicator of possible changes in weather-induced pressure differences over the course of the measurements and assesses whether groups of measurements represent the same data population.

To account for the bias caused by the neutral level shift when the air-handler fan is turned on, the duct leakage calculations for this method include a correction factor. A different factor is used depending on whether the ducts are at a high level or low level within the building. No correction is applied if the ducts are located at low and high levels. The correction increases calculated duct leakage for high level ducts and reduces its for low level ones. No correction is made for potentially large precision errors and the minor positive bias that is introduced by a variation in actual envelope leakage distribution from the assumed distribution (50% in floor and 50% in ceiling). The magnitude of these precision errors related to envelope leakage distribution strongly depends on the envelope leakage location and can be of the same order as the duct leakage flow. The bias in duct leakage due to including duct leakage as part of the envelope leakage is reduced by including the intermediate estimates of duct leakage flows and measured duct system pressures in the duct leakage calculations.

An advantage of this test is that it does not require the sealing of all supply grilles or the separation of the supply and return systems at the air handler. This means the test is less time-consuming and less susceptible to poor sealing or seal failure during test than the duct pressurization test.

Nulling Pressure Test: The nulling pressure tests (NPT) (Walker et al. 1998a) is similar to the house pressure test except that a fan-assisted flow meter is used to balance the duct leakage flows instead of using the building envelope. This reduces the uncertainty of the measured flows. However, there is still the problem of reliably measuring the small envelope pressures and the added difficulty of controlling a fan to exactly balance the duct leakage flow imbalances. The developers of this technique have produced automated methods for controlling the flow and taking long time-averages of pressures that mitigate these uncertainties. The problem with leaky envelopes resulting in small envelope pressure differences still exists.

Tracer Gas Test: A tracer gas test involves injecting a tracer gas into the house and the duct system at various locations. Samples are than taken from the house and duct system (and outside) and the changes and differences in tracer gas concentration are used to calculate duct leakage flows. This test requires considerable time and expensive, delicate equipment. In addition, the tests can only be reliably performed by highly skilled technicians with many years of experience in tracer gas testing and analysis. Traditionally, tracer gas studies of airflows in buildings have been the standard against which other diagnostics are evaluated. However, for duct leakage, the poor mixing of tracer gas in the various duct locations outside conditioned space and the inability to sample correctly at return leaks means that the tracer gas measurements can have large uncertainties and cannot always be used as a reference.

Pressure Pan Test: The pressure pan test (Siegel and Manclark 1998) uses a blower door and a pressure pan. The latter device is simply a small box that is open on one side and contains a static pressure probe. The open side is pressed against the building surface surrounding a grille. Like a conventional flow hood, the pan edge in contact with the building surface must be well sealed to avoid leakage. “Pan pressure” is the pressure inside the pan (grille side) relative to indoor pressure. This test is used to estimate the ratio between duct-leakage flows to indoors and those flows to outdoors. It involves depressurizing the house to 50 Pa relative to outdoors. If the pressure pan reading is near zero, then most of the duct leakage (if any) is to indoors. If the reading is near 50 Pa, then the duct leakage is primarily to outdoors. However, intermediate zone (e.g., attic or crawlspace) pressures can affect pressure pan readings. If the ducts leak to the intermediate zone and the zone pressure is less than 50 Pa relative to outdoors, then the maximum pressure pan reading for those leaks will be the intermediate zone pressure.

This test is not recommended for commissioning except as a rapid screening supplement to more elaborate tests, because its pressure indication does not uniquely determine leakage. The results of this test are susceptible to pressure drops in the duct system caused by dirty air filters or coils and partly closed dampers. Grilles located close together will have similar pressure pan readings. High duct leakage to indoors can mask exterior leaks. Systems with large flows in one branch compared to others can cause duct pressure in low-flow branches to be excessively influenced by exterior conditions (wind and stack effects). This will in turn make duct leakage appear to be larger than it actually is.

Air-Handler Airflow

Sum of Grille Flows: This method of assessing air-handler airflow uses the sum of all measured grille flows. Methods of measuring grille flow are described elsewhere in this report. The sum of flows must be corrected to account for measured duct leakage. Due to the number of measurements required in a typical house, this test is time consuming. However, the test has the advantage that a separate air-handler flow measurement does not need to be carried out if grille

flows and duct leakage are being measured anyway. This test is particularly subject to uncertainty due to the type of hood used.

Temperature Split: Software available to assess refrigerant charge (Downey and Proctor 1999) includes the ability to assess air-handler airflow as well. It uses the "temperature split" method to determine whether the airflow rate through the evaporator is adequate.

In this test, the "measured" temperature split is the difference between the dry-bulb temperatures of the return air entering evaporator and the supply air exiting the evaporator. Proper airflow at design conditions is indicated by a measured split within 3.5ºF (2°C) of the target split at test conditions. If the measured split is larger than the target split plus 3.5ºF (2°C) at test conditions, then this indicates that the evaporator airflow is too low at design conditions. If the measured split is too low, then this indicates low cooling capacity at design conditions due to problems such as high evaporator airflow, a dirty condenser coil, low condenser airflow, restricted refrigerant lines or orifice, compressor problems, or contaminated refrigerant.

The target split at design conditions for cooling equipment with a sensible-only load is about 28ºF (16°C), based on the typical assumption of 400 cfm/ton, an air density of 0.075 lbm/ft^3 (1.2 kg/m^3), and a specific heat of 0.240 Btu/(lbm·ºF) (1.0 kJ/kg). The target split at test conditions differs from this value depending on environmental conditions and equipment response at the time of the test, which usually is not the design condition. Specifically, the capacity of the equipment varies as a function of indoor dry- and wet-bulb and outdoor dry-bulb temperatures. The software determines the target split for the part-load test condition based on the expected variation of capacity as a function of these parameters. That split will then result in the appropriate flow at design conditions.

There are several potential problems in using measured plenum air temperatures to calculate airflow. One is the non-uniformity of temperatures in plenums. As Appendix A indicates, this problem is particularly pronounced when the refrigerant charge is low and parts of the evaporator contain superheated refrigerant vapor. A second is the possible radiant errors if a temperature sensor views coil, plenum, or duct surfaces that have a significantly different temperature compared to the air temperature. A third is inappropriate temperature differences. Low differences increase the uncertainty associated with the measurement. High differences introduce an air density error. Differences between 15ºF (8°C) and 50ºF (28°C) are generally acceptable in the absence of other problems.

Tracer Gas: Tracer gas assessment of air-handler airflow uses a constant injection of a non-reactive tracer gas not typically found in the ambient air (e.g., SF_6). The concentration of gas in the air downstream of the injection point is sampled and the airflow rate is calculated as the simple ratio of injection rate to downstream concentration. This test requires the use of elaborate, fragile, and expensive test equipment such as a specific vapor analyzer.

The test is subject to error because of poor tracer gas mixing and the type of sampling. Poor mixing can occur due to air handler and duct system topology. If the tracer is not uniformly mixed in the air stream, then single-point sampling is not appropriate. In that case, injection and sampling must occur over the entire plane of the sampled air stream to determine an average concentration. Such injection and sampling requires the use of manifolds, which can be difficult to install in an air handler or duct system. Mixing can be improved in some cases by injecting the tracer gas upstream of the air-handler fan so that the fan mixes the tracer before the tracer is sampled downstream of the fan.

Fan Curve Interpolation: An approximate method to estimate air-handler airflow uses the manufacturer's fan curve data with the measured total operating pressure difference (sum of operating pressure differentials between the supply and return plenums and the indoor air). There are three problems with this method:

1. Manufacturer's fan curve data may not be available, especially for existing houses.
2. Errors in manufacturer's fan curve data will be propagated in the airflow calculation.
3. Even if the manufacturer's data are accurate, they may not accurately represent the installed performance of the fan due to system effects such as 90º return duct approaches to the air handler, and how the fan is mounted in the air handler cabinet (often fans are too large for the cabinets containing them, which leads to severe inlet restrictions). These system effects can vary significantly and are difficult to estimate. Consequently, although this method is simple, it has unknown uncertainty.

Thermal Distribution System and Ventilation System Airflows

Conventional Flow Hood: Commercially-available conventional flow hoods are made of fabric supported by a rigid conical or pyramidal frame. This geometry can sometimes limit hood use, because of interference with surrounding objects. The flow hood is placed over a grille to capture the entire flow. A good seal (e.g., sponge rubber) at the gap between the hood and the adjacent building surface is necessary to avoid air leakage that would not be measured by the hood metering element.

The metering element in these devices is typically a multi-port total pressure manifold (with upstream and downstream holes) located centrally within the flow hood restriction. A hot-wire probe or other flow sensor such as a deflecting vane or a pressure transducer is used to determine the average airflow rate based on air velocity or average pressure response within the manifold. The manifold inlets are subject to blockage by dirt.

Recirculation regions within the hood (along sides) when measuring supply flows can change the flow pattern over the manifold and introduce error. Manufacturers recommend using a flow hood size close to the grille size to reduce the recirculation problem. 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. The hood constriction at the flow measuring section can cause backpressure in an air distribution system, particularly when multiple grilles are located near each other on the same distribution system branch. Backpressure reduces measured flow and causes further error.

To determine a flow correction factor that will account for recirculation and back pressure errors, ASHRAE Standard 111 (1988) recommends using a pitot-static-tube traverse of the duct section upstream of a grille, with and without hood in place. In many cases, the correction can be negligible, but in some cases, a correction as large as 50% may be needed. This correction can be very specific to a given grille due to flow rate, grille type, and duct topology. Carrying out such upstream pitot-static-tube traverses in a house can be difficult or impossible in some cases, which means the conventional flow hood should not be used in these cases. When pitot-static-tube traverses upstream of many grilles must be carried out, they make the use of this flow hood redundant.

Anemometry: Anemometry involves external traverses over the plane of a grille, normal to the exiting or entering air stream, using a commercially-available vane or hot-wire anemometer.

The calculation of the airflow rate uses built-in calibrations based on vane rotation speed or on hot-wire power consumption (temperature dependent) to determine air velocity. This calculation requires good characterization of the effective open area of the grille. However, determining this area in the field can be difficult, because of angled louvers on the grille. Uncertainty in determining this area and off-normal sampling of the air-stream by a vane anemometer or directional hot-wire sensor (which introduces a cosine error in the measured air velocity) can lead to large uncertainty in the calculated airflow.

Vane anemometers may be subject to friction drag at low air velocities (50 ft/min or less), depending on the type of vane shaft bearing. Hot-wire anemometers should be used instead for measuring low air velocities. However, hot-wire anemometers are subject to fouling by dirt and other contaminants, which will reduce their accuracy.

Due to their rapid response, hot-wire anemometers require instrumentation to provide time-averaged air velocities in fluctuating flows. Vane anemometers are simpler, because their inertial effects provide built-in averaging. However, these inertial effects also introduce a bias error due to the slow response of the device in fluctuating flows.

Flow Grid: A flow grid is a simple, inexpensive device that uses a set of tubes each closed at one end and connected together in a manifold at the other end. It is similar to the flow plate and grid device described in the main body of the report for measuring air-handler airflow, but has no orifice plate. Due to the absence of the flow plate, this device has a negligible effect on airflow. The manifold increases the pressure differential between total and static pressure. As such, it provides better resolution compared to a pitot-static tube.

The device is commercially available and commonly used in air-to-air heat exchanger duct systems to assist balancing of the supply and exhaust flows. A disadvantage is that the equipment typically is integrated as part of the duct system and is a permanent fixture. However, this allows subsequent tests to be carried out more easily. A further disadvantage is that it is often difficult to find a suitable installation location with uniform flow. On-site calibration can be used to correct for the effects of non-uniform flow. However, this step is time consuming.

Flow grid accuracy can be impaired by physical damage (during installation or by duct cleaning), by blockage of pressure ports with dirt or other contaminants, and by leaks in the tubing connecting it to the pressure transducers. Cleaning the pressure ports and surrounding grid often requires duct disassembly.

Pitot-Static-Tube Traverse: This method of determining airflow involves an internal traverse with a commercially-available pitot-static tube over the cross-section of the duct upstream of the grille, normal to the exiting or entering air stream. The pitot-static tube measures total and static pressure at each measuring point.

The calculation of airflow rate requires that the area of the duct be subdivided into sections using the log-Tchebycheff method (ASHRAE 1988). That method minimizes the error associated with improperly accounting for large flow gradients near duct walls. For round ducts, the cross section is divided into annular sectors. For rectangular ducts, the cross section is divided into rectangular sectors. The pitot-static tube must be placed centrally in each area. To accomplish this, the pitot-static tube is inserted through three holes drilled 60º apart or two holes drilled 90º apart. Accuracy is increased by using more measurements. At least 12 measurements must be made over the cross section of a round duct; rectangular ducts require about double that number. Total and static pressures are then used to determine the velocity pressure for each sampled area. The

flow rate for each area is then calculated and summed to determine the total flow rate through the duct section. These traverses are time consuming.

Uncertainty in determining the insertion depth, off-normal sampling of the air-stream (which introduces a cosine error in the measured total pressure), velocities below 500 ft/min (2.5 m/s), and flow non-uniformities within the duct can lead to large uncertainty in the calculated airflow.

Further uncertainty is introduced by duct leakage. Reducing this uncertainty by measuring near grilles is problematic for two reasons. First, to reduce the effects of flow non-uniformities, measuring is best carried out at least 7.5 hydraulic diameters downstream and at least 3 hydraulic diameters upstream of turns, flow obstructions, or changes in duct cross-section. However, most residential systems do not permit measurements within these constraints, because of their short duct runs, so accuracy is impaired. Second, in some houses, it is difficult or impossible to access ducts near grilles for such measurements.

Pitot-static tube accuracy can be impaired by physical damage, by blockage of pressure ports with dirt or other contaminants, and by leaks in the tubing connecting it to the pressure transducers.

Plastic Bag Test: A simple inexpensive flow assessment test (CMHC 1998) uses a large plastic bag of known volume with a wire frame fastened to the bag opening to keep it open. To measure supply flows, the bag is deflated by collapsing it away from the grille. Its opening is then held tightly over the grille, while swinging the bag to assist inflation. Time for the airflow to inflate the bag is recorded. The airflow rate is then calculated using the bag volume and inflation time. A similar but reverse technique can be used to assess return or exhaust flows. In that case, the bag must be inflated before placing it over the grille. This can be achieved by moving the bag through the ambient air as the bag approaches the grille.

This technique is limited by the uncertainty in timing inflation or deflation and by the uncertainty in the air volume added to or removed from the bag. To reduce the timing uncertainty effects, several measurements should be made and then averaged.

An advantage of this device is the bag does not have a significant effect on system pressure due to its low mass.

Thermal Distribution System Delivery Efficiency and Room Distribution Effectiveness

Delivery efficiency and room-by-room distribution system effectiveness are complex metrics that are calculated using diagnostic inputs such as duct location, surface area, and thermal resistance (obtained through a combination of observation and simple calculation), duct leakage, and by determining the flow for each branch of the duct system.

Andrews et al. (1996), as well as Siegel and Davis (1998) have suggested that electric coheating can be used to measure system efficiency before and after retrofits. However, this technique may not be practical for commissioning, because it requires the use of nighttime short-term monitoring over about a half-day to two-day period, which is time consuming. The house is preferably unoccupied during the test, which further limits the utility of this method when testing existing houses.

Air Exchange

Tracer Gas: There is a substantial body of literature from the past 20 years related to determining room and whole-building air exchange rates, as well as ventilation effectiveness and efficiency. Most techniques rely upon the use of tracer gases.

There are fundamentally two types of tracer gas tests: active (decay, constant injection, or constant concentration) and passive (e.g., constant emission with integrating samplers). All of these tests can be carried out with or without the air handler operating. Both types of tests are well developed.

The decay test uses rapid (pulse) injection of a non-reactive tracer gas not typically found in the ambient air (e.g., SF_6). To provide good mixing (uniform concentrations indoors), the tracer is injected in or near an air distribution system return grille with the air-handler fan running and all supply grilles open. Additional mixing by portable oscillating fans may be needed if the air handler is not operating during the decay period. The concentration of the tracer gas in room air is sampled at least twice after injection, often near a return grille. The air exchange rate is then calculated using the difference between starting and ending tracer gas concentrations over the measurement period, the length of that period (nominally two hours), and the building volume. The required time depends on the air exchange rate: high exchange rates require less time, low exchange rates require more time. To measure the tracer gas concentrations, this test requires the use of elaborate and fragile test equipment, such as a specific vapor analyzer that actively samples the air on site. Alternatively, grab samples can be used along with subsequent laboratory analysis.

In the constant injection test, tracer gas is injected at a constant rate into the indoor air either directly or more commonly into the air distribution system (with the air handler operating). The time-varying response of the tracer gas concentration indoors is then monitored, usually with a computerized data acquisition system and a specific vapor analyzer. For each measured concentration, the air exchange rate can be calculated based on the injection rate and building volume. This test requires even more elaborate equipment than the decay test. Grab sampling can be used as an alternative, but due to the large number of concentration measurements involved and subsequent cost of individual analyses, this method of sample collection tends to be impractical.

The constant concentration test uses the most complicated system for injection and concentration measurement. It requires a sophisticated control system that samples the tracer gas concentrations in one or more zones and then adjusts the injection rate to maintain those concentrations. This test is advantageous in occupied buildings, because there is less risk of producing potentially harmful tracer gas concentrations. Another advantage is that this test can be used to null interzonal tracer gas flows, so that only outdoor airflows are determined. The other test methods are subject to uncertainty in determining outdoor airflows if the tracer gas concentrations differ between indoor zones at any time during the test (poor interzonal mixing).

The perfluorocarbon tracer (PFT) test uses constant emission sources and passive integrating absorption samplers that are spread throughout the building. The air exchange rate is based on the ratio of the source emission rate to the total amount of tracer absorbed over the measurement period (few days to several weeks), and on the building volume. This test uses small, relatively inexpensive, and easy to install devices during the test. A disadvantage is that a laboratory must analyze the samplers after the test to determine the amounts of absorbed tracer.

The air exchange rate determined by the decay and PFT tests is uncertain due to changing weather conditions. The uncertainty increases as building envelope leakage increases. Although all the tests are sensitive to short-term variation in air exchange, only the constant injection and constant concentration tests can separate short-term effects from long-term ones. The other tests reported integrated values over the test period and cannot show the short-term variation (e.g., peaks). Poor room mixing conditions can also cause uncertainty in these two tests.

Interior door closures (changes the flow resistance, flow patterns, and apparent volume of the building) or window opening (changes flow patterns and ventilation rate) in occupied houses can cause further uncertainty if the goal is to assess the impact of the envelope and mechanical ventilation systems on air exchange.

All these techniques are problematic for determining spatial or temporal ventilation effectiveness and the ventilation efficiency of mechanical ventilation systems in houses, because they include infiltration effects that these metrics assume can be ignored (ASHRAE 1997). Also, tests with the air-handler fan operating to mix the tracer gas include infiltration induced by leaks in the duct system and therefore measure the infiltration rate with the air handler operating. For leaky duct systems, this may be significantly different from the air infiltration with the air handler off. Well-developed calculation techniques (Sherman 1986) that use ventilation models to estimate infiltration as a function of envelope leakage, weather, terrain, shielding, and mechanical ventilation operation can be used to partly circumvent this problem.

COOLING EQUIPMENT

Steady-State Capacity, Power Consumption, and Efficiency

Short-Term Monitoring: Equipment steady-state capacity and efficiency can be calculated using data collected over the period of several hours (ASHRAE 1995). To determine capacity, a computerized data acquisition system is used to monitor the difference between return and supply air enthalpy. The evaporator airflow rate when the air handler is providing cooling is measured separately. Temperature and relative humidity sensors are used to determine the dry-bulb temperatures and humidity of the air upstream (return plenum) and downstream (supply plenum) of the evaporator coil. Several sensors may be needed in the plenums if the airflow is not thermally well-mixed due to uneven coil temperatures or if duct branches enter or exit the plenum. In humid climates, the condensate flow rate and temperature must also be measured to account for the cooling energy loss. The average condensate flow rate can be measured using a tipping bucket with a pulse output indicating the occurrence of each tip.

Air-handler fan, condenser fan, and compressor power consumption can be measured by separate wattmeters or by using the building's electrical service wattmeter with all other devices turned off or disconnected if necessary. However, turning off devices (or disconnecting them if power is used in standby mode) can be time consuming, especially when many equipment timers and clocks must be reset after their power supply is restored. Using separate closed-loop wattmeters can be problematic due to the electrical hazards involved in attaching them to high-voltage power supply wires. Clamp-on devices are available, but their accuracy is not as good as closed-loop ones.

Steady-state efficiency is calculated using the ratio of the calculated steady-state capacity and the measured power consumption.

The calculated steady-state capacity and efficiency and measured power consumption are at test conditions, which are not necessarily the same as equipment rating conditions. Computer

simulation using cooling equipment models allows these test results to be extrapolated to other operating conditions, such as the rating conditions or to others more representative of the regional climate.

Coheating: Sonderegger et al. (1980) have suggested that electric coheating can be used to determine cooling efficiency (coefficient of performance, COP). That technique involves maintaining constant indoor air temperatures using electric heaters and continuously measuring the input power for the heaters and cooling system while the cooling system is operating. The power input to the heaters indicates the net heat removed by the cooling system. The efficiency of the cooling system can then be calculated as the ratio of the heater power input to the power consumption of the cooling system. This test requires that the cooling system be manually cycled on and off to represent the cycling performance of interest. A computerized data acquisition system is required for this time consuming test. Further research is required to evaluate the accuracy of this technique, because of all the other heat transfer process occurring simultaneously in the house during the testing.

Refrigerant Charge Level

Sight Glass: This method uses a sight glass in the refrigerant liquid line (between the condenser and refrigerant flow control device). It is a qualitative subcooling test that uses the presence of bubbles to assess insufficient charge level. It is assumed that the charge is correct when liquid with no bubbles can be observed (lack of charge causes bubbles). However, low discharge pressure from the compressor or a restriction upstream of the sight glass can also cause bubbles to appear, regardless of the amount of charge. As a result, the results of this test are unreliable. This method cannot be used to assess overcharging.

TXV Frosting: Observing thermostatic expansion valve (TXV) frosting is a qualitative test that uses the presence of frost as an indicator of charge level. It is assumed that charge is correct when an even layer of frost can be observed on the TXV body as far upstream as the liquid line inlet fitting. Insufficient charge will reduce frosting, especially near the liquid line. Like the sight glass method, this method cannot be used to assess overcharging. It also has limited usefulness, because it cannot be used for above-freezing evaporator operation conditions or in dry environments where there is little humidity in the air to produce frosting.

Motor Signature Analysis: Motor signature analysis (Miller et al. 1989) is a quantitative test that uses an inductive clamp-on current probe attached to the power supply of the condensing unit. Real-time analysis of the electrical signal using a frequency analyzer during system startup can detect motor load variation patterns associated with under or over charging of refrigerant. The repeatability of this test is questionable in field applications when voltage and ambient temperatures cannot be controlled. This method is not well developed and only preliminary research has been carried out to examine the concept.

COMBUSTION APPLIANCES

Backdrafting and Spillage Potential

Long-Term Monitoring: An additional method to assess backdrafting and spillage potential is reported by ASTM (1999b) and in part by Fugler (1989). The ASTM method involves continuously monitoring vent differential pressure (static pressure at the base of the common vent relative to indoors), air temperature at the draft hood rim, indoor carbon monoxide and carbon dioxide concentrations, and appliance operation status over the period of about a week or more under natural conditions. A computerized data acquisition system that monitors the

pressure difference, temperatures, concentrations, and operation status is necessary for the test. The method reported by Fugler involves only the temperature monitoring. Although both methods provide definitive measurements of performance during the monitoring period, they are impractical for commissioning due to their time requirements.

Combustion/Dilution Air Supply

Airflow Capability: Apart from simple dimensional measurements to ensure that combustion/dilution air supply ducts or grilles (with or without fan assist) meet specifications, the airflow rate through these devices needs to be determined. Air does not necessarily always flow inward from outdoors through these devices. The direction of flow can be influenced by wind and stack effects, as well as by the operation of air-moving devices within the house.

Well-developed diagnostics are available to determine the airflow through combustion/dilution air devices. For passive devices (no fan assist), a fan-assisted flow meter connected to the device can be used to determine its leakage area based on a multi-point test similar to using a blower door to test the envelope. In lieu of testing, commercially-available duct design software could be used to characterize the leakage area. Monitored pressure differentials across the device during normal operation can then be used with its leakage area to determine short- or long-term airflow rate histories. A disadvantage of this technique is the need for extended monitoring of the device pressure differentials and the uncertainty associated with the leakage area determination.

Alternatively, a fan-assisted flow hood, anemometry, or a pitot-static-tube traverse can be used to measure the operating flow under the test conditions for the passive or active (fan-assisted) devices. However, these tests only provide a spot measurement and do not necessarily represent the flows under other operating conditions. An in-situ-calibrated flow grid can be used with either type of device to provide longer-term flow data.

Furnace Heat Exchanger Leakage

Visual Inspection and Tracer Gas: DeWerth and Sobieski (1985) have described a three-step diagnostic method to detect combustion gas leakage in furnace heat exchangers. Step 1 relies upon visual inspection of the heat exchanger after cleaning. A mirror and bright light are used to examine the heat exchanger inside and outside for split seams, cracks, and holes. Any such defects are unacceptable. A disadvantage of this method is that inspecting the upper internal surfaces and the external surfaces can be difficult due to limited access.

Step 2 involves observing burner flame patterns with and without the air handler operating. Flame lifting, roll out, or other distortion that occurs with the air handler operating and not with it off indicates an unacceptable heat exchanger leak. This step is highly subjective.

Step 3 involves the detection of a tracer gas above a warm heat exchanger that is continuously flooded with tracer gas when the burner and air handler are off. Continuous flooding requires large amounts of tracer (typically on the order of 7 cfm, 3 L/s), due to the discharge of tracer gas from the open heat exchanger exhaust ports. Detecting the tracer above the heat exchanger can be difficult due to limited access. The tracer gas recommended is 14.3% non-odorized methane in nitrogen.

No specific data are provided to indicate what concentration of methane in air detected outside the heat exchanger constitutes unacceptable leakage. However, the authors indicate that the concentration should be equivalent to that produced by the heat exchanger leaking 200 ppm air-free carbon monoxide (CO) into the air outside the heat exchanger and producing no more than a

15 ppm CO concentration indoors over an 8 hour period. The meaning of this constraint will vary from house to house, depending on the pressure difference across the heat exchanger surfaces, the size of heat exchanger defects, the ventilation rate of the house, and the house volume. The only other description of unacceptability is that when an indicator lights on a combustible gas detector, the leakage is unacceptable. The definition of unacceptable leakage requires further research.

The use of a tracer gas such as methane that is lighter than air can be advantageous. The reason is that it tends to rise without aspiration in the heat exchanger toward higher elevation leaks, which can be in air-stream suction regions. However, lower elevation leaks may not be detected. Apart from the potential hazard of using methane, this gas has an advantage that people servicing combustion equipment may already have detectors for such gases.

Other methods exist to detect leakage, such as using combustion gas products, smoke (acidic in some cases), sodium salt spray, halocarbons, or odors (oil of wintergreen or sulfur) as tracers. However, these methods can be less reliable due to their qualitative nature and some may be potentially damaging and/or hazardous.

Fuel- and Electricity-Related Performance

Spot Measurements: Spot diagnostic methods to assess the fuel- and electricity-related performance of combustion appliances are well developed.

Pressure differential measurements using a manometer or pressure gauge attached to the gas line are used as a diagnostic when adjusting operating fuel pressures.

Steady-state input capacity can be derived using simple methods such as gas meter “clocking” (Dutton 1994). That technique involves measuring the time for one or more revolutions of a gas meter indicator and then multiplying that time with the volume equivalent of those revolutions and the average energy content of a unit volume of the fuel. To test an individual appliance, this test requires that the tested appliance run continuously and that all other appliances using that meter be shut off. A correction needs to be applied to the meter indication to account for the difference between the local barometric pressure and the meter calibration pressure.

Steady-state output capacity for a furnace can be determined using measured air-handler flow and temperature rise across the heat exchanger. Several temperature sensors may be needed in the supply or return plenums if the airflow is not thermally well-mixed due to uneven heat exchanger temperatures or if duct branches enter or exit the plenums.

Visual inspection can be used to assess flame deficiencies such as flame lifting, yellow tipping, quenching, flashback, and roll out. However, this test is subjective and should not be relied upon solely when adjusting the primary air shutters on a burner. Instead, these settings should be based on optimizing steady-state combustion efficiency, which can be determined primarily using measurements of combustion gas product temperature and concentrations of carbon dioxide, supplemented with measurements of combustion gas product carbon monoxide and oxygen concentrations.

Power consumption of the air-handler fan can be measured by a separate wattmeter or by using the building’s electrical service wattmeter with all other devices turned off or disconnected if necessary. However, turning off devices (or disconnecting them if power is used in standby mode) can be time consuming, especially when many equipment timers and clocks must be reset after their power supply is restored. Using a separate closed-loop wattmeter can be problematic

due to the electrical hazards involved in attaching it to a high-voltage power supply wire. Clamp-on devices are available, but their accuracy is not as good as closed-loop ones.

Steady-state equipment efficiency for a furnace can be calculated using the ratio between the calculated steady-state output and the steady-state input capacity combined with the measured fan power consumption.

Steady-state tests can be difficult to carry out in some houses, because inadequate airflow across the heat exchanger may cause the high-limit control for the furnace to shut the burner off before steady-state is achieved. Many of these tests can be time consuming.

Short-Term Monitoring: Most short-term diagnostic methods to assess the fuel- and electricity-related performance of combustion appliances are also well developed.

Seasonal efficiency for a furnace, as represented by its annual fuel utilization efficiency (AFUE), is normally determined using a complex time-consuming laboratory test (ASHRAE 1993a). The test uses a computerized data acquisition system to monitor temperatures and energy consumption over a 2 to 4 hour period. A temperature-sensor grid must be installed in the flue for this test. The test involves monitoring the furnace operation from startup to steady-state operation initially, followed by a cool-down period and then another heat-up period. The length of each period is based on how long it takes the flue gas temperature to stabilize in each case. Predefined empirical correction factors are applied in subsequent data analyses to account for operation at part-load conditions. This test can also be carried out as a field diagnostic. However, the test may be difficult to carry out in some houses, because inadequate airflow across the heat exchanger may cause the high-limit control for the furnace to shut the burner off before steady-state is achieved.

ASHRAE (1993b) includes a simple test to determine water heater recovery efficiency, which is the ratio of tank water energy change to energy input. The change in tank water energy is a function of the specific heat of water, tank volume, and the average tank temperature at the start and end of the test. This test uses short-term monitoring over a 2 to 3 hour period with simple temperature sensors and a timer. The test involves heating the tank of cold water to the maximum thermostat temperature setting for the water heater. Initial tank temperature is based on running a hot water faucet (with the main burner off) until the faucet water temperature is within 2ºF (1ºC) of the cold water supply temperature to the tank. The final hot water temperature is based on the water temperature at the faucet just after the thermostat turns the burner off at the end of the test. Input energy is determined as described above for the steady-state input capacity test.

Water heater cycling efficiency, as represented by the energy factor (EF), is normally determined using a complex time-consuming laboratory test (ASHRAE 1993b). That test uses a computerized data acquisition system to monitor water and air temperatures and energy consumption over a 24 hour period. Six temperature sensors need to be installed inside the tank for this test. Water flow rates are measured using a water meter or weigh scale. The test involves six equal volume water draws at hourly intervals, which are followed by an 18 hour standby period to assess standby losses. Sherman et al. 1987 developed a related but simpler field diagnostic to determine standby losses only. That diagnostic also requires a computerized data acquisition system and long periods without hot water use between two burner cycles (more than 12 hours at a time). The length of the burner off period is based on normal operation, as governed by tank thermostat operation. A disadvantage of both tests is that it is difficult or

impossible to reliably carry them out in occupied houses, because the periods between hot water use in these houses tend to be too short (on the order of 8 hours). This problem is exacerbated when the water heater is located in a space such as a garage or basement that is warm compared to outdoors. The warm air reduces the standby loss and increases the length of time between burner cycles. Further development of this test is required before it is practical for residential commissioning.

INDOOR ENVIRONMENTAL QUALITY

Related to the performance of thermal and ventilation distribution systems are a host of indoor environmental quality (IEQ) issues that encompass thermal comfort and indoor air quality (IAQ). IAQ includes the generation, transport, and removal of pollutants. Many types of pollutants might be found in a house. Examples include non-biological gaseous ones (e.g., carbon monoxide, nitrogen oxides, formaldehyde, radon), particulates (e.g., dust, soot), bioaerosols (e.g., molds, fungi, mites), and moisture.

Metrics for thermal comfort include room air temperature, radiant environment temperature, and room air velocity. Spatial asymmetry and cyclic or non-cyclic drift rates of these temperatures are other metrics related to thermal comfort. Another related metric is relative humidity. Complex metrics that combine several parameters in attempts to quantify occupant satisfaction with the indoor thermal environment include operative temperature (ASHRAE 1992), the "Overall Liking Score" of Levermore et al. (1999), standard effective temperature, predicted mean vote, and predicted percent dissatisfied. Pulldown time is another metric associated with thermal comfort (Walker et al. 1998c). It represents the time it takes to reduce the air temperature to an acceptable level after cooling startup, such as when occupants return home on a hot summer afternoon.

For pollutants, generation rates (e.g., emission, desorption), concentration, level, index, and removal rates (e.g., sorption, absorption, deposition) are relevant metrics. Literature on specific metrics for the generation and removal of pollutants is sparse or non-existent, other than to describe pollutant sources in general. Most metrics reported in the literature for pollutants are in the form of a pollutant level or index. Depending on the type of pollutant, these metrics may be in standardized units of PPM, mass per unit volume of air, colony forming or biological units per unit volume, mass of allergen per unit of particulate, particulate mass deposited per unit area, and number of mites per sample sheet. Most of these metrics represent an integrated quantity over a desired period. Airborne moisture itself has several well-known metrics that include vapor partial pressure, relative and absolute humidity, humidity ratio, and dew-point temperature. Related metrics are condensation potential for windows and surface water activity (Flannigan 1992), both of which provide an indication of the availability of moisture for microbial growth. Moschandreas and Sofuoglu (1999) have suggested an "Indoor Pollution Index" metric that attempts to sum the effects of multiple pollutants to determine their synergistic effect.

Many well-developed diagnostics are already available to determine IEQ metrics. However, they tend to be complex, time consuming, and require expensive equipment or analyses and well-trained diagnosticians. Without selecting an appropriate diagnostic to target specific concerns or dissatisfaction of occupants, the cost of attempting to address the apparent myriad of possible comfort and IAQ problems is prohibitive. As a result, most IEQ diagnostics tend to be impractical for residential commissioning at this time.

Thermal Comfort

Thermal comfort depends on indoor temperatures, humidity, and air velocities, which change in response to diurnal weather patterns and HVAC operation. It also depends on enclosure temperatures and their resulting radiant output, which also change due to these effects, but less rapidly than air temperature and air velocity. As a result, spot measurements to characterize thermal comfort are not generally useful.

Instead, a computerized data acquisition system with multiple sensors should be used to collect data over time. However, without the use of wireless technology (which is not common), the computerized system must be connected to each sensor. Connecting wires are prone to damage or disconnection, especially in occupied buildings. The computerized system has the advantage that all sensors are monitored by the same system and data are already synchronized for subsequent analyses. Such diagnostics tend to be complex and time consuming.

When only humidity and/or air temperature data are needed, stand-alone recorders can be used instead. This latter system has the advantage that these recorders are commercially-available, relatively inexpensive, easy to install, less obtrusive, and perhaps more secure from tampering compared to the former system. However, stand-alone humidity recorders have the disadvantage of slow response rates, because they are typically not aspirated.

Air Temperature: To characterize the air temperature in a room, measurements at representative locations are necessary. The temperature stratification effect in many houses is small and a single location can be used, such as waist height based on anthropometric measurements of a typical person. When there is the possibility of stratification in a room due to solar heating effects or if the room is a tall "atrium"' space such as a modern entrance area, measurement locations should include ankle height, waist height, and neck height. These locations should also be used when making air velocity measurements at these heights. Lateral location is also important, with preferable locations away from nearby walls, direct sunlight, supply grille flows, radiant heaters, and drafts from open windows or doors.

Small aspirated shielded temperature sensors are preferable. Other sensors without these features are subject to error due to slow response rates and radiation effects. A disadvantage of aspirated sensors is that they are more expensive and larger. Although shielded sensors are commercially available, aspirated sensors are not commonly available. Liquid-in-glass thermometers are not recommended, because they generally have too long a response time for use in thermal comfort testing. In addition, they are not amenable to use within a computerized data acquisition system.

Porous media thermography is an uncommon research technique for determining room air temperature patterns (Hassani and Stetz 1994). This technique is based on using infrared thermography to visualize the temperature distribution of a low-thermal-mass, porous fiberglass screen placed within an enclosure. It assumes that the screen does not affect airflow patterns and that it will be in equilibrium with the temperature of the surrounding air that flows through it. This technique has problems similar to those described in the section on using infrared thermography for assessing building envelope deficiencies. It also requires substantial analyses to determine temperatures from the thermographic images, especially if multiple images are used to determine temperature histories. These analyses are also necessary to correct for radiant interchange between the screen and the room enclosure. Care is required to ensure that solar radiation is not incident on the screen. This test, although impractical for residential

commissioning, could be useful in determining appropriate locations for other temperature sensors.

Humidity: To characterize the humidity in a room, measurements at several representative locations are not necessary, because thermal comfort is only a weak function of humidity (and moisture gradients in the room air are small). A common location is waist height based on anthropometric measurements of a typical person. However, lateral location remains important and preferable locations are away from direct sunlight, supply grille flows, radiant heaters, and drafts from open windows or doors.

To reduce slow response times that can introduce data synchronization errors, an aspirated sensor should be used to measure humidity. The sensor can be one of several inexpensive commercially-available devices. One type is a simple shielded dry-bulb and wet-bulb thermometer matched pair with a constant supply of distilled water to keep the wet-bulb wick moist. Wet-bulb based sensors are inappropriate for measuring low humidity (<20% relative humidity), because cooling the wet-bulb to its full depression is difficult under these conditions. Another type is an electronic capacitive relative humidity sensor. Care is required with some capacitive sensors, because exposure to high humidity (>95% relative humidity) can permanently damage the sensor. A chilled-mirror dew point transducer (relies on the presence of fogging at the dew point) can also be used and is very accurate, but its relatively high cost and delicacy makes it less desirable for general field use. Aspiration of these devices is typically achieved using an integrated fan.

All humidity transducers are subject to contamination by dirt or chemicals, which alters their response and introduces a bias error. Other than chilled-mirror transducers (which require regular cleaning), these devices require frequent calibration, which is time consuming. Such calibrations require controlled temperature and humidity conditions (e.g., carefully-mixed salt solutions located within an environmental chamber).

Air Velocity: Measuring air velocity at representative locations is necessary, because people are particularly sensitive to drafts on unclothed areas of their bodies. As a result, measurements should be carried out at ankle height, waist height, and neck height based on anthropometric measurements of a typical person. Discomfort associated with drafts is also a function of frequency effects, such as turbulence with fluctuations on the order of 2 Hz or less.

These measurements are typically made using an expensive commercially-available omni-directional hot-wire anemometer with a short time constant to enable the detection of turbulence intensity and low air velocities (down to 2 in/s, 50 mm/s). Omni-directionality is important, because airflow direction can change rapidly at these low velocities. Hot-wire anemometers are subject to fouling by dirt and other contaminants, which will reduce their accuracy.

A Kata thermometer can also be used, but its mass will introduce a bias error when air velocities fluctuate substantially, will obscure transients by its integrating effect, and is not amenable to use with a computerized data acquisition system. A Kata thermometer is an alcohol-filled thermometer that is heated in a water bath, dried, and then allowed to stand undisturbed in an airflow. The cooling time of the thermometer over a fixed temperature range (typically 5ºF, 3ºC) and device calibrations are used to determine the air velocity.

Vane anemometers are inappropriate for measuring room air velocities, because they are incapable of measuring low air velocities and are not omni-directional.

Radiant Environment: Operative temperature combines both radiation and convective effects to better approximate the response of the human body to these conditions in an enclosure. It is defined as the uniform temperature of a radiantly black enclosure that will transfer as much heat by radiation and convection to an occupant as the actual environment. A disadvantage of measuring this parameter is that, by combining the effects of two heat transfer modes, a problem in one mode cannot be distinguished from the total measurement. Therefore, operative temperature measurements must be supplemented by air temperature and air velocity measurements so that the radiant and convective effects can be separated. Calculations are required to determine these components of the operative temperature.

A black globe thermometer can be used to measure operative temperature. This device is a hollow sphere, such as a painted table tennis ball, with a temperature sensor centrally located. The sensor shell has a low mass material such as thin plastic instead of metal to improve its response to airflow transients. However, its shape, color, and convective to radiative heat transfer ratio are poor representations for the response of lightly-clothed human bodies to enclosure surface temperatures, solar radiation, and convection. A commercially-available gray ellipsoid transducer provides a better approximation. The ellipsoid sensor orientation has the additional advantage that it can be adjusted to represent standing, sitting, and lying positions (each of which have different view factors relative to the enclosure).

Multiple operative temperature measurements are necessary within each room due to possible non-uniformities in airflow patterns and because enclosure view factors change with position in a room. For example, measurements near a window in an otherwise well-insulated room will provide a different operative temperature near the window compared to the opposite side of the room.

Radiant temperature asymmetry is a related measurement. It is the difference between the apparent radiant temperatures on two opposite sides of a small black element. Radiant asymmetry can be determined using a commercially-available handheld plane radiant asymmetry sensor. This sensor consists of two identical faces, each of which detects the hemispherical radiation incident on its surface. Radiative and convective heat transfer effects are separated by measuring the surface temperature of each probe face and by using two materials of different emissivity: one with low emissivity (e.g., gold) and the other with high emissivity (e.g., black). The sensor can be oriented in any direction. As such, it can also be used to evaluate mean radiant temperature of an enclosure.

Sources of Indoor Contaminants

Source Characterization: Building materials and occupant activities can be sources of indoor contaminants. These include emissions such as:

- formaldehyde from particleboard;
- volatile organic chemicals from carpets, paint, adhesives, cleaning products, and personal hygiene products;
- tobacco smoke;
- unvented combustion appliance use for heating or cooking;
- vehicle exhaust in attached garages;
- dust from renovations or woodworking;

- ozone from home office equipment;
- biological particles such as mold spores, pollen, insects, and skin flakes;
- moisture, grease, and smoke from cooking; and
- moisture from bathing, showering, plants, clothes drying, and the building envelope.

External contaminant sources can also contribute to indoor contaminant levels. These sources can include outdoor air containing ozone or contaminant types similar to those indoors, as well as soil gases contaminated with radon, land-fill gases, or volatile organic chemical vapors.

Vented combustion appliances, in some circumstances, can also be a source due to backdrafting and spillage or due to furnace heat exchanger leakage. Diagnostics to assess these particular sources are described elsewhere in this report.

Material emission, ambient air, and soil gas testing is complex, so most diagnostics will be limited to a checklist audit of possible sources to determine which sources may be present. Such an audit may also include determining particular contaminant sensitivities of occupants. Sampling of some indoor contaminant concentrations can also be used to identify the presence of contaminant sources (e.g., radon).

Source Control: Preferably, indoor contaminants from stationary indoor sources should be controlled by collection and removal at or as close as possible to their source rather than by whole-house dilution ventilation. This removal can be accomplished by particulate filtration and local ventilation.

Apart from simply checking that equipment is installed correctly, field diagnostics to assess source control are limited. Particulate filtration can be assessed by measuring particle concentrations upstream and downstream of filters in the air distribution systems and by measuring particle concentrations in the indoor air. Assessing the performance of local ventilation systems can include diagnostics for measuring indoor concentrations of the contaminant intended to be controlled, as well as measuring the associated ventilation airflow and air exchange rates. These diagnostics are described elsewhere in this report.

Indoor Contaminant Concentrations

Indoor contaminant concentrations can be measured using non-aspirated (passive) or aspirated (active) sampling techniques. Currently, it is economically impractical to sample all possible contaminants. Except during the startup period (e.g., at construction completion and 3 and 6 months after), sampling should only be used when obvious sources have been ruled out and problems still exist. Therefore, a checklist audit of possible sources should be used to determine which sources may be present and which samplers are appropriate. Such an audit may include determining particular contaminant sensitivities of occupants.

Regardless of sampling method, a measured concentration that is elevated beyond a threshold is only a snapshot: it indicates that there may be a problem sometimes. Contaminant concentrations below the threshold do not mean there is always no problem. Instead, they mean there is likely no problem at the time of monitoring. This may be due to an absence of sources of concern or due to high ventilation rates that are maintaining low concentrations. Sources or ventilation rates can change over time (e.g., new carpeting, moisture-induced biological growth, air sealing measures). As a result, it may be desirable to sample multiple times over the life cycle of the building.

Non-Aspirated (Passive) Sampling: Passive samplers are small tubes or canisters that collect contaminants without aspiration using diffusion, permeation, chemical reaction, and/or radioactive decay. Most non-aspirated samplers are meant to be exposed for short periods of time, typically two weeks or less. No air sample pump is required. After sampling, the samplers are sealed and sent to a laboratory for analysis to determine the amount of contaminant that they have absorbed. Using these data along with tube exposure time, the integrated average concentration can be calculated for each tube location. Some samplers use colorimetric elements intended to visually indicate the concentration and avoid subsequent lab analyses. However, these devices have limited accuracy due to the subjectivity involved in interpreting color changes or matches. Some colorimetric samplers can be analyzed in a laboratory to improve their usefulness and accuracy.

Non-aspirated samplers are commercially available and well developed for many of the common chemicals and radioactive elements of concern in houses, such as carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), formaldehyde, volatile organic chemicals, and radon. An advantage of passive samplers is that they can be constructed to be worn as badges on clothing near the breathing zone to indicate occupant exposure. All these samplers are subject to post-test pre-analysis contamination and create storage and data tracking problems. However, they are not subject to the contaminant loss that sometimes occurs in the tubing of aspirated samplers.

Other non-aspirated sampling techniques include tape extraction of sedimentary bioaerosols and particulates. The tape is placed over a sample region. When removed, the media being sampled remain attached to the tape. The tape is then sent to a laboratory for subsequent analyses of number of media and type.

Integrated sampling obscures short-term variations (e.g., peaks) in contaminant concentration. Such obscuration can be hazardous if the time scale of concern is less than the integration period. For example, a rare but brief hazardous concentration of a toxic contaminant would be obscured when the concentration was normally low over the remainder of the sampling period. The sampler would then indicate there was no problem, when in fact there may have been. In spite of this problem, non-aspirated samplers are useful for characterizing long-term exposure to contaminants.

Aspirated (Active) Sampling: Aspirated sampling generally involves collecting air samples using a sample pump contained within a recording monitor that analyzes the sample on-site to determine its concentration. A disadvantage of this equipment is that it tends to be expensive and fragile. Furthermore, sampling pumps tend to be noisy and can be irritating to building occupants. Multiple grab bag samples collected over time can be used instead to reduce the equipment cost and the duration of the noise. The bags are initially evacuated and then are inflated on site with an air sample pump. A disadvantage of the grab bag technique is that chemically-stable sample bags can be expensive to buy and to analyze. However, this analysis step offers the advantage of using laboratory techniques that are more sophisticated to determine which contaminants are present in the sampled air. These techniques include gas chromatography or mass spectroscopy. Due to their size, grab bags cannot be used practically to indicate exposure. As with passive samplers, grab bags are subject to post-test pre-analysis contamination and create storage and data tracking problems.

These aspirated devices are commercially available and well developed, but require more on-site expertise than non-aspirated samplers. In addition to microprocessors, their analytical elements

include electrochemical cells to detect CO, O_2, SO_2, NO_2, and combustible gases; non-dispersive infrared samplers to detect CO and CO_2; chemiluminesence samplers to detect ozone, NO, and NO_2; and portable radiation samplers to detect radon and its decay products. Other aspirated samplers with vacuum sampling and opacity measurement are available to determine bioaerosol and particulate concentrations. Vacuum sampling with filter collection or electrostatic precipitation, followed by laboratory gravimetric and/or microscopic analysis of the filter or electrostatic plate, is also an available technique to determine these concentrations. The latter technique is more expensive than on-site analysis, but has the advantage that bioaerosol and particulate type can be determined. Impingement and precipitation collectors are used in some particulate samplers to separate particles by size.

Aspirated samplers require careful and frequent calibration to reset their zero and span, due to the delicacy of their internal sensors and due to aging and contamination effects. Some samplers include automatic rerouting of the sample air stream on a periodic basis through scrubbers or filters to reset their zero. Sensors are included in some devices to provide automatic compensation for the effects of temperature and humidity. Monitors without these features require careful analysis of the data to correct for zero drift and for the effects of temperature and humidity.

All aspirated samplers also require careful adjustment of their airflows, especially when sampling in another air or gas stream, such as in a flue. If the sampling airflow is too low, much of the air stream will pass the sample tube without entering. This is particularly a problem when particles with large inertia are involved, because they cannot easily change direction into the sampling tube. Equipment used to sample combustion gas products in flues may need to be more robust due to the higher temperature associated with sampling these hot gases. Care must also be exercised to ensure sample tubing does not leak. Leaks outside the desired sample area can bias the measurement.

A disadvantage of aspirated samplers is they cannot be used to indicate occupant exposure, because they are too large to be fastened on clothing near the breathing zone. Some samplers are mounted on belts, but they are awkward, prone to damage, and their accuracy in indicating exposure in the breathing zone is reduced. Unlike passive samplers, aspirated samplers are not subject to post-test pre-analysis contamination of samples and they can facilitate storage and data tracking through a recording feature.

Aspirated samplers with built-in analyzers have the advantage that they can continuously monitor instantaneous contaminant concentrations. These data can then be used to indicate short-term hazards or can be integrated to indicate longer-term concentrations.

CONTROLS AND OTHER EQUIPMENT

In commercial commissioning, control problems are the key item of concern. While not as important in residential houses, controls can still play an important role, especially when the systems become complex (e.g., multistage systems, integrated heat-pump/ventilation systems) Even common heating setback / cooling setup thermostats need to be properly commissioned. Heat pumps share many of the same problems associated with cooling systems, but have some unique features. Use of electric resistance ("strip") heaters can significantly increase energy consumption due to malfunctioning or misadjusted controls. Making sure that these controls are doing what was intended or is appropriate is often crucial to achieving good energy performance.

Except for Keithly (1999), we found no metrics in the literature to describe residential control performance. Even then, Keithly only describes common deficiencies with thermostat installations. Some metrics that are relevant to thermostat performance include accuracy, setup/setback strategy, and anticipator or temperature swing setting. Other controls in the space conditioning system include those for the burner of a heating system and the refrigerant flow control in a cooling system. Specific metrics for the burner include fuel pressure, fuel orifice size, and primary air supply flow. For refrigerant flow controls, relevant metrics are the orifice size, thermostatic expansion valve (TXV) size, as well as the superheat bulb location and bulb-line contact resistance. Other metrics include heat pump outdoor thermostat and defrost timer settings, blower and burner thermal limit switch settings, blower motor speed, automatic control sequence for duct damper on outdoor air intake, and ventilation switch settings (e.g., humidistats, or run and defrost timers).

Apart from the HVAC system, there are many other electrical appliances in the house. Some of them (e.g., stoves, water heaters, refrigerators, clothes dryers) can be quite large consumers of electricity. Improper configuration of some appliances (e.g., clogged dryer vent) can cause poor performance. Most of these appliances require only simple commissioning.

Only a few references were located that discuss metrics relevant to the commissioning of residential electrical appliances. For water heaters, one metric is its recovery efficiency. Others include its energy consumption, energy factor, standby energy loss, and how much insulation is located around the tank. For appliances associated with plug loads, such as refrigerators, metrics include energy consumption and interior compartment temperature. An important metric for electric water heaters and these appliances is the electric load, both at startup and while operating.

Controls

Configuration and Operation Assessment: Diagnostics for controls are often little more than checking configurations and settings. For space conditioning systems, these checks can include verifying indoor thermostat accuracy, setup/setback strategy, deadband width, and anticipator or temperature swing setting. For refrigeration systems, checks can include the orifice size, thermostatic expansion valve (TXV) size, as well as the superheat bulb location and bulb-line contact tightness and cleanliness. Other checks may include heat pump outdoor thermostat and defrost timer settings, blower and burner thermal limit switch settings, blower motor speed, automatic control sequence for duct damper on outdoor air intake, and ventilation switch settings (e.g., humidistats, or run and defrost timers).

Assessing control operation is currently limited to simple observation and timing, or to more complex monitoring using a computerized data acquisition system. Other than diagnostics intended for laboratory use or for commercial energy-management control systems (EMCS), there are no useful diagnostic protocols for quantifying control operation during residential commissioning. As a result, diagnostics to quantify control performance require research and development.

Other Equipment

Configuration Check: As with controls, diagnostics for electrical equipment separate from the space conditioning and ventilation systems are often little more than checking configurations and settings. The electrical equipment of interest includes water heaters, stoves, refrigerators, freezers, and clothes washers and dyers, which can be large consumers of electricity.

Configuration checks can include determining whether water supply filters on clothes washers are present or blocked or whether dryer vents are too long or blocked. Water heater thermostat setting, oven control calibration, and settings for refrigerator and freezer compartment temperatures also need to be checked.

A simple diagnostic for all electrical equipment, including smaller appliances connected as plug loads, is to measure the associated power consumption and demand.

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Potential Benefits of Commissioning California Homes

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EXECUTIVE SUMMARY

The Overall Benefit of Commissioning California's Houses

Commissioning California's houses can result in better performing systems and houses. In turn, this will result in more efficient use of energy, carbon emission reductions, and improved occupant comfort. In particular, commissioning houses can save a significant amount of HVAC-related energy (15 to 30% in existing houses, 10 to 20% in new conventional houses, and up to 8% in advanced energy efficiency houses). The process that we considered includes corrective measures that could be implemented together during construction or during a single site visit (e.g., air tightening, duct sealing, and refrigerant and air handler airflow corrections in a new or existing house). Taking advantage of additional, more complex opportunities (e.g., installing new windows in an existing house, replacing the heating and air conditioning system in a new or existing house) can result in additional HVAC-related energy savings (60 to 75% in existing houses, and 50 to 60% in new conventional houses).

The commissioning-related system and house performance improvements and energy savings translate to additional benefits throughout California and beyond. By applying commissioning principles to their work, the building community (builders and contractors) benefit from reduced callbacks and lower warranty costs. HERS raters and inspectors will have access to an expanded market sector. As the commissioning process rectifies construction defects and code problems, building code officials benefit from better compliance with codes. The utilities benefit from reduced peak demand, which can translate into lower energy acquisition costs. As houses perform closer to expectations, governmental bodies (e.g., the California Energy Commission and the Air Resources Board) benefit from greater assurance that actual energy consumption and carbon emissions are closer to the levels mandated in codes and standards, resulting in better achievement of state energy conservation and environmental goals. California residents' quality of life is improved through better indoor environmental comfort and lower energy bills. Lower energy bills free up money for residents to spend on other needs or goals, such as additional education and health and welfare. With an expansion of existing industries and the development of new commissioning-related industries, related jobs and tax revenues will increase, further increasing the quality of life for California.

Background

Significant opportunities to improve energy efficiency and comfort exist in California houses. The California Energy Commission is evaluating ways to expand and accelerate the implementation of these opportunities.

Residential commissioning is a means to achieve this goal. In addition to improving system and equipment efficiency on a component-by-component basis, commissioning considers the house as a system and takes advantage of the interactions between systems and components. It combines auditing, testing, and implementing energy efficiency and comfort improvements to enhance component and system performance. By doing so, it is possible to leverage capital and operating cost savings to fund measures that are more

expensive. Such an integrated approach allows energy-efficiency measures that make little sense individually (e.g., windows) to be cost-effective and attractive together within the whole system, due to concurrent benefits such as reduced equipment size and improved comfort (RMI 1997).

There is a broad spectrum of potential energy and non-energy benefits for various stakeholders such as builders, consumers, code officials, utilities, state agencies, and energy planners. For example, builders and/or commissioning agents will be able to improve 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 in terms of improved indoor environmental quality, housing durability, and resale value. Also, 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, which will benefit the environment as a whole.

The work reported here is the third step in a larger project that is laying the groundwork for a residential commissioning industry in California focused on end-use energy and non-energy issues. This report describes our assessment of the potential quantitative and qualitative benefits one can realistically expect from commissioning prototypical new and existing California houses. Our assessment expands upon our recent literature review and annotated bibliography (Wray et al. 2000), which facilitates access to 469 documents related to residential commissioning published over the past 20 years. It also expands upon our assessment of 117 diagnostic tools for evaluating residential commissioning metrics (Wray et al. 2001).

We will use the results of these efforts to prepare a separate commissioning guide that describes how typical contractors and service providers could achieve the benefits that we identify. That guide will contain specific recommendations on what diagnostics to use and how to use them to commission new and existing houses. The guide will also explain the potential benefits of using these diagnostics.

Report Structure

Quantitatively, this report focuses on the energy and operating cost benefits related to commissioning houses in California. It also qualitatively discusses related non-energy benefits. Within the report introduction, we first describe the need for commissioning and how it fits into the life cycle of a house. Next, we briefly identify the benefit types, the stakeholders, and who may place value on a particular benefit. Our intent here is to set the context for our analyses and discussions.

Following the introduction, we have divided the report into the following eight sections:

- “Analysis Framework – Modeling Tools and Methodology”, which provides an overview and flowchart of the modeling structure that we used to quantify the energy performance benefits.
- “Analysis Framework – Building and Climate Characteristics”, which provides our analytical assumptions, summarizes the pre-commissioned house cases that we

considered, and discusses the commissioning and opportunity measures that we modeled.

- "Energy Performance Benefits", which discusses the modeled energy consumption, and operating cost savings in terms of specific components and the house as a whole.
- "Non-Energy Benefits", which discusses other commissioning benefits, such as house durability, indoor environmental comfort, the environment, and the economy.
- "Conclusions", which summarizes our results regarding the impact of commissioning on California's residents, businesses, and the state as a whole.
- "Appendix A: Analysis Assumptions", which provides additional details regarding our analytical approach, assumptions, and climate/case specific findings.
- "Appendix B: Peak Demand", which discusses peak demand impacts, as determined from the DOE-2 peak consumption outputs.
- "Appendix C: Comfort Call Cases", which discusses the potential benefit of commissioning houses where comfort calls may occur due to the existing HVAC systems.

Analysis Overview

In evaluating the commissioning-related benefits (component and system efficiency improvements and energy and cost savings), we have quantitatively considered how several envelope and HVAC-related measures work together synergistically to improve energy utilization efficiency, energy consumption, operating costs, comfort, ventilation, and environmental effects. We have also briefly considered some non-energy benefits involving durability, indoor environmental quality, the environment, and the economy.

We determined benefits relating to commissioning California's houses using 128 hour-by-hour simulations with data derived from our field and laboratory studies to evaluate commissioning diagnostics (Wray et al. 2001) and from other sources referenced in the commissioning literature study (Wray et al. 2000). In particular, we determined building performance (e.g., ventilation rates, energy consumption and operating costs) using simulation programs (DOE-2, RESVENT [Sherman and Matson 1993, 1997]) and the requirements of codes and standards (Title 24, ASHRAE Standards 62.2P and 152P [ASHRAE 1999]). We conducted our evaluations using combinations of three commissioning phases (audit, commissioning, and opportunity), three house prototypes (existing, new and advanced), two housing quality analysis sets (typical and poor) and four climate zones (two coastal climates and two inland valley climates). The following summarizes the characteristics of these simulation elements. Details are contained in the body of the report and in Appendix A.

Commissioning Phases. The three commissioning phases that we considered include:

- the audit phase, when the current conditions and performance of the house are evaluated;
- the commissioning phase, when systems and materials are tuned and tweaked to improve efficiency and to perform better; and

- the opportunity phase, which identifies additional energy-efficiency measures that could be installed and implemented.

The commissioning phase includes measures that could be implemented during the commissioning visit or as part of the correction of construction defects (e.g., air tightening, duct sealing, and refrigerant and air handler airflow corrections in new and existing houses; improved insulation installation quality in new houses; installation of correct windows in new houses). If commissioning takes place during construction, implementation is more cost-effective than after completion.

The opportunity phase includes additional energy efficiency measures and improvements that cannot be implemented easily during a commissioning visit. These measures would require additional funds and decisions regarding overall cost-benefits (e.g., improved insulation and windows in existing houses; more efficient HVAC equipment in new and existing houses).

House Prototypes. The three house prototypes that we modeled include:

- An existing house, representing the existing housing stock built before Title 24;
- a new house, representing the current Title 24 requirements; and
- an advanced house, representing the level of energy-efficiency construction currently being built in advanced energy efficiency programs, such as Building America.

Typical and Poor Construction Cases. In order to evaluate the impact of commissioning a typical California house versus a "worst case" California house, we modeled typical and poor condition cases.

- The typical cases represent the California housing stock and our assessment of the penetration of individual energy efficiency measures within it. These measures are the same measures implemented or improved upon in the commissioning and opportunity case models. The measures include improved insulation installation quality, correct windows (low-E glass when specified), envelope and duct air leakage reduction, air handler airflow corrections, and refrigerant charge corrections.
- The poor cases represent "worst case" California houses where none of these measures are installed or where they are all operating in an inefficient and deficient manner.

Energy and Operating Cost Savings from Commissioning

Table I summarizes the range of electricity consumption, natural gas consumption, and operating cost savings that we calculated for the commissioning and opportunity cases for our three house types in four climate zones. All savings are presented as savings over the unimproved audit case. No opportunity cases are listed for the advanced houses, because they are already engineered and designed to be energy efficient.

Annual operating cost savings are based on the annual electricity and natural gas consumption values for each case, using the DOE/EIA 1999 California annual fuel costs of $0.1071/kWh (EIA 2000) and $0.634/therm (EIA 2001). Energy price increases and

price volatility will further enhance the attractiveness of commissioning California's houses.

The following summary compares the data in Table I on a house-by-house type basis for each benefit type.

Existing Houses

Electricity. Commissioning the existing house results in electricity savings ranging from 14 to 18% (typical) and 20 to 28% (poor). In the opportunity phase, adding insulation, low-e double-pane windows, and equipment with a thermostatic expansion valve (TXV) and an electronically commutated motor (ECM), results in substantial savings compared to the audit case. Within this phase, the overall electricity saving range from 61 to 74% for the typical cases and from 71 to 80% for the poor cases.

Natural Gas. Natural gas savings are from 18 to 21% for the typical cases and from 33 to 36% for the poor cases. Implementing the opportunity phase improvements substantially increases natural gas savings to 44 to 54% for the typical cases and from 59 to 67% for the poor cases.

Operating Costs. Operating cost savings in the commissioning phase range from 15 to 18% (typical) and 25 to 30% (poor). Implementing the opportunity phase measures substantially increases the operating cost savings to 59 to 64% (typical) and from 69 to 73% (poor).

Table I: Commissioning-Related Energy and Operating Cost Savings

		Electricity Consumption Savings	
		Typical	Poor
Existing	Commissioning	14 to 18%	20 to 28%
	Opportunity	61 to 74%	71 to 80%
New	Commissioning	7 to 11%	55 to 71%
	Opportunity	8 to 12%	62 to 72%
Advanced	Commissioning	7 to 10%	52 to 73%

		Natural Gas Consumption Savings	
		Typical	Poor
Existing	Commissioning	18 to 21%	33 to 36%
	Opportunity	44 to 54%	59 to 67%
New	Commissioning	24 to 25%	18 to 35%
	Opportunity	28 to 31%	22 to 41%
Advanced	Commissioning	2 to 3%	-19 to -10%

		Energy Operating Cost Savings	
		Typical	Poor
Existing	Commissioning	15 to 18%	25 to 30%
	Opportunity	59 to 64%	69 to 73%
New	Commissioning	12 to 17%	50 to 62%
	Opportunity	17 to 22%	51 to 63%
Advanced	Commissioning	6 to 8%	45 to 66%

New Houses

Electricity. The electricity savings in the commissioning phase range from 7 to 11% (typical) and 55 to 71% (poor). In the opportunity phase, adding equipment with a TXV and an ECM increases savings only slightly (one to seven percentage points more).

Natural Gas. Natural gas savings in the commissioning phase are about 25% for the typical cases and from 18 to 35% for the poor cases. In the opportunity phase, installing a higher efficiency furnace (90% instead of 80%) increases natural gas savings slightly to about 30% for the typical cases and from 22 to 41% for the poor cases.

Operating Costs. Operating cost savings in the commissioning phase range from 12 to 17% (typical) and from 50 to 62% (poor). In the opportunity phase, installing the HVAC equipment with a TXV, an ECM, and higher furnace efficiency increases the operating cost savings to 17 to 22% (typical) and from 51 to 63% (poor).

Advanced Houses

Because the advanced houses are already engineered and designed to be energy efficient, relative savings for the typical cases are lower than those for the typical existing and new houses. For the advanced houses, the primary difference between the typical and the poor cases is the incorrect installation of clear glazing in place of low-e glazing. Correcting

this problem in the poor cases drives the energy consumption and savings closer to the levels seen with the new houses.

Electricity. The commissioning phase electricity saving range from 7 to 10% (typical) and from 52 to 73% (poor).

Natural Gas. Natural gas savings range from 2 to 3% for the typical cases. Due to a reduction in solar gains when the incorrect clear double-pane windows are replaced with low-e double-pane windows, the poor advanced commissioning cases have higher gas consumption, resulting in negative gas savings, from –19 to –10%.

Operating Costs. The typical case operating cost savings range from 6 to 8%. The operating cost savings for the poor case are higher, ranging from 45 to 66%.

Other Commissioning Benefits

Qualitatively, we expect that commissioning will provide benefits beyond the occupant's reduced energy bills and increased satisfaction with the operation of their home. For example, decreased electrical demand will provide greater system reliability for utilities. Reduced electricity and gas consumption translates directly into reduced carbon emissions. Commissioning can result in space conditioning related carbon emission savings of about 20% for typical existing and new houses, and about 4% for the typical advanced houses. Implementing additional opportunities can result in an additional 40% reduction in typical existing houses and an additional 10% in typical new houses. Greater carbon emission reductions can be realized in houses where significant improvements can be made. Commissioning poor condition existing and new houses can result in about 40% carbon emission reductions. Additional opportunities can provide an additional 30% carbon emission reduction in these poor condition existing houses and 10% in poor condition new houses. Improved building performance and better indoor environmental comfort helps improve the quality of life for occupants. We also expect greater envelope durability and longer HVAC equipment life by improving the building and its systems (e.g., adding insulation, reducing duct leakage, and correcting charge and airflow). This will reduce callbacks and warranty costs, which will provide the business community with increased profits. As the commissioning industry expands, we expect that the building industry will find an increased role that may require a larger workforce and lead to new jobs. This will benefit the state and the economy.

Cost of Commissioning

The focus of this report is to evaluate the potential benefits from commissioning California houses. Ultimately, however, it is unlikely that stakeholders will adopt commissioning unless the anticipated benefits outweigh the anticipated costs, so it is important to address the issue of cost at some level.

The cost of commissioning will be highly variable. It will depend on the specific implementation of a commissioning program and will depend on how commissioning is folded in with other programs. It will depend on the training of the personnel and level of commissioning chosen. Commissioning could be a loss leader, a built-in cost, a profit center, or part of a public purpose program or regulation.

Because of all this variability, dollar-cost estimates for commissioning are not terribly useful. However, we can indicate some ranges of required resources. Testing a house as

part of the commissioning described in this study should take a trained crew from 4 to 6 person-hours, excluding tuning and tweaking of the building and its systems. The amount of special-purpose equipment required for the tests would cost between $6,000 and $15,000. The biggest variation in the total cost comes from using additional equipment to automatically control duct leakage and grille airflow tests. Together, a data acquisition system and computer for this control cost about $3,000 to $5,000. Automatic control is not necessary to carry out these tests, but tests without it will take about 50% longer (6 hours rather than 4 hours). With automatic control, it is likely that a two-person commissioning team could test two houses a day, excluding travel time. Computerized systems can also be used to generate reports (and advice) on-site and can be a useful marketing tool. Another large variation in the total cost is the price of blower doors: they currently cost about $1,600 to $3,500.

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INTRODUCTION

The Need for Commissioning

The State of California has made long-standing efforts to reduce the residential building sector's energy consumption through codes and standards for new houses and through retrofit activities and rebate programs for existing houses. In spite of these efforts, houses still do not perform optimally, or as predicted in forecasts based on codes and expectations.

Studies have found that 50% of the heating-related and 30% of the cooling-related energy consumption could be reduced in new houses (Edminster 2000). In existing houses, even greater savings are possible. Through analyses of existing programs, researchers have found that codes and standards have been helpful in reducing California's per-house energy consumption. However, predicted savings based on required Title 24 components are not as high as expected.

A substantial reason for these differences 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. For example, Walker et al. (1998a) found large variations in duct leakage, even between side-by-side houses with the same system design and installation crew. This has resulted in as much as a factor of two variation in thermal distribution system efficiency for these houses. This and other studies (e.g., Jump et al. 1996) indicate that duct leakage testing and sealing can readily improve thermal distribution system efficiency and achieve a 25 to 30% reduction in energy consumption.

As another example, consider that for at least 20 years the building industry has recognized the substantial impact of envelope airtightness 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.

In recognition of these problems, the California Energy Commission is considering approaches to improve building performance. One way to meet this goal is to apply appropriate and agreed upon field measurement and verification procedures to the residential building sector. These procedures would ensure that the components, materials, and systems of California's houses are installed as specified, and can operate closer to expectations, within the Title 24 requirements, and as well as possible. These procedures also can be used to point out additional energy savings improvements.

Such a practice has already begun in the commercial building sector, usually to tune component and system performance and verify savings related to energy savings performance contracts. The California building industry is also implementing various residential commissioning elements, but only on a component-by-component basis (e.g., testing and correcting building and duct airtightness, air handler airflow, and refrigerant charge problems).

The work reported here is the third step in a larger project that is laying the groundwork for a residential commissioning industry in California focused on end-use energy and non-energy issues. This report describes our assessment of the potential quantitative and

qualitative benefits one can realistically expect from commissioning prototypical new and existing California houses. Our assessment expands upon our recent literature review and annotated bibliography (Wray et al. 2000), which facilitates access to 469 documents related to residential commissioning published over the past 20 years. It also expands upon our assessment of 117 diagnostic tools for evaluating residential commissioning metrics (Wray et al. 2001).

We will use the results of these efforts to prepare a separate commissioning guide that describes how non-experts could achieve the benefits that we identify. That guide will contain specific recommendations on what diagnostics to use and how to use them to commission new and existing houses. The guide will also explain the potential benefits of using these diagnostics.

The CEC is currently looking at how to combine and enhance these practices for use by a residential commissioning industry. This project looks at test methods and protocols that can be used towards this goal. The purpose of this benefits study is to determine the energy and non-energy benefits of commissioning California's houses.

Commissioning within the House Life Cycle

The types of opportunities and the amount of implementation possible will depend on where a given house is in its life cycle: whether it is being built, has just been completed, is fully occupied, or is built based on older construction practices. In new construction, there are two possible times at which changes pointed out in the commissioning process can be implemented: during and/or after the construction process.

Correcting problems during the construction process, while the building framework and surfaces are still open, is often more first-cost effective and could result in significant savings. At this stage in the building life cycle, construction defects can be more easily rectified and system and component efficiencies can be improved. This can reduce the builder's costs, reduce callbacks, and reduce impacts on the environment, while providing better comfort and house performance for the occupants.

At the time of completion, a new house is similar to an existing house: it is difficult to improve insulation installation problems without the expensive process of taking apart and rebuilding part of the house. However, it is still relatively easy to tune and tweak component and system performance to what is intended or expected (e.g., reduce envelope and duct leakage, correct air handler airflow, or correct refrigerant charge). Opportunities to replace existing equipment and materials with more efficient or better performing components can be identified. An example is replacing HVAC equipment with more-efficient, equipment; another is improving insulation levels and upgrading windows.

Benefit Types and Stakeholders

In evaluating the potential benefits of commissioning California houses, we considered several benefit types and several stakeholders who could be influenced by commissioning activities. This section briefly identifies the benefit types, the stakeholders, and who may place value on which particular benefit.

Stakeholders who may be affected by, and receive benefits from, residential commissioning include occupants (tenants and homeowners), builders and the building

community, utilities, governmental agencies and bodies, insurance and banking industries, and the State (the public-at-large). Table 1 provides an overview of the types of benefits that may interest each stakeholder. For each benefit type and each stakeholder, we evaluated whether there is a perceived direct value now to the commissioning user relating to each of the commissioning benefits. The diamonds signify that a given stakeholder may see value now in the benefit listed. The term "warranty" signifies that the builders could expect reduced callbacks and reduced warranty costs related to these benefits.

Table 1: Benefits Framework
"Is there a perceived direct value now to the commissioning user relating to:"

	Tenants	Owner Occupants	Builders	Utilities	CEC & Code Authorities	Insurance & Banking Industries
Energy Consumption	◆	◆		◆	◆	
Energy Operating Cost	◆	◆		◆	◆	◆
Peak Electrical Demand	◆	◆		◆	◆	
Durability / Maintenance / Replacement		◆	◆ warranty			
House Resale Value		◆				◆
Thermal Comfort	◆	◆	◆ warranty			
Indoor Air Quality	◆	◆	◆ warranty		◆	◆
Environmental Protection	◆	◆		◆	◆	
Economic Benefits	◆	◆	◆	◆	◆	

The Benefits

Energy Consumption, Energy Operating Cost, and Peak Electrical Demand. A primary goal of commissioning is to improve the energy efficiency of building systems and components. This will reduce energy consumption, peak demand, and operating costs while ensuring sufficient space conditioning and ventilation to maintain acceptable thermal comfort and indoor air quality.

Durability, Maintenance, Material Replacement, and House Resale Value. Through commissioning, building envelope and equipment durability is improved and maintenance and material replacement activities and costs are reduced. Increased energy savings can increase house resale values (Nevin and Watson 1998).

Thermal Comfort and Indoor Air Quality. Commissioning to reduce uncontrolled air infiltration, to provide appropriate ventilation capacity, and to achieve more consistent surface temperatures through better-installed insulation can help reduce moisture and comfort problems. It will also help ensure that the intended space conditioning systems can deliver the expected amount of space conditioning capacity.

Environmental Protection. Improvements in system and component performance (e.g., capacity and efficiency) reduce energy consumption, which translates into a reduction in carbon emissions. Longer equipment life and improved durability reduces the amount of additional materials needed to replace existing equipment and maintain an existing house, thus reducing embodied energy and reducing waste disposal into the environment.

Improving the Economy. The economy benefits from reduced energy costs, increased business opportunities and related jobs, and a better quality of life resulting in greater available household funds.

The Stakeholders

Occupants. The occupants of California's houses, whether tenants or homeowners, are the direct recipients of commissioning benefits. Through commissioning, occupants will benefit from improved quality assurance of their homes, improved interactions between house elements, improved comfort, more efficient use of energy, reduced peak demand and reduced utility bills.

The Building Community. The building and contracting industries (e.g., homebuilders, contractors, HERS raters, home inspectors, and energy professionals) may implement commissioning activities in California's houses. As such, the building community will benefit economically by an expansion and increase in business activity, decreased warranty and callback expenses, and improved recognition for quality work. The building community will also benefit from streamlined methods for validating and improving the performance of houses and their systems.

Utilities. The utilities and energy service providers benefit from reduced demand from the grid due to increased efficiency and reduced equipment power consumption from downsizing equipment and, correspondingly, avoided capital expense related to building new generation facilities and reduced risk of exposure to high energy prices.

Governmental Agencies and Bodies. State agencies such as the CEC will find better agreement between projected and actual energy consumption of California's houses. Code authorities and officials will see better compliance with building codes as the commissioning process identifies and corrects code violations.

Insurance and Banking Industries. The insurance industry is interested in reducing their liability due to building defect claims, whether it is part of a natural disaster claim or a standard homeowner claim. As such, the insurance industry will benefit when the commissioning process improves the construction quality and corrects construction defects that could have led to insurance claims. The banking industry will benefit from increased home loan profits, increased investments, increased resale values, and increased monies available for other activities.

The State (Public-at-Large). The State, which is a surrogate for the public-at-large, will benefit from increased electricity reliability, due to reduced demands, and reduced energy operating costs, which frees up household dollars to use for other purposes, such as education, leisure, health, and well-being. The expansion of the building community to include commissioning activities will result in additional jobs from the technician to executive level. The increase in business revenues will increase the related tax revenues for the state.

Sizing: Peak Load and Comfort

The focus of this report is to look at the direct energy benefits of commissioning. As such the body of the report does not address issues related to sizing or peak loads. With the recent electricity crisis in California, however, issues relating to peak demand are much more important than when the study was begun. We have used the information available from our analysis to draw some conclusions about the impacts of commissioning on peak loads and have summarized them in Appendix B, but a thorough analysis of the peak load impacts requires a more extensive effort than can be done in the current context.

Proper sizing of the HVAC system requires understanding both the operating strategy of the occupants and an acceptable amount of discomfort in the form of temperature exceedence. If the system fails to meet the load during some hours of the year, then the impact of commissioning will be to improve house performance, which increases comfort rather than decreases energy consumption for those periods.

Because determination of optimal sizing is not part of this effort, we have made the assumption that the HVAC system can meet the load during each hour of the year. Thus, all the benefits of commissioning appear as consumption reductions. In many real houses, especially those in poor condition, the system may not be able to provide comfort (or the occupants may not wish to pay for it to provide comfort) all the time. In such cases, the energy savings will be reduced as occupants “take back” the savings in the form of increased comfort.

To give some indication of how capacity limitations might impact our analysis of energy savings, we have included cases in Appendix C in which the cooling system is not able to meet load during a significant number of hours during the summer. While not statistically representative, those results are indicative of how the California stock would operate.

ANALYSIS FRAMEWORK – MODELING TOOLS AND METHODOLOGY

We conducted our quantitative analyses using a combination of simulation tools. Specifically, we used hour-by-hour DOE 2.1E simulations (SRG 1976-2001) to determine annual space conditioning energy consumption. A number of other simulation tools, standards, and data sources were used to determine inputs for DOE-2.1E. These inputs include house characteristics, hourly combined infiltration / ventilation airflow rates, duct system efficiency, and the effect of refrigerant charge and system airflow on air conditioning system performance. Figure 1 illustrates the main analysis components. Appendix A provides a more detailed discussion of each of these analyses.

The *background data* (Title 24 (CEC 2001), DOE/EIA Residential Energy Characteristics Survey (EIA 1999), the Building America Program (Ueno 2000), the Richard Heath Associates 100 House Study (Heath 2000), the LBNL Leakage Database (Sherman and Dickerhoff 1998)) were used to develop the house and system characteristics and various inputs to the DOE2.1E model for each of the cases.

To determine hourly ventilation rates, we used the *RESVENT* computer program developed by Sherman and Matson (1993, 1997). This program uses the LBL infiltration model (Sherman and Modera 1984) to calculate infiltration and then combines it with intermittent and continuous mechanical ventilation. An extra step was required for the advanced houses, because their ventilation systems are integrated with the central HVAC systems. In these cases, we used DOE 2.1E to determine the HVAC hourly part load ratios (the fraction that the central HVAC system operates per hour) and then used these values in RESVENT to schedule intermittent mechanical ventilation when calculating the ventilation rates for these houses. Further details on the integrated supply ventilation system modeling are provided in Appendix A.

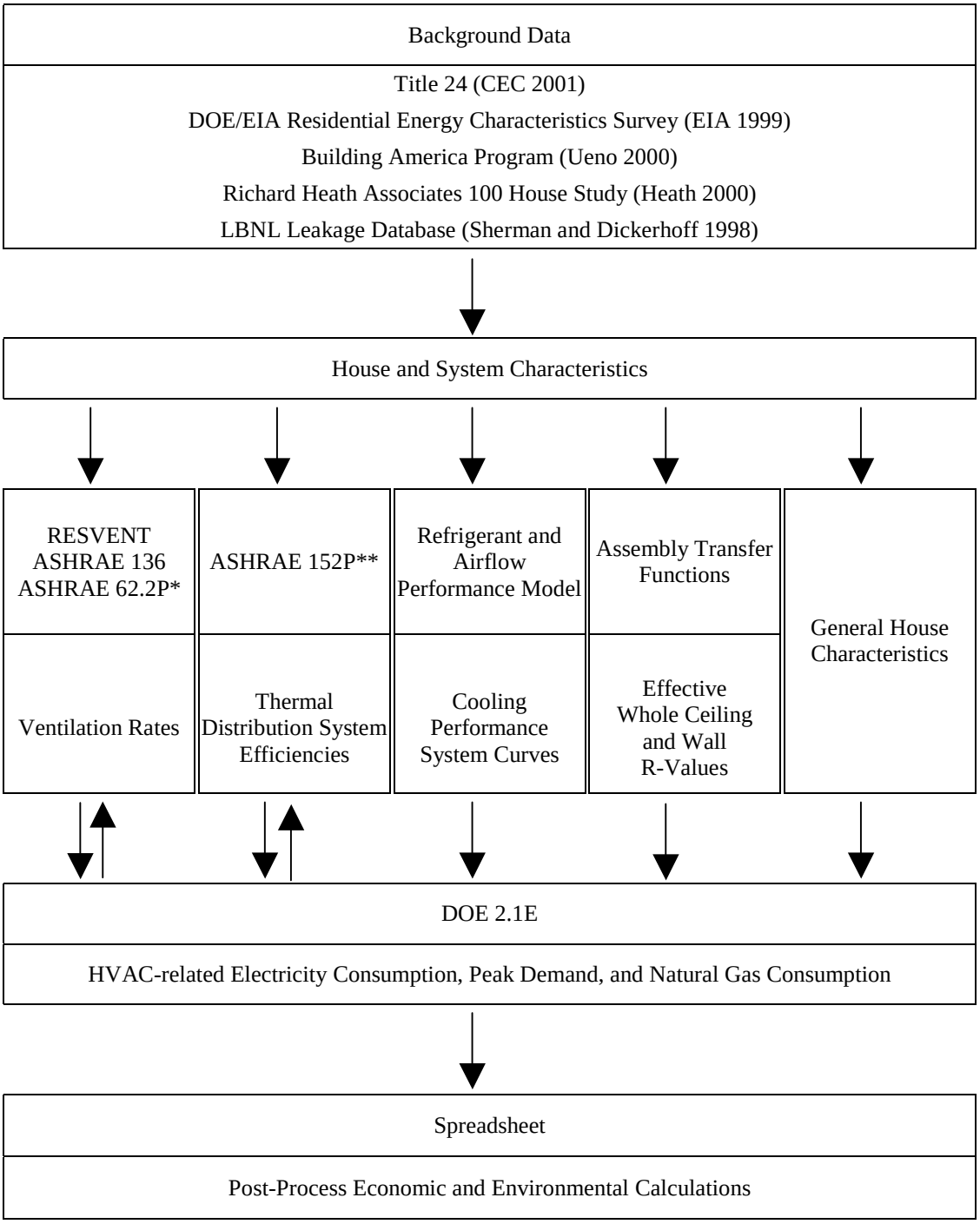
ASHRAE Standard 152P – Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems (ASHRAE 1999) was used to determine the heating and cooling seasonal duct efficiencies for each case. Because the HVAC equipment capacities and airflows are inputs to this method, DOE 2.1E and the 152P models were run iteratively to determine equipment sizes and duct efficiencies. For each analysis case, the average of the heating and cooling seasonal duct efficiencies was used as an input to DOE 2.1E.

The *Refrigerant and Airflow Performance Model* is used to determine the effect of refrigerant charge and system airflow deficiencies on air conditioning system capacity and efficiency. This model uses the charge and airflow degradation algorithms included in the REGCAP model (Siegel 2001), which were originally developed by Proctor Engineering Group (Proctor 2001). The resulting system capacities and efficiencies were used to develop corresponding cooling system performance curves for use in DOE 2.1E.

An LBNL procedure, called WALFERF, for determining DOE 2.1E thermal *assembly transfer functions* was used to evaluate the effect of insulation installation quality issues on overall ceiling and wall R-values. This procedure builds the ceiling or wall assembly in adjacent layers from defined materials with specified thermal variables (conductance, specific heat and density). It uses a finite difference calculation of two-dimensional heat transfer to determine heat transfer through the overall assembly and which allows the

modeling of framing factors, concrete blocks, and other construction not integral to DOE-2.1E.

The *general house characteristics* are the dimensional, material, and HVAC system characteristics used in the DOE 2.1E model. To insure that the heating and cooling hourly loads are met by the HVAC systems for each of the analysis cases, we first sized the HVAC systems based on DOE 2.1E's recommended equipment capacities. DOE2.1E uses the peak loads and the equipment performance curves to determine the heating and cooling equipment at standard conditions (47ºF dry-bulb for heating and 95°F dry-bulb / 67°F entering wet-bulb for cooling). The pre-commissioned low distribution system efficiencies and degraded equipment efficiencies due to low air handler airflow and refrigerant charge were taken into account when adjusting the total capacities upward to insure adequate cooling during the cooling season. We then selected the next larger size of commercially available cooling and heating equipment. A constraint on the gas furnace selection was that they have sufficient airflow for the cooling mode (based on a nominal 400 cfm per ton of air conditioning). This constraint usually leads to oversized furnaces.



*Iterative DOE-2/RESVENT modeling to determine central system contribution to ventilation rates (advanced houses).
**Iterative DOE-2/152P modeling to calculate overall system effect on thermal distribution system efficiencies.

Figure 1: Modeling Structure.

ANALYSIS FRAMEWORK – BUILDING AND CLIMATE CHARACTERISTICS

Our analysis is based on three commissioning phases (audit, commissioning, and opportunity), three house prototypes (existing, new, and advanced), two housing quality analysis sets (typical and poor), and four climate zones (two coastal climates and two inland valley climates).

The Commissioning Phases

The residential commissioning process can be split into three distinct phases – audit and diagnostic (audit phase), tuning and tweaking (commissioning phase), and opportunity identification (opportunity phase). To evaluate the potential energy and cost benefits associated with commissioning-related house improvements, we modeled these three phases in our prototypical houses.

The "audit" phase represents the pre-commissioned houses and is based on what could be found in the houses during the audit and diagnostic phase. This case defines the conditions and possible problems that might be found when commissioning houses in California.

Commissioning and Opportunity Phases – Measures Implemented

Table 2 summarizes the improvements modeled for the commissioning and opportunity phases. The "commissioning" phase includes all measures and improvements that were judged to be within the scope of a normal commissioning visit and resulting from tuning and tweaking the existing structures, components, and systems. For the new houses, we include correcting construction defects (insulation installation quality and incorrect window installation), improving the building envelope and duct system air tightness, and correcting the HVAC system's air handler airflow and refrigerant charge. In the existing houses, the list of commissioning improvements includes envelope and duct air tightening, insulating the ducts, and correcting air handler airflow and refrigerant charge.

The "opportunity" phase includes all measures and improvements implemented in the commissioning case plus any measures and improvements that are more extensive and that would require cost-benefit decision-making and additional owner buy-in and costs. The opportunity case for the existing houses includes insulation installation, improved windows, and the installation of HVAC equipment with a thermostatic expansion valve (TXV), an electronically commutated fan motor (ECM), and higher furnace efficiency (90% AFUE). For the new houses, HVAC equipment with a TXV, an ECM, and 90% AFUE furnace is installed. As the advanced houses already have these improvements, no further opportunities are evaluated for these houses.

Table 2: Commissioning and Opportunity Improvements Modeled

	Commissioning Improvements	Opportunity Improvements
Existing House	- Envelope Air Tightening - Duct Leakage Reduction - Duct Insulation - Air Handler Airflow - Refrigerant Charge	- Insulation Installation - Upgraded windows - HVAC with: TXV ECM Motor 90% AFUE furnace
New House	- Insulation Installation Quality Improvements - Correct Windows Installed - Envelope Air Tightening - Duct Leakage Reduction - Air Handler Airflow - Refrigerant Charge	- HVAC with: TXV ECM Motor 90% AFUE furnace
Advanced House	- Correct Windows Installed - Envelope Air Tightening - Duct Leakage Reduction - Air Handler Airflow - Refrigerant Charge	- No opportunity phase improvements

The following paragraphs summarize the issues addressed in this analysis. As discussed later, we assume that all of these conditions occur in the poor case and to a lesser extent in the typical case.

Insulation Installation Quality. Several studies have found that insulation installation quality varies widely, often with missing, compressed, or improperly installed insulation. In a CEC-funded study, Davis Energy Group found that due to missing or compressed insulation, fiberglass wall insulation performed at 70% of its nominal value, affecting 8.3% of the net wall area (CEC 2000c). Christian et al. (1998) indicate that insulation deficiencies can increase whole-wall heat transfer by about 14%, increasing energy consumption and reducing comfort. Uniacke (2000) found that typically five percent of the attic floor area has no insulation at all, while the rest of the attic is 20% under-insulated due to over-fluffing. Based on the Davis Energy Group and Oak Ridge studies, we assumed a 15 to 16% net reduction in wall assembly insulation effectiveness. For the attics, we assumed that 2.5% of the insulation was missing and that the attic insulation was reduced by 20% due to over-fluffing. Building Science Corporation (Ueno 2001) specifies cocooned insulation methods and blown in cellulose for Building America houses, which eliminates insulation voids or over-fluffing. As such, we assume that the advanced houses do not have any insulation quality degradation.

Correct Windows. The primary purpose of windows is to allow occupants to see outdoors. They also serve as a light source, as an aperture for solar heat gains (desirable during the heating season, but undesirable during the cooling season), and as openings (if operable) for ventilation and free cooling. With the exception of some advanced windows that are not commonly installed, window thermal resistance is much lower than that of opaque elements. Because of these characteristics, windows can be one of the largest contributors to heating and cooling loads in a house. In addition, during the heating season, the use of an inappropriate window can lead to low temperatures on the window's

interior surfaces, which in turn can cause thermal comfort and indoor air quality problems (e.g., increased radiative heat loss from occupants to nearby cool window surfaces, biological growth due to condensation on windows). As a result, having an appropriate window type installed correctly is important.

For example, Carmody et al. (2000) indicate that the thermal conductance and solar heat gain coefficient (SHGC) for a double-glazed window can each be reduced about 60% by using a low solar-gain low-emittance (low-e) coating and a vinyl frame, compared to using clear glazing and an aluminum frame. The spectral selectivity of the low-e coating allows the window to block out much of the sun's heat while transmitting substantial daylight. In turn, this can reduce the peak-cooling load for a typical southern-climate house by about 25%. Glazing emittance and the location of the low-e coating (on the inside surface of the outer pane) are the most important contributors to this difference.

In spite of the importance of these factors, mislabeled windows are still installed in some new California houses. A recent survey involving about 110 houses (approximately 2,800 windows) found on average that 3% of the windows are mislabeled (ConSol 2000). In two of the houses, as many as 17% of their windows were mislabeled. The mislabeling occurs during window manufacturing and is related to placing the virtually invisible low-e coating on the wrong pane (increases SHGC by about 20%) or the window having clear glazing instead of low-solar gain low-e glazing.

The installation of mislabeled windows with the low-e coating missing or located on the wrong pane can increase the solar heat gain coefficient (SHGC) by up to 45% (ASHRAE 1997), increasing window-related space conditioning loads. We assume that all of the poor and 3% of the typical new and advanced houses have clear double-pane windows rather than low-e double pane windows. The existing houses have single-pane windows.

Envelope Air Tightening. Infiltration, or uncontrolled air leakage through the building envelope, can account for up to half of a house's space conditioning loads (Liddament 1996). It is advantageous to reduce infiltration-related space conditioning loads, while still providing sufficient ventilation for indoor air quality purposes. The building envelope leakage values used in this analysis were selected so that they would represent the existing building stock and current new construction practices in California. Sherman and Matson (1997) have used measured building envelope leakage areas to determine a representative range of normalized leakage areas (NL) for existing U.S. housing. Our field measurements found an average normalized leakage of 0.25 for four Las Vegas Building America houses. The Las Vegas houses have construction similar to that found in the Tracy, California Building America houses. These two sets of data were used to estimate normalized leakage values for the analysis cases. For our audit cases, we assumed that the normalized leakage of:

- the existing houses would be equal to that of the existing U.S. housing stock (NL=1.2) for the typical houses and one standard deviation greater for the poor houses (NL = 1.4)
- the new houses would be equal to that of the new California houses built since 1990 in the database (NL = 0.75) for the typical houses and one standard deviation greater for the poor houses (NL = 1.0), and

- the advanced houses would be equal to that found in the Las Vegas Building America houses (NL = 0.25).

Note that Title 24 (CEC 2001b) specifies a default envelope leakage area of 0.49 (SLA=4.9) for new houses.

Duct Leakage Reduction and Duct Insulation. Space conditioning duct systems in un-retrofitted existing houses have typically had, on average, 28% total duct leakage to outside (Jump et al. 1996). For new California houses, Title 24 assumes a default of 22% total duct leakage to outside (CEC 2001). LBNL field measurements in the Las Vegas Building America houses have found an 11% total duct leakage rate to outside. We assigned these values, respectively, to the existing, new, and advanced houses. These values are all higher than the 6% maximum duct leakage required for the Title 24 tight duct credit. In all cases, we are assuming that the duct leakage is split evenly between the supply and return ductwork.

Air Handler Airflow and Refrigerant Charge. Even in new houses, air conditioning systems rarely perform as intended (Sherman et al. 1987). Ensuring good delivery effectiveness and room-by-room distribution efficiency of thermal and ventilation distribution systems depends on maintaining proper airflow across the evaporator coil and through the duct system. Refrigerant charge also has an 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 cooling capacity by 8 to 22% and the energy efficiency ratio (EER) by 4 to 16%, depending on outdoor conditions. Typically, 15% under charge and 15% low evaporator airflow has been seen in residential field studies (Wray 2001). Note that while short-tube orifices are more common than capillary tube orifices, they perform similarly at the 15% under-charge and low flow conditions modeled.

More Efficient HVAC Equipment. Implementing commissioning and opportunity measures will result in lower building space conditioning loads. In existing houses, replacing older HVAC equipment with more efficient equipment having TXVs, ECM motors, and higher gas furnace efficiencies can result in better comfort and lower relative energy costs. Thermostatic expansion valves are less sensitive to variations in refrigerant charge and system airflow than capillary tubes, and are required to avoid air handler flow and refrigerant charge tests in the AB970 modifications to Title 24 (CEC 2001). As such, we have modeled the replacement of capillary tubes with TXV controls. Additional savings can be realized by changing out existing furnace and air handler motors with ECM motors. Extensive field studies (Phillips 1998) have shown that air handler fan motors typically use 0.5 watts per cfm. Phillip's research indicates that using an ECM motor can reduce this fan energy by 20% at high cooling speeds and by 75% at low heating speeds. We took this into account when determining space conditioning-related fan energy.

House Prototypes

Table 3 summarizes the general house characteristics of the three prototypes modeled (existing, new, and advanced). The characteristics of the *existing* houses are based on California and Pacific Region house characteristics derived from the DOE/EIA

Residential Energy Consumption Survey (EIA 1999) and the PG&E 100 house duct study (Richard Heath and Associates 2000).

The characteristics of the new construction houses are based on the Building America houses currently being built by Pulte Homes in Tracy, CA. Building Science Corporation supplied us with the house characteristics (construction, insulation levels, equipment efficiencies, air tightness) for the Pulte control and optimized Building America houses (Ueno 2000). We used the Pulte control house characteristics and the AB970-revised CEC Title 24 Prescriptive Package D requirements (CEC 2000) to develop the *new* houses. Likewise, the characteristics of the *advanced* house were based on the Pulte Building America houses currently being built in Tracy, California.

Table 3: Analysis Prototypes: General House Characteristics

	Existing	New	Advanced
Floor Area (ft^2)	1,455	2,500	2,500
Stories	1	2	2
Bedrooms	3	4	4
Glazing (% of Floor Area)	20% (Coastal) 16% (Inland Valley)	20% (Coastal) 16% (Inland Valley)	20% (Coastal) 16% (Inland Valley)
Foundation	Slab on grade	Slab on grade	Slab on grade
Attic	Outside conditioned space	Outside conditioned space	Inside conditioned space
Duct Location	Attic	Attic	Inside conditioned space

*Coastal climates are El Toro (CEC climate zone 8) and Pasadena (CEC climate zone 9). Inland Valley climates are Sacramento (CEC climate zone 12) and Fresno (CEC climate zone 13).

"Poor" and "Typical" Construction Cases

To provide bounds on our analysis, we have evaluated two construction cases. The "typical" construction case represents our best assumption based on information available today of the mix and penetration of energy efficiency improvements typically found in the California residential building stock. To define the typical construction case any finer would require large-scale stock characteristic analyses, which is beyond the scope of this project. The "poor" construction case represents a worst-case scenario in which the building materials and systems are not optimized and only minimal energy efficiency improvements have been made. The typical cases provide an average level of energy savings and benefits while the poor case defines a much higher level of energy savings and benefits.

Poor Construction Case. Table 4 summarizes the "poor" case characteristics for the three house prototypes. In terms of commissioning benefits, all of the commissioning and opportunity phase improvements included in this analysis are realized to the largest extent in the poor case.

Typical Construction Case. Table 5 summarizes the weighting used to develop the typical house prototypes. The weighting, or the percent of the stock estimated to have a certain characteristic, are based on data from RECS (EIA 1999), the LBNL Leakage Data base (Sherman and Dickerhoff 1998), and field observations (Wray 2001). Eighty separate analyses were conducted, taking into account all of the combinations of improvements (insulation, windows, envelope air tightness, duct air tightness, airflow and refrigerant charge). Analysis results for the various combinations of energy efficiency features were aggregated, based on their weighting, to obtain overall typical case results for each house and commissioning phase case.

Table 4: "As-Found" House Conditions – Poor Case

	Existing	New	Advanced
Insulation	No wall insulation Ceiling: R30 (D) (all Climate Zones)	Walls: R13 (D) (Coastal) R19 (D) (Inland Valley) Ceiling: R30 (D) (Coastal) R38 (D) (Inland Valley)	Walls: R13 (Coastal) R19 (Inland Valley) Roof: R22 (all climate zones)
Windows	Single Pane Aluminum	Clear Double Pane Aluminum	Clear Double Pane Aluminum
Envelope Air Tightness	Loose Existing Construction NL = 1.4	New construction NL = 1.00	Tighter new construction NL = 0.25
Ventilation	Bathroom and kitchen intermittent exhaust fans	Bathroom and kitchen intermittent exhaust fans	Mechanical supply ventilation system, outside air duct to return side of furnace, sized to ASHRAE 62.2P (nominal 62.5 cfm airflow, the ventilation rate can be up to 20% higher when the furnace runs for more than 20 minutes per hour)
Ducts	28% total leakage to outside split evenly between supply and return) No duct insulation	22% total leakage to outside (split evenly between supply and return) R4.2 Duct Insulation	11% total leakage to outside (split evenly between supply and return) R4.2 Duct Insulation
Air Handler Flow	15% reduction in fan flow Standard motor	15% reduction in fan flow Standard motor	15% reduction in fan flow ECM Motor
Air Conditioner Refrigerant Charge	15% undercharged Capillary tube	15% undercharged TXV	15% undercharged TXV
Furnace AFUE	78%	80%	90%
Nominal SEER	10.00	10.00	10.00

*(D) denotes degraded installation quality. Insulation R-value listed is the nominal R-value for the insulating material. The net R-value used in the model takes into account framing factors and insulation installation quality degradation due to missing, compressed or over-fluffed insulation.

Table 5: Typical House Prototypes – Weighting of Characteristics

Existing House		Audit	Commissioning	Opportunity
Insulation	R0 Walls R30 (D) Ceilings	75%	75%	-
	R11 Walls R30/38 Ceilings	25%	25%	100%
Windows	Clear Single Pane Aluminum	75%	75%	-
	Double Pane Vinyl Low-E	25%	25%	100%
Envelope Air Tightness	NL = 1.2	50%	-	-
	Tightened to Std. 62.2P**	50%	100%	100%
Duct Leakage	28% leakage to outside	50%	-	-
	6% leakage to outside	50%	100%	100%
Airflow and Charge	15% low charge / airflow	50%	-	-
	Correct charge / airflow	50%	100%	100%

New House		Audit	Commissioning	Opportunity
Insulation	R13/19 (D) Walls R30/38 (D) Ceilings	40%	-	-
	R13/19 Walls R30/38 Ceilings	60%	100%	100%
Windows	Double Pane Aluminum	3%	-	-
	Double Pane Vinyl Low-E	97%	100%	100%
Envelope Air Tightness	NL = 0.75	75%	-	-
	NL = 0.50	25%	100%	100%
Duct Leakage	22% leakage to outside	50%	-	-
	6% leakage to outside	50%	100%	100%
Airflow and Charge	15% low charge / airflow	50%	-	-
	Correct charge / airflow	50%	100%	100%

Advanced House		Audit	Commissioning	Opportunity
Insulation	R13/19 Walls R22 Roof	100%	100%	100%
Windows	Double Pane Aluminum	3%	-	-
	Double Pane Vinyl Low-E	97%	100%	100%
Envelope Air Tightness	NL = 0.25	25%	-	-
	NL = 0.17	75%	100%	100%
Duct Leakage	11% leakage to outside	50%	-	-
	4% leakage to outside	50%	100%	100%
Airflow and Charge	15% low charge / airflow	50%	-	-
	Correct charge / airflow	50%	100%	100%

*(D) denotes degraded installation quality. Insulation R-value listed is the nominal R-value for the insulating material. The net R-value used in the model takes into account framing factors and insulation installation quality degradation due to missing, compressed or over-fluffed insulation.

**Existing house commissioning case building envelope normalized leakage values (NL) are the level needed to meet the ventilation requirements of ASHRAE Standard 62.2P, and are: El Toro (NL = 0.65), Pasadena (NL = 0.56), Sacramento (NL = 0.49) and Fresno (NL = 0.54).

HVAC Equipment Sizes

Our models assume that the HVAC equipment capacities modeled are sufficiently large enough to meet the loads every cooling hour of the simulation. This allows us to look at the relative energy savings between commissioning phases. In order to evaluate the impact of commissioning houses in which there are existing comfort issues, we modeled a second case, our "comfort call case". This case is discussed only in Appendix C.

Thermostat Setpoints

In order to exchange data between our two hourly models (RESVENT, LBNL's ventilation model based on the LBL infiltration model, and DOE-2) and still obtain a realistic evaluation of temporal ventilation air change rates, we were limited to using a non-setback thermostat approach.

Weather Data

The analysis was conducted for four California climate zones, two in transitional coastal-inland areas ([El Toro [climate zone 8] and Pasadena [climate zone 9]) and two in inland valley areas (Sacramento [climate zone 12] and Fresno [climate zone 13]). These climates were selected to reflect mild and more severe climates, areas with significant existing housing stock, and areas with increases in new residential construction. Table 6 summarizes the ASHRAE and National Weather Service climate data for these climates.

Table 6: Climate Data

		Cooling				Heating	
		Dry bulb Temperature * (F)	Wet bulb Temperature * (F)	Dry Bulb Temperature Range* (F)	Cooling Degree Days**	Dry bulb Temperature * (F)	Heating Degree Days**
El Toro (Long Beach)	1%	88	67	16.7	1201	43	1430
	2%	84	66				
Pasadena (LA County)	1%	81	64	10.9	1537	45	1154
	2%	78	64				
Sacramento	1%	97	69	33.3	1237	33	2749
	2%	94	68				
Fresno	1%	101	70	30.9	1967	32	2556
	2%	98	69				

Sources: *ASHRAE 1997, **National Weather Service 2001

ENERGY PERFORMANCE BENEFITS

The key, readily quantifiable benefits from commissioning California houses are improved energy utilization and reduced operating costs. To demonstrate these benefits, this section first will discusses the individual building improvements that we implemented in the commissioning and opportunity phases. It then discusses the synergistic impact of these improvements on energy consumption and energy-related operating costs.

Building Improvements

Building improvements that we implemented in the commissioning and opportunity phases include insulation and window improvements, envelope air tightening and ventilation, duct efficiency improvements, airflow and refrigerant charge corrections, and using more efficient HVAC equipment. We expect that the combination of these improvements can reduce building space conditioning closer to what was expected when the heating and cooling systems were specified and installed. This reduces energy consumption and correspondingly, the occupant's energy bill. It also may improve occupant comfort, especially when the un-commissioned heating and cooling systems were not able to meet the total space conditioning loads. The following describes the improvements that we modeled.

Insulation

Tables 7 through 9 summarize the nominal (insulation material only) and net (whole assembly) R-values that we modeled for the wall and ceiling assemblies. The audit case assembly R-values reflect the effect of missing, compressed, and/or over-fluffed insulation installation. The existing houses (audit case) have no wall insulation, but have over-fluffed and missing nominal R-30 ceiling insulation (net R-18.5). By adding R-11 wall insulation and additional ceiling insulation to R-30 or R-38 during the opportunity phase, the net insulating values increase by 70% for the walls and by 37 to 40% for the ceilings of the existing houses. By correcting the insulation installation quality problems during the commissioning phase in new houses, net insulating values increase by 16% for walls, and by 37-40% for the ceilings. Because the advanced houses use blown-in cellulose (walls) and cocooned cellulose (roof) that are well installed and do not typically have voids, no commissioning-related insulation improvements are modeled for these houses.

Improving the insulation installation quality in new houses and adding insulation in under-insulated houses reduces envelope-related building space conditioning loads and can help reduce diurnal indoor temperature swings. It can also reduce envelope cold spots where condensation problems might occur and cause building decay and indoor air quality problems.

Table 7: Net Wall Assembly R-Values

		Audit		Commissioning		Opportunity	
		Nominal	Net	Nominal	Net	Nominal	Net
Existing	Coastal	R-0	2.7	R-0	2.7	R-11	9.1
	Inland Valley	R-0	2.7	R-0	2.7	R-11	9.1
New	Coastal	R-13 (D)	8.3	R-13	9.8	R-13	9.8
	Valley	R-19 (D)	11.5	R-19	13.8	R-19	13.8
Advanced	Coastal	R-13	9.8	R-13	9.8	R-13	9.8
	Inland Valley	R-19	13.8	R-19	13.8	R-19	13.8

*(D) denotes degraded installation quality. Insulation R-value listed is the nominal R-value for the insulating material. The net R-value used in the model takes into account framing factors and insulation installation quality degradation due to missing, compressed or over-fluffed insulation.

Table 8: Net Ceiling Assembly R-Value

		Audit		Commissioning		Opportunity	
		Nominal	Net	Nominal	Net	Nominal	Net
Existing	Coastal	R-30 (D)	18.5	R-30 (D)	18.5	R-30	29.5
	Inland Valley	R-30 (D)	18.5	R-30 (D)	18.5	R-38	37.5
New	Coastal	R-30 (D)	18.5	R-30	29.5	R-30	29.5
	Inland Valley	R-38 (D)	22.3	R-38	37.5	R-38	37.5

*(D) denotes degraded installation quality. Insulation R-value listed is the nominal R-value for the insulating material. The net R-value used in the model takes into account framing factors and insulation installation quality degradation due to missing, compressed or over-fluffed insulation.

Table 9: Net Roof Assembly R-Value

		Audit		Commissioning		Opportunity	
		Nominal	Net	Nominal	Net	Nominal	Net
Advanced	Coastal	R-22	17.9	R-22	17.9	R-22	17.9
	Inland Valley	R-22	17.9	R-22	17.9	R-22	17.9

Windows

Table 10 summarizes the shading coefficients and U-values of the windows modeled in each of the three cases. We assume that the clear (no low-e coating) double-pane windows of the new and advanced houses are replaced with the correct low-e double pane vinyl window in the commissioning phase. Low-e double pane vinyl windows are also installed in the existing houses during the opportunity phase.

Table 10: Window Thermal Properties

	Audit				Commissioning				Opportunity			
	Window Type	SHGC	SC	U	Window Type	SHGC	SC	U	Window Type	SHGC	SC	U
Existing	Single	.86	1.00	1.27	Single	.86	1.00	1.27	Double Low-E	.41	.48	.39
New	Double	.75	.87	.51	Double Low-E	.41	.48	.39	Double Low-E	.41	.48	.39
Advanced	Double	.75	.87	.51	Double Low-E	.41	.48	.39	Double Low-E	.41	.48	.39

Source: ASHRAE 1997. DOE 2.1E uses shading coefficients (SC) in determining window-related space conditioning loads. Shading coefficients are for glazing only. The Solar Heat Gain Coefficients (SHGC) is for glazing at normal incidence angles. U-values (U) are in Btu/F-ft^2-hr.

Refrigerant Charge and Air-Handler Airflow Correction

Running an air conditioner with low refrigerant charge and/or low air-handler airflow reduces equipment and system capacities and efficiencies (e.g., EER). Common airflow and charge deficiencies are 85% of the nominal air handler flow and 85% of the required refrigerant charge. The Proctor refrigerant charge algorithms (Proctor 2001) were used in conjunction with fan flow adjustment factors (Rodriguez 1995) to model this effect.

By correcting charge and air-handler airflow problems, air conditioners can more closely provide the expected cooling capacity and operate closer to the expected efficiencies. This reduces discomfort hours, air conditioner-related peak demand, and seasonal energy consumption. By incorporating refrigerant and airflow checks and corrections into the commissioning process, builders and contractors can expect that the equipment they specify is capable of providing the cooling capacity expected, thus reducing service calls and unnecessary equipment change-outs in the future.

Envelope Air Tightening and Ventilation

Tightening the building envelope takes place in the commissioning phase for all of the analysis cases. Envelope air tightening is a standard component of weatherization and energy-efficient construction efforts. It reduces the amount of uncontrolled ventilation, minimizes space-conditioning energy related to excess ventilation, allows better control of the indoor thermal environment and, correspondingly, increases occupant comfort. In tighter houses such as the advanced houses, adding mechanical ventilation allows occupants to better control air movement in their homes and to reduce point source indoor air quality problems (such as moisture and cooking odors).

Table 11 summarizes the ranges of annual effective air change rates calculated based on each of the analysis cases. Climate and case-specific values are provided in Appendix A. We calculated the annual effective air change rates using the methodology on which ASHRAE Standard 136 (ASHRAE 1993) is based, taking into account the hourly infiltration and ventilation airflow rate variations over the year. The effective air change rate is the constant outdoor air change rate that would result in the same average pollutant concentration over the same period of time as actually occurs under varying conditions.

The initial (audit case) effective ventilation rates range from 0.71 to 0.93 ACH (typical) and 0.82 to 1.08 ACH (poor), and are two to three times greater than the ventilation rates required by ASHRAE Standard 62.2P. The effective ventilation rates for the new houses range from 0.44 to 0.57 ACH (typical) and from 0.58 to 0.76 ACH (poor), and are up to double that required. The effective ventilation rates for the advanced houses are the lowest (0.40 to 0.46 ACH) and are 15 to 30% higher than the rate required by the ASHRAE standard.

The existing house envelope leakage is reduced during the commissioning phase to the levels needed to meet the ventilation requirements of ASHRAE Standard 62.2P: El Toro (NL = 0.65), Pasadena (NL = 0.56), Sacramento (NL = 0.49) and Fresno (NL = 0.54). This reduces the annual effective ventilation rates to 0.30 ACH, a reduction of 45 to 58% for the typical cases and 52 to 68% for the poor cases. For the new houses, we reduce the annual effective ventilation rates to 0.30 to 0.39 ACH, a reduction of 32 to 33% for the typical cases and 48 to 49% for the poor cases. Even with these large relative reductions in ventilation and no whole-house mechanical ventilation, all but one of the existing and new air-sealed cases still have effective air change rates equal to or greater than the Standard 62.2P requirements. The effective ventilation rate for the air-tightened El Toro new house is slightly below the Standard 62.2P requirement. Because the large reductions in building envelope leakage provide much lower effective air change rates that are closer to the Standard 62.2P values, we expect there should also be significant reductions in ventilation-related space conditioning energy consumption for the existing and new houses. We did not carry out separate simulations to isolate this reduction.

By reducing envelope leakage for the advanced case during commissioning, we found that the annual effective ventilation rate drops only slightly to 0.39 ACH. After these already tight building envelopes are tightened further, the central system fan runtime modulates upwards to deliver the required ventilation airflow. Had they not had mechanical supply ventilation systems, the advanced houses would not meet ASHRAE Standard 62.2P.

Table 11: Envelope Air Tightening and Ventilation
Annual Effective Ventilation Rates - Air Change per Hour (ACH)

	Standard 62.2P Requirement	Audit Poor Case	Audit Typical Case	Commissioning & Opportunity
Existing	0.38	0.82 to 1.08	0.71 to 0.93	0.39
New	0.34	0.58 to 0.76	0.44 to 0.57	0.30 to 0.39*
Advanced**	0.34	0.40 to 0.41	0.40 to 0.41	0.39

* The El Toro new house does not meet Standard 62.2P when it is tightened to the 0.50 normalized leakage value.

** The advanced houses have mechanical supply ventilation systems, an outside air duct to return side of furnace, sized to ASHRAE 62.2P (nominal 62.5 cfm airflow, the ventilation rate can be up to 20% higher when the furnace runs for more than 20 minutes per hour)

Duct Leakage and Thermal Distribution System Efficiency

Poor construction and operation of residential thermal energy distribution systems can cause comfort problems, poor indoor air quality, and structural moisture problems, as well as wasted energy. In particular, ducts 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 of the conditioned space, duct leakage, duct insulation compression, and other poor installation practices. Reducing duct leakage increases the thermal distribution system efficiency, reduces the amount of energy lost to unconditioned space, and increases the amount of conditioned air delivered to the living spaces.

Table 12 summarizes the ranges of thermal distribution system efficiencies that we modeled (See Appendix A for climate and case specific data). The duct systems for the existing and new houses are located primarily in the unconditioned attics (63% of the total duct surface area) and respectively have 28% and 22% total duct leakage to the outside. By reducing duct leakage during commissioning of the existing houses, duct efficiencies increase from a range of 78 to 82% (poor) and 83 to 85% (typical) to a range of 88 to 90%. For the new houses, those duct efficiencies increase from a range of 81 to 85% (poor) and 83 to 85% (typical) to a range of 86 to 87%. The commissioned new house duct efficiencies are lower than those for the commissioned existing house because the new houses have proportionally more duct surface area in the attics. During the opportunity phase, these efficiencies may drop slightly when implementing smaller HVAC equipment with the same duct system (i.e., the duct system is oversized in relationship to the replacement equipment).

The advanced house duct systems are relatively airtight (11% total leakage to outside) and are located in the conditioned attic. We measured temperature differences between the attic of the Las Vegas Building America houses and outside that were 10% of the temperature difference measured in the control (non-cathedralized attic) house, so the advanced house ducts are modeled assuming that 10% of the duct surface area is in what Standard 152P considers an unconditioned attic and the remainder is in the conditioned space. When air-tightening the advanced house ducts during commissioning, the

corresponding duct efficiencies rise only slightly: the audit case duct efficiencies range from 90 to 91% (poor) and 91 to 92% (typical) while the commissioning case duct efficiencies range from 93% to 94%.

Table 12: Thermal Distribution System Efficiencies

	Audit		Commissioning		Opportunity**
	Poor	Typical*	Poor	Typical*	
Existing	78 to 82%	83 to 85%	89 to 90%	88 to 90%	86 to 87%
New	81 to 85%	83 to 85%	86 to 87%	86 to 87%	86 to 87%
Advanced	90 to 91%	91 to 92%	93 to 94%	93 to 94%	n/a

*Thermal distribution systems efficiencies for the typical cases are aggregated based on the individual typical case component runs.

**Smaller HVAC equipment with the same duct system can result in slightly lower thermal distribution system efficiencies.

More Efficient HVAC Equipment

The opportunity case includes the installation of equipment with thermostatic expansion valve controls (TXVs), electronically commutated motors (ECMs), and higher-efficiency gas furnaces. Each of these improvements addresses a separate part of the energy picture: by installing more efficient equipment, the equipment is better able to meet the load and operate in a more efficient manner; the thermal expansion valve allows for better refrigerant control and less impact on air conditioner performance due to low refrigerant charge and low airflow conditions; the electronically-commutated motor reduces the air conditioning and furnace parasitic electricity consumption by 75% at low-speed heating airflow and 20% at high-speed cooling airflow; and the higher efficiency gas furnace reduces overall gas consumption and related carbon emissions.

The House as a System – Commissioning Benefits

Rather than improving system and equipment efficiency on a component-by-component basis, commissioning considers the house as a system and takes advantage of the interactions between systems and components. By doing so, it is possible to leverage capital and operating cost savings to fund measures that are more expensive. Such an integrated approach allows energy-efficiency measures that make little sense individually (e.g., windows) to be cost-effective and attractive together within the whole system, due to concurrent benefits such as reduced equipment size and improved comfort (RMI 1997). In evaluating the commissioning-related benefits (energy and cost savings), we have quantitatively considered how several measures work synergistically to reduce energy consumption, operating costs, and environmental impacts.

Energy Consumption

Our evaluation of the benefits from commissioning California's houses has considered two levels of related energy savings. The first is the amount of energy saved in the commissioning phase (basic tuning and tweaking) through improving building and duct air tightness, correcting air-handler airflow and refrigerant charge in new and existing

houses alike, and by installing correct windows and improving insulation installation quality in new houses. The second level is the amount of energy saved during the opportunity phase if the homeowner implements all of the improvement opportunities suggested, plus improved insulation and windows in existing houses, and more efficient HVAC equipment (TXV, ECM, and 90% AFUE furnace efficiencies) for the existing and new houses.

Aggregation of Energy Consumption Results

Energy usage and corresponding savings are determined for each case by aggregating the individual building energy usage relating to the commissioning and opportunity measures. As discussed previously and in Appendix A, these values are derived from DOE-2.1E and other modeling that we used to determine annual electricity and natural gas consumption. The aggregate energy consumption values are based on space conditioning energy (cooling, heating, ventilation, and related fans). All results are discussed in terms of site energy.

Typical Cases - Aggregation of Energy Consumption Results. The typical case energy consumption results are calculated by weighting the aggregate energy consumption values for the individual typical case runs. For example, the electricity consumption results from the individual typical existing audit case runs are weighted based on the penetration rate of the individual components to obtain the average electricity consumption values for the typical existing audit case.

Electricity Consumption and Savings

The annual space conditioning-related annual electricity consumption rates and percent savings are summarized in Table 13. Electricity consumption values are provided per square foot of conditioned space to provide comparisons between building types. All savings percentages are reported in terms of savings over the audit cases.

Audit Cases

For the typical audit cases, the one-story existing houses use the highest annual space conditioning-related electricity consumption (1.6 to 4.3 kWh/ft^2 - yr. The electricity consumption of the advanced and new audit case houses are similar (0.7 to 1.8 kWh/ft^2/year and 0.6 to 1.8 kWh/ft^2/year, respectively). In all house types, the electricity consumption of the coastal houses is on the lower end of the range, followed by Sacramento and Fresno. The Fresno houses have almost double the electricity consumption as the Sacramento houses, driven by the more severe Fresno cooling climate. While the advanced audit case houses have tighter envelopes and ducts and mechanical ventilation systems, the coastal and Sacramento climate advanced houses use 9 to 24% more electricity than the new houses. We found that the tighter advanced houses had less available infiltration and ventilation-driven free cooling in these climates and required more air conditioning-related electricity consumption. The Fresno houses are less affected by infiltration-driven free cooling, resulting in lower electricity consumption for the advanced house than for the new house.

The poor cases represent houses in which all of the commissioning and opportunity measures would be applicable. As would be expected, compared to the typical cases, the

poor audit cases use about 30% more electricity for the existing house and two to three times more for the new and advanced houses.

Commissioning and Opportunity Cases

Existing Houses: Commissioning activities in the existing houses include envelope and duct air-sealing and correcting air handler airflow and refrigerant charge. The typical existing cases, when commissioned, show a 14 to 18% reduction in electricity consumption. The poor existing cases have higher envelope leakage values and show a 20 to 28% reduction in post-commissioning electricity consumption. Taking it one step further in the opportunity phase (wall and increased ceiling insulation, low-e double pane window upgrades, and more efficient HVAC equipment), it is possible to reduce electricity consumption by 61 to 74% for the typical cases and 71 to 80% for the poor cases. Note that the inland valley climates have slightly higher commissioning-related savings percentages than the coastal climates. This percentage difference levels out when the additional opportunities are implemented.

New Houses: Commissioning activities in the new houses include correcting insulation installation problems, installing correct windows, envelope and duct air-sealing and correcting air handler airflow and refrigerant charge. The typical new houses, when commissioned, show a 7 to 11% reduction in electricity consumption. The poor new cases show a larger reduction in electricity consumption (55 to 71%), driven by replacing clear double pane windows with low-E double pane windows. The installation of more efficient HVAC equipment in the opportunity phase does not make a significant difference in the typical new cases. Savings are increased by one percentage point at most over the savings achieved in the commissioning phase.

Advanced Houses: Commissioning the advanced houses includes the same measures implemented in the new house (correcting insulation installation problems, installing correct windows, envelope and duct air-sealing, and correcting air handler airflow and refrigerant charge). As the advanced audit cases already have relatively air tight envelopes (NL=0.25) and ducts (11% leakage to outside), and do not have significant insulation installation problems, the savings are small (7 to 10%) for the typical cases. As found with the new poor cases, replacing incorrectly-installed clear double pane windows with the correct low-e double pane windows increases the savings significantly to 52 to 73%.

Table 13: Space Conditioning System Electricity

		Electricity Consumption (kWh/ft^2/year)							
		Typical				Poor			
		El Toro	Pasadena	Sacramento	Fresno	El Toro	Pasadena	Sacramento	Fresno
Existing	Audit	1.62	2.20	2.29	4.26	2.13	2.87	3.04	5.69
	Commissioning	1.37	1.90	1.92	3.50	1.69	2.30	2.30	4.10
	Opportunity	0.42	0.69	0.75	1.66	0.42	0.69	0.75	1.66
New Title 24	Audit	0.55	0.81	0.89	1.83	1.76	2.21	2.07	3.57
	Commissioning	0.51	0.75	0.81	1.62	0.51	0.72	0.81	1.62
	Opportunity	0.50	0.71	0.79	1.61	0.50	0.71	0.79	1.61
Building America	Audit	0.68	0.87	0.96	1.79	2.21	2.55	2.25	3.49
	Commissioning	0.61	0.79	0.89	1.67	0.61	0.79	0.89	1.67
		Electricity Savings (% of Audit Case)							
		Typical				Poor			
		El Toro	Pasadena	Sacramento	Fresno	El Toro	Pasadena	Sacramento	Fresno
Existing	Audit	-	-	-	-	-	-	-	-
	Commissioning	15%	14%	16%	18%	21%	20%	25%	28%
	Opportunity	74%	69%	67%	61%	80%	76%	75%	71%
New Title 24	Audit	-	-	-	-	-	-	-	-
	Commissioning	7%	7%	9%	11%	71%	67%	61%	55%
	Opportunity	8%	12%	11%	12%	72%	68%	62%	55%
Building America	Audit	-	-	-	-	-	-	-	-
	Commissioning	10%	10%	7%	7%	73%	69%	60%	52%

Natural Gas Consumption and Savings

The annual space-conditioning-related natural gas consumption and savings are summarized in Table 14. Compared to the new and advanced typical audit cases, the existing typical audit cases use two to four times more gas per square foot. Comparing the poor cases to the typical cases, the poor audit cases use about 40% more gas for the existing houses, about the same (coastal climates) to 20% more (inland climates) for the new houses, and about the same for the advanced houses.

Commissioning the existing and new houses results in significant natural gas savings. For the existing houses, savings range from 18 to 21% (typical cases) and 33 to 36% (poor cases). Implementing opportunity measures such as wall and improved ceiling insulation, double pane low-E windows, and improved HVAC equipment increases the existing house savings to 44 to 54% (typical cases) and 59 to 67% (poor cases). With these improvements, the opportunity phase existing houses use about the same amount of gas per square foot as the audit case new houses. For the new houses, commissioning-related savings range from 24 to 25% (typical cases) and 18 to 35% (poor cases). Improving the furnace efficiency in the opportunity phase increases these savings slightly to 28 to 31% (typical cases) and 22 to 41% (poor cases).

The advanced typical cases realize a small range of commissioning-related savings (2 to 3%). The corresponding poor cases see negative savings (-19 to –10%). These low and negative heating-related gas consumption savings are due to the reduction in heating season solar gain by installing the correct low-e double pane windows.

Table 14: Space-Conditioning-Related Natural Gas

		Natural Gas Consumption (Therm/ft^2/year)							
		Typical				Poor			
		El Toro	Pasadena	Sacramento	Fresno	El Toro	Pasadena	Sacramento	Fresno
Existing	Audit	0.13	0.14	0.35	0.31	0.18	0.19	0.48	0.42
	Commissioning	0.11	0.11	0.27	0.25	0.12	0.13	0.31	0.28
	Opportunity	0.07	0.07	0.16	0.14	0.07	0.07	0.16	0.14
New Title 24	Audit	0.07	0.07	0.18	0.16	0.06	0.07	0.21	0.18
	Commissioning	0.05	0.05	0.14	0.12	0.05	0.05	0.14	0.12
	Opportunity	0.05	0.05	0.12	0.11	0.05	0.05	0.12	0.11
Building America	Audit	0.04	0.04	0.09	0.09	0.03	0.03	0.08	0.08
	Commissioning	0.04	0.04	0.09	0.08	0.04	0.04	0.09	0.08

		Natural Gas Savings (% of Audit Case)							
		Typical				Poor			
		El Toro	Pasadena	Sacramento	Fresno	El Toro	Pasadena	Sacramento	Fresno
Existing	Audit	-	-	-	-	-	-	-	-
	Commissioning	18%	19%	21%	19%	33%	35%	36%	34%
	Opportunity	44%	47%	54%	53%	59%	62%	67%	66%
New Title 24	Audit	-	-	-	-	-	-	-	-
	Commissioning	25%	24%	24%	24%	18%	22%	35%	34%
	Opportunity	29%	28%	31%	31%	22%	26%	41%	40%
Building America	Audit	-	-	-	-	-	-	-	-
	Commissioning	2%	2%	3%	3%	-19%	-18%	-10%	-10%

Annual Operating Costs

We calculated annual operating costs based on the annual electricity and natural gas consumption values for each case, using the DOE/EIA 1999 California annual fuel costs of $0.1071/kWh (EIA 2000) and $0.634/therm (EIA 2001). These values provide a base level of comparison. Energy price increases, such as those experienced during the winter 2000/2001 California energy crisis, will further enhance the attractiveness of commissioning California's houses. The annual space-conditioning-related annual operating costs and savings are summarized in Table 15.

As expected for the typical audit cases, the existing houses have the highest space conditioning-related operating costs ($0.26 to $0.65 per square foot). The new house operating costs are lower. While the advanced cases use 40 to 50% less gas than the new cases, they use up to 24% more electricity. As a result, the operating costs for the advanced houses are about the same as for the new houses ($0.10 to $0.29 per square foot for the new houses and $0.10 to $0.25 per square foot for the advanced houses). The corresponding existing poor audit cases have 33 to 36% higher operating costs while the new and advanced poor audit cases have two to three times the operating costs of the typical cases. This increase is primarily due to the large impact of clear versus low-E double pane windows in the poor new and advanced audit cases.

For the typical cases, commissioning results in operating cost savings of 15 to 18% for the existing houses, 12 to 17% for the new houses, and 6 to 8% for the advanced houses. Implementing opportunity phase building and equipment improvements results in 59 to

64% savings in the existing houses and a slight increase to 17 to 22% savings in the new houses.

Operating cost savings are highest for the poor cases, ranging from 25 to 30% for the existing cases, 50 to 62% for the new cases, and 45 to 66% for the advanced cases. The opportunity phase improvements result in 69 to 73% operating cost savings for the existing cases. Implementing the higher furnace efficiency and the ECM motor increases the new operating cost savings slightly to 51 to 63%.

Table 15: Space-Conditioning-Related Operating Costs

		Operating Costs ($/ft^2/year)							
		Typical				Poor			
		El Toro	Pasadena	Sacramento	Fresno	El Toro	Pasadena	Sacramento	Fresno
Existing	Audit	0.26	0.32	0.46	0.65	0.34	0.43	0.63	0.88
	Commissioning	0.22	0.27	0.38	0.53	0.26	0.33	0.44	0.62
	Opportunity	0.09	0.12	0.18	0.27	0.09	0.12	0.18	0.27
New Title 24	Audit	0.10	0.13	0.21	0.29	0.23	0.28	0.35	0.50
	Commissioning	0.09	0.11	0.17	0.25	0.09	0.11	0.17	0.25
	Opportunity	0.08	0.11	0.16	0.24	0.08	0.11	0.16	0.24
Building America	Audit	0.10	0.12	0.16	0.25	0.26	0.29	0.29	0.42
	Commissioning	0.09	0.11	0.15	0.23	0.09	0.11	0.15	0.23

		Operating Cost Savings (% of Audit Case)							
		Typical				Poor			
		El Toro	Pasadena	Sacramento	Fresno	El Toro	Pasadena	Sacramento	Fresno
Existing	Audit	-	-	-	-	-	-	-	-
	Commissioning	16%	15%	18%	18%	25%	24%	30%	30%
	Opportunity	64%	63%	61%	59%	73%	72%	71%	69%
New Title 24	Audit	-	-	-	-	-	-	-	-
	Commissioning	15%	12%	17%	15%	62%	61%	51%	50%
	Opportunity	17%	17%	22%	18%	63%	62%	54%	51%
Building America	Audit	-	-	-	-	-	-	-	-
	Commissioning	8%	8%	6%	6%	66%	63%	48%	45%

Non-Energy Benefits

In addition to reducing energy consumption and associated operating costs, implementing commissioning and opportunity measures helps improve building and system durability, reduces maintenance and material replacement costs, increases house resale value, improves indoor environmental quality, and benefits the environment and the economy.

Durability, Maintenance, Material Replacement, and Resale Value

Improved Durability

By improving the building structure through airtightness, insulation, and window upgrades, we expect that there would be a reduction in building envelope failure problems, such as material decay due to moisture damage. A more uniformly insulated

and airtight building envelope can help reduce cold spots, which foster moisture and material damage.

Reduced Maintenance, Material, and Equipment Replacement

Improving the air conditioner efficiency and increasing the delivered capacity in a well-performing house sets the stage for the house and equipment to operate as designed or expected. In the case of air conditioning systems, this could reduce the number of burned-out motors and compressors caused by incorrect refrigerant charge and low air-handler airflow. It follows that equipment could last longer, which would reduce replacement costs over the life of a house. There also could be a reduction in maintenance costs, especially related to equipment performance problems.

Increased Resale Value

Housing value and utility costs reported in the American Housing Survey (Nevin and Watson 1998) indicate that house resale value increases from $10 to $25 for each dollar of annual energy savings. This relationship was evaluated for a variety of sample sizes (national vs. all metropolitan statistical areas), housing types, and heating fuels. More specifically, for single-family detached houses, regardless of fuel type, they found a $20 average increase in housing resale value per dollar of annual energy savings.

The California Association of Realtors (CAR 2001) reports the average price of an existing; single-family detached house in California during January 2001 was $246,380 (based on 508,060 closed escrow sales) and $262,980 in March 2001 (Sinton 2001). Based on these prices and our energy analyses, and assuming a $20 average increase in housing resale value per dollar of annual energy savings, the energy savings realized through commissioning could result in average incremental resale value increases of:

- $1,200 to $3,500 (typical) and $2,500 to $7,600 (poor) in existing cases,
- $700 to $2,300 (typical) and $7,000 to $12,300 (poor) in new cases, and
- $400 to $700 (typical) and $8,400 to $9,500 (poor) in advanced cases.

Taking advantage of additional opportunities identified in the commissioning process could result in an additional incremental energy-related increased resale values from $3,600 to $7,600 (typical) and $4,800 to $10,000 (poor) more in existing cases and up to $400 more in poor new cases.

The energy-savings-related increased resale values described above are on the low end of the scale for the coastal climates and on the high end of the scale for the inland valley climates.

Comfort and Indoor Air Quality

An important benefit of commissioning is the improvement of thermal comfort, indoor air quality, and combustion safety (which in part affects indoor air quality). Indoor environmental quality issues are not directly addressed in the DOE-2.1E modeling, but we expect that by improving the building envelope and the building systems, thermal comfort can be improved by providing more uniform conditions throughout the house. Reducing infiltration reduces the amount of air that is brought into the house from crawlspaces, garages, and other areas having moisture or contaminants that negatively

affect indoor air quality. Improving the building envelope through air tightening and improved insulation quality reduces cold spots that could lead to envelope moisture problems. Improving HVAC equipment through duct air tightening and correcting refrigerant charge and air-handler and duct airflow problems delivers more conditioning capacity to the house and is better able to keep the house comfort conditions closer to set-points and within occupants expectations. These improvements contribute to a better indoor environment.

Environmental Protection

By improving the durability and energy efficiency of California houses through commissioning, the environment benefits from reduced building energy consumption-related carbon emissions and lower embodied energy and waste over the lifetime of the houses.

Reduced Carbon Emissions

Typical households contribute carbon emissions to the atmosphere by using electricity and natural gas in their homes. By reducing electricity and natural gas consumption in California houses, we are able to reduce the corresponding carbon emissions into the atmosphere. For the purpose of this analysis, we are using a marginal emission rate of 0.10 kg/kWh of site energy consumption, based on utility electricity production using improved generation and emissions technologies. This marginal rate assumes that efficient, low-emission generation plants are used. For natural gas, we are using a marginal emission rate of 5.2 kg/therm of site energy consumption (ASHRAE 1997). Table 16 summarizes the space conditioning-related carbon emission reductions. As the carbon emissions scale with the amount of electricity and natural gas consumed in a house, the relative amount of carbon emission reductions follows the same general trends seen with electricity, natural gas and operating cost savings.

For the typical cases, commissioning the existing and new houses results in 200 to 600 kg/house/year carbon emission reductions (19 to 23%, existing, and 23 to 26%, new). The advanced house, due to its already advanced energy efficient construction, sees a smaller 30 to 60 kg/house/year carbon emission reduction (4%). When additional opportunities are implemented the carbon emission reductions almost triple in the existing houses, to 630 to 1630 kg/house/year (56 to 62%), and increase slightly in the new houses, to 260 to 750 kg/house/year (28 to 33%).

The commissioned poor existing and new cases have twice as much net carbon reductions as the typical houses, from 500 to 1450 kg/house/year (35 to 40%, existing, and 41 to 44%, new). The advanced houses see an almost ten-fold net carbon emissions, from 230 to 360 kg/house/year due to the replacement of clear double pane windows with low-e double pane windows. When additional opportunities are implemented the carbon emission reductions almost double in the existing houses, to 1070 to 2690 kg/house/year (71 to 77%) and increase slightly in the new houses, to 490 to 1430 kg/house/year (44 to 50%).

Table 16: Space Conditioning System – Related Carbon Emission Reductions

		Kg/house-year					
		Typical			Poor		
		Electricity Related	Gas Related	Total Fuel Related	Electricity Related	Gas Related	Total Fuel Related
Existing	Commissioning	40 to 110	180 to 550	220 to 610	70 to 230	460 to 1330	530 to 1440
	Opportunity	170 to 380	450 to 1400	630 to 1640	250 to 590	820 to 2440	1070 to 2690
New	Commissioning	10 to 50	210 to 570	220 to 580	310 to 490	140 to 960	460 to 1270
	Opportunity	10 to 50	250 to 720	260 to 750	320 to 490	170 to 1110	490 to 1430
Advanced	Commissioning	20 to 30	10 to 40	30 to 60	340 to 460	-110 to -80	230 to 360

		Percent of Audit Case					
		Typical			Poor		
		Electricity Related	Gas Related	Total Fuel Related	Electricity Related	Gas Related	Total Fuel Related
Existing	Commissioning	14 to 18%	20 to 24%	19 to 23%	20 to 28%	39 to 42%	35 to 40%
	Opportunity	61 to 74%	52 to 63%	56 to 62%	71 to 80%	68 to 78%	71 to 77%
New	Commissioning	7 to 11%	28 to 29%	23 to 26%	55 to 71%	21 to 41%	41 to 44%
	Opportunity	8 to 12%	33 to 36%	28 to 33%	55 to 72%	26 to 47%	44 to 50%
Advanced	Commissioning	7 to 10%	2 to 4%	4%	52 to 73%	-23 to 12%	15 to 36%

Lower Embodied Energy and Waste

Qualitatively, because commissioning improves the envelope and its component systems and materials, material and equipment replacement are needed less frequently. The lifetime of the house is also lengthened. In terms of the environment, this translates into a lower use of natural resources and correspondingly, a lower embodied energy (the amount of energy required for manufacture, construction, and deconstruction and waste reduction and decay) over the lifetime of the house.

The Economy

The economy, within and beyond the State of California, is a direct benefactor of the building improvements implemented in the commissioning and opportunity phases. Commissioning contributes to reduced energy costs, which frees up increased funds for other purposes; expanded business opportunities; the development of new industries; increased jobs for California residents; and increased tax revenues.

Reduced Energy Costs = Increased Funds for Other Purposes

Improving the energy efficiency of California's houses will reduce energy bills for California residents. These reduced energy bills allow occupants opportunities to live better within their means and to use funds freed up by reduced energy costs to pursue other goals, such as education and improved health and comfort. This correspondingly helps the related California industries, such as education, health, and leisure-related industries.

Expanded Business Opportunities

California's construction, HVAC, rating and weatherization, and energy consulting industries already implement parts of the overall commissioning package on a piecemeal basis. Commissioning practices described here build upon this local business base. Integrating commissioning services into their current business practices will allow these industries to expand their services, provide additional benefits to their customers, and provide a much higher level of service in the short, medium, and long-term.

In order for these industries to expand, however, we need to insure that there are sufficient contractors and service providers. Because of their established business areas and skill sets, CHEERS raters and HVAC contractors are most able to expand their businesses to include commissioning. Home inspectors, who have a good general background and are trained to look for problems could learn how to do detailed instrumented testing and to implement commissioning improvements. As such, we see commissioning as an opportunity to expand the current market activities and open it up to new participants.

Development of New and Expanded Industries

The implementation of residential commissioning in California will influence the development of new measurement techniques, new technologies, and new services (such as integrated, whole-house commissioning and building improvement services). The expanding industries that implement residential commissioning practices in California should lead to best practice guides and protocols, improved building and energy codes, and enhanced Home Energy Rating Systems (HERS). The implementation of commissioning will begin to stimulate the development of improved products by equipment and component manufacturers and of improved services by HVAC contractors, energy service companies, and other residential market participants. The California building, HVAC, and energy service industries will be able to implement and market improved residential building energy systems, equipment and other products, and energy efficiency services as part of their normal business practices. There are opportunities for added market penetration of new products related to commissioning, Title 24, and HERS implementation in the new construction and existing residential market. This will result in the development of new industries, encompassing providers of expanded commissioning services and the segment of the manufacturing industries constructing and marketing new commissioning-related test equipment and materials within and outside of California.

Increased Jobs for California Residents

To maximize successful implementation of commissioning in the California residential market, a trained and knowledgeable work force is necessary. The existing construction, HVAC, weatherization, rating and energy consulting industries provide a structure within which the existing workforce can be trained to provide commissioning services. As residential commissioning becomes a part of these industries' normal operating procedures, this will result in more jobs for California, from technician to CEO.

Increased Tax Revenues

The State of California will receive additional tax revenues on sales and services relating to commissioning of California houses. In addition, California will receive income taxes related to the additional jobs required to perform commissioning services and implement commissioning and opportunity phase measures.

CONCLUSIONS

The Benefits of Commissioning

By commissioning California houses, many parties benefit. The magnitude of the benefits to a specific party or stakeholder depends on how that stakeholder weighs the commissioning-related economic and non-economic benefits.

The *occupants*, whether they are homeowners or renters, benefit from better performing systems and houses, increased comfort, and more efficient use of the energy they are paying for. The efficiency improvements result in reduced energy consumption and reduced energy bills, freeing up their energy dollars for other needs and goals. Homeowners see greater building and system durability and, correspondingly, longer lifetimes for house system and components. This reduces maintenance and replacement costs and increases home resale values. Through energy reductions and performance improvements realized by the implementation of commissioning, occupants help the environment by reducing carbon emissions, lowering embodied energy, and reducing use of natural resources.

Members of the *building community* (e.g., builders, HVAC contractors) benefit from an improvement in building and system performance and quality, which can reduce their callback and warranty costs. The building community, including HERS raters and house inspectors, will have access to an expanded market sector with a more diverse client base. This will allow them greater employment and greater revenues through increased business. They will see an integration of commissioning services into their normal business model, allowing for an expansion of maintenance and installation services.

The *utilities* benefit from reduced peak demand, translating into lower energy acquisition costs. The utilities also benefit from realizing lower carbon emissions, allowing them increased compliance with environmental regulations.

Governmental bodies (the California Energy Commission and the Air Resources Board) benefit from greater assurance that actual energy consumption and carbon emissions are closer to the levels mandated in codes and standards, resulting in better achievement of state energy conservation and environmental goals.

Building code officials benefit from better compliance with codes as the commissioning process catches construction defects and code problems.

The *insurance industry* benefits from reduced insurance claims and litigation due to problems caused by poor-performing building envelopes and systems.

The *banking industry* benefits from increased economic activity due to reduced house operating costs and increased revenues for commissioning-related businesses.

The State benefits directly and indirectly from commissioning activities. Improved building performance and better indoor environmental comfort helps improve the quality of life for California residents. The corresponding reduced energy bills free up money for residents to spend on other needs or goals, such as additional education and health and welfare. In the expansion of existing industries and the development of new industries related to commissioning, the state sees an increase in jobs and tax revenue, improving the quality of life for the state as a whole.

Commissioning Makes Sense for California's Houses

While building codes and energy standards lead towards greater efficiency of new houses, commissioning results in even greater energy efficiency in both new and existing houses. Commissioning benefits limited to tuning and tweaking of existing buildings and systems (building air tightness, duct tightening, refrigerant charge and HVAC system airflow correction) may result in 15 to 30% HVAC-related operating cost savings. Implementing opportunities identified in the commissioning process (insulation, improved windows, more efficient HVAC equipment, and mechanical ventilation) may result in 60 to 75% HVAC-related operating cost savings in existing houses. In new houses, commissioning benefits related to correcting construction defects and tuning and tweaking the building and systems may result in 10 to 20% HVAC-related operating cost savings in typical houses and 50 to 60% savings in houses with significant problems (clear instead of low-e double glazed windows, poor installation quality and poor building and system performance). Advanced energy-efficient new construction with typical building and system performance problems may see up to 8% operating cost savings. Where significant problems occur, these buildings may realize up to 65% operating cost savings.

Commissioning also helps reduce peak demand and improve the indoor environment in a subset of homes throughout the state. Quantification of these benefits, however, requires further study.

Houses Perform Closer to Expectations

Currently, the energy savings estimated due to energy codes are not being realized. By improving performance, it is more likely that the energy savings realized would be closer to estimates and expectations. For the occupant, defining expectations and acceptability is difficult. By improving building and system performance, the houses will be better able to provide sufficient space conditioning and improved thermal comfort which work towards meeting the occupant's expectations.

Commissioning as Part of the Business Package

Various players in the building industry currently do some level of commissioning, however small. For example, through compliance credits, California's Title 24 energy code already provides some commissioning elements for evaluating the energy performance of new houses (e.g., visual inspection, functional performance diagnostics). Many of these elements can be integrated into new industry guidelines for testing and tuning system performance in new and existing houses.

The existing California residential building industry and new developing industries can be augmented and expanded to include commissioning services. The Home Energy

Rating Systems (HERS), home inspection services, and home performance consulting industries provide a framework within which to incorporate the commissioning model. Commissioning can be integrated into existing business models, however training and business assistance would be needed to make sure that businesses offering commissioning services to their clients are able to provide significant parts of the commissioning package. Implementing only one part of commissioning, such as correcting air handler airflow and refrigerant charge, without checking duct air tightness results in missed opportunities and leads the homeowner to believe that the house has been optimized and cannot perform any better. But, if that same contractor had been able to look at the house as a system and evaluate and tweak and tune the performance of all parts of the house, a much more efficient house would result and more opportunities may be implemented.

Commissioning Helps California

The benefits of commissioning California's houses are widespread. The improvements incorporated in the commissioning phase results in a significant level of energy savings in existing houses as well as in new houses. Implementing the opportunity phase measures in existing houses can reduce their energy consumption per square foot down to the level of the new houses. Of course, this is at a greater cost than if it were implemented during the design and construction process. All of the stakeholders (occupants, homeowners, builders and contractors, utilities, state agencies, code authorities, the insurance and banking industry, the environment, and the economy) stand to benefit from the implementation of commissioning-related performance improvements in California's houses. By understanding the types and magnitudes of benefits, California's business community should be able to realize increased business and profitability.

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APPENDIX A – MODELING ASSUMPTIONS

Opaque Envelope Elements

The opaque envelope elements modeled include walls, ceilings, roofs and floors. Floors are un-insulated slab on grade. Table A-1 summarizes the overall characteristics of the remaining elements.

Table A-1: Wall, Ceiling and Roof Characteristics

	Framing	Framing Fraction	Cavity Insulation Type	Interior Surface Type	Exterior Surface Type
Walls	All Existing Houses and Coastal New Houses: 2”x4” @ 16” on center Inland New Houses: 2” x 6” @ 24” on center	25%	Existing: Blown Cellulose* Title 24: Fiberglass Batt Advanced: Blown Cellulose	½” gypsum	Stucco
Ceiling	2”x6” @ 24” on center	10%	Existing and Title 24: Blown Cellulose Advanced: None	½” gypsum	Attic Air
Roof	2” x 4” @ 24” on center	10%	Existing and Title 24: None Advanced: Blown Cellulose (Cocooned)	Attic air	Shingles, Building Paper, ½” Plywood

*Opportunity case only.

Insulation Installation Quality. Several studies have found that insulation installation quality varies widely, often with missing, compressed, or improperly installed insulation. In a CEC-funded study, Davis Energy Group found that due to missing or compressed insulation, fiberglass wall insulation performed at 70% of its nominal value, affecting 8.3% of the net wall area (CEC 2000c). Christian et al. (1998) indicate that insulation deficiencies can increase whole-wall heat transfer by about 14%, increasing energy consumption and reducing comfort. Uniacke (2000) found that typically five percent of the attic floor area has no insulation at all while the rest of the attic is 20% under-insulated due to over-fluffing. Based on the Davis Energy Group and Oak Ridge studies, we assumed a wall insulation void factor of 30%. For the attics, we assumed that 2.5% of the insulation was missing and that the attic insulation was reduced by 20% due to over-fluffing. Building Science Corporation (Ueno 2001) specifies cocooned insulation methods and blown in cellulose for Building America houses, which eliminates insulation voids or over-fluffing. As such, we assume that the advanced houses do not have any insulation quality degradation.

For the new commissioning cases, our model assumes these installation problems are resolved. The model for the existing opportunity case assumes that R-11 wall insulation

and additional ceiling insulation has been correctly installed. Tables A-2, A-3 and A-4 summarize the nominal and net (whole assembly) R-values for the wall, ceiling (existing and new houses), and roof (advanced houses) assemblies. Because the advanced houses use blown-in cellulose (walls) or cocooned cellulose (roof) cavity insulation that is well installed and does not typically has voids, no commissioning-related insulation improvements are modeled.

Table A-2: Net Wall Assembly R-Values

		Audit		Commissioning		Opportunity	
		Nominal	Net	Nominal	Net	Nominal	Net
Existing	Coastal	R-0	2.7	R-0	2.7	R-11	9.1
	Inland Valley	R-0	2.7	R-0	2.7	R-11	9.1
New	Coastal	R-13 (D)	8.3	R-13	9.8	R-13	9.8
	Valley	R-19 (D)	11.5	R-19	13.8	R-19	13.8
Advanced	Coastal	R-13	9.8	R-13	9.8	R-13	9.8
	Inland Valley	R-19	13.8	R-19	13.8	R-19	13.8

*(D) denotes degraded installation quality. Insulation R-value listed is the nominal R-value for the insulating material. The net R-value used in the model takes into account framing factors and insulation installation quality degradation due to missing, compressed or over-fluffed insulation.

Table A-3: Net Ceiling Assembly R-Value

		Audit		Commissioning		Opportunity	
		Nominal	Net	Nominal	Net	Nominal	Net
Existing	Coastal	R-30 (D)	18.5	R-30 (D)	18.5	R-30	29.5
	Inland Valley	R-30 (D)	18.5	R-30 (D)	18.5	R-38	37.5
New	Coastal	R-30 (D)	18.5	R-30	29.5	R-30	29.5
	Inland Valley	R-38 (D)	22.3	R-38	37.5	R-38	37.5

*(D) denotes degraded installation quality. Insulation R-value listed is the nominal R-value for the insulating material. The net R-value used in the model takes into account framing factors and insulation installation quality degradation due to missing, compressed or over-fluffed insulation.

Table A-4: Net Roof Assembly R-Value

		Audit		Commissioning		Opportunity	
		Nominal	Net	Nominal	Net	Nominal	Net
Advanced	Coastal	R-22	17.9	R-22	17.9	R-22	17.9
	Inland Valley	R-22	17.9	R-22	17.9	R-22	17.9

Windows

The audit case existing houses are modeled with 1/8” thick, single-pane aluminum frame windows without thermal breaks. The audit case new houses (new and advanced) are modeled with 1/8” thick double-pane vinyl frame windows. They have ½-inch air gaps

with a metal spacer. All windows are operable and are evenly distributed around the house perimeter, with a 1.5 foot overhang two feet above the windows. Interior drapes shade the windows during the cooling season.

In the commissioning phase, the clear (no low-e coating) double-pane windows of the new and advanced houses are replaced with correct low-e double-pane vinyl-frame windows having an emissivity of 0.05. Low-e double-pane vinyl-frame windows are also installed in the existing houses during the opportunity phase. Low-e coatings are located on the interior surface of the exterior pane. Table A-5 summarizes the shading coefficients and U-values of the windows that were modeled.

Table A-5: Window Shading Coefficients and U-Values

	Audit				Commissioning				Opportunity			
	Window Type	SHGC	SC	U	Window Type	SHGC	SC	U	Window Type	SHGC	SC	U
Existing	Single	0.86	1.00	1.27	Single	0.86	1.00	1.27	Double Low-E	0.41	0.48	0.39
New	Double	0.75	0.87	.51	Double Low-E	0.41	0.48	0.39	Double Low-E	0.41	0.48	0.39
Advanced	Double	0.75	0.87	.51	Double Low-E	0.41	0.48	0.39	Double Low-E	0.41	0.48	0.39

Source: ASHRAE 1997. DOE2.1E uses shading coefficients (SC) in determining window-related space conditioning loads. Shading coefficients are for glazing only. The Solar Heat Gain Coefficient (SHGC) is for glazing at normal incidence angles. U-values (U) are in Btu/(ºF-ft^2-hr).

Envelope Air Tightness and Ventilation

Air Tightness Levels in the Audit Phase (Pre-Commissioning)

Normalized leakage (NL), as defined in ASHRAE Standard 119 – Air Leakage Performance for Detached Single-Family Residential Buildings (ASHRAE 1988), is an approximate surrogate for annual effective infiltration rates in absence of mechanical ventilation. We selected the building envelope normalized leakage values in this analysis so that they would represent the existing building stock and current new construction practices in California. Sherman and Matson (1997) have used measured building envelope leakage areas to determine a representative range of normalized leakage areas (NL) for U.S. housing. Our field measurements of four Las Vegas Pulte Building America houses resulted in an average normalized leakage of 0.25. We used these two sets of data to estimate normalized leakage values for the analysis cases. For the audit cases, the following normalized leakage values are assumed:

- the existing houses would be equal to that of the existing U.S. housing stock (NL=1.2) for the typical houses and one standard deviation greater for the poor houses (NL = 1.4),
- the new houses would be equal to that of the new California houses in the database (NL = 0.75) for the typical houses and one standard deviation greater for the poor houses (NL = 1.0), and
- the advanced houses would be equal to that found in the Las Vegas Pulte Building America houses (NL = 0.25).

Air Tightness Levels in the Commissioned Houses

The commissioning-phase air tightness goals were to tighten the houses to meet the requirements of corresponding standards, codes, or design specifications.

Existing Houses. In commissioning the existing house, we assume that it would be possible to tighten the existing house envelope to the level needed to meet the ventilation requirements of ASHRAE Standard 62.2P (ASHRAE 2000) through infiltration alone. Accounting for climatic differences, the resulting normalized leakage values ranged from 0.49 to 0.65. To determine the normalized leakage values for each of the existing houses, we used methodology based on ASHRAE Standard 136 (ASHRAE 1993). The resulting normalized leakage is given as:

$$NL = \frac{7.32 \cdot Q_{tot,62.2}}{(W \cdot A_f)} \qquad \textbf{Equation (A1)}$$

where:

$Q_{tot,62.2}$ = (3 cfm /100 ft^2) * A_f [ft^2] + 7.5 cfm * (1+ number of bedrooms)

W = ASHRAE Standard 136 climate factor

A_f = Conditioned Floor Area [ft^2]

Bedrooms = Three (existing houses) and four (new and advanced houses)

New Houses. We assumed that the new house would be tightened to the default level assumed in Title 24 (NL=0.5) (CEC 2001).

Advanced Houses. Building Science Corporation specifies that the Tracy, CA Pulte Building America houses should have a normalized leakage value of 0.17 (Ueno 2000). We assumed that the advanced houses would be tightened to that level.

Ventilation Systems

Title 24 (CEC 1999) requires the installation of whole-house mechanical ventilation systems when the specific leakage area (SLA) is below 3.0 (NL = 0.3).

Existing and New Houses. The normalized leakage values for the existing and new houses are all above the 3.0 SLA and 0.3 normalized leakage values. Consequently, Title 24 does not require that these houses have mechanical ventilation systems nor are they traditionally installed in these houses. As such, we modeled only local, intermittent bathroom and kitchen exhaust fans in the existing and new houses. Table A-6 summarizes the airflow, fan power and operating schedules for these fans.

Table A-6: Intermittent Exhaust Fans

	Airflow	Fan Power	Start	Run Time
Bathroom	50	30	5 a.m.	0.5
Bathroom	50	30	6 a.m.	0.5
Kitchen Fan	100	60	4 p.m.	0.5
Clothes dryer	250	n/a	7 p.m.	1.0

Advanced Houses. Title 24 requires that the advanced houses, which we modeled with normalized leakage values of 0.25 and 0.17, have whole-house mechanical ventilation systems. The Pulte Building America Houses in Tracy, CA have supply-only mechanical ventilation. This system consists of an outside air duct connected to the return duct system of the central HVAC air-handler and is controlled with an AirCycler™ run-time controller (Ueno 2000). Outdoor air flows through the outside air duct due to return duct suction whenever the system blower operates. The controller turns on the blower whenever thermal demands are insufficient to cause the system to run a preset minimum time in any one-hour period. In this analysis, that minimum run time was 20 minutes per hour.

We calculated the whole-house ventilation airflow rate for the advanced ventilation system based on the ASHRAE Standard 62.2P requirements and the methods described by Rudd and Lstiburek (1999). ASHRAE 62.2P requires a continuous mechanical ventilation airflow rate of 1 cfm per 100 square foot of conditioned space plus 7.5 cfm per person, where the number of people equals one plus the number of bedrooms (ASHRAE 2000). To take into account the cycling of the central HVAC system, the outdoor airflow (Q_{FAC}) is three times the ASHRAE 62.2P required continuous mechanical ventilation airflow rate. Each hour's *actual* airflow was based on the actual run time of the blower in that hour ($t_{frac,i}$), but at a fraction of the forced-air outdoor airflow rate:

$$Q_{supply,i} = Q_{FAC} \times Max(t_{fac,i}, 20/60) \qquad \textbf{Equation (A2)}$$

In order to determine the central system hourly run time, thermal demands on the space conditioning system were evaluated using DOE 2.1E. A set of 8,760 hourly thermal part-load factors was saved to an hourly output file. Each part-load factor represents the fraction of an hour ($t_{frac,i}$) that the system had to run to meet the load imposed upon it by the house thermal demands. This part load profile is used by RESVENT to calculate the hourly effective ventilation rates. Fan energy associated with operating the system blower was calculated based on the additional ventilation-related central fan run time. The audit case HVAC systems run from 900 to 1000 hours for space conditioning alone. An additional 2000 hours of central fan runtime is needed to provide ventilation. When commissioned, the HVAC systems run from 400 to 900 hours for space conditioning and an additional 2000 to 2500 hours to provide ventilation. Note that this additional fan run time was not taken into account in the DOE-2 analysis.

RESVENT Results – Hourly and Annual Effective Ventilation Rates

We calculated the hourly combined (infiltration and ventilation) airflow rates for each of the analysis cases and used them as hourly inputs into the DOE-2.1E model. These airflow rates are calculated by simulating the cases with a modified version of RESVENT.

RESVENT is a computer program developed by Sherman and Matson (1993, 1997), which uses the LBL infiltration model (Sherman and Modera 1984). RESVENT inputs include building characteristics (floor area, height, envelope leakage, and leakage distribution parameters), ventilation system factors (fan airflow rate, fan power, and operation schedules), and hourly weather data (temperature and wind speed). The houses are modeled with the windows closed. RESVENT calculates the hourly combined airflow rates by superimposing each hour's infiltration rate with the corresponding mechanical whole-house and local ventilation rates to determine the actual hour by hour ventilation rate ($Q_{tot,i}$).

$$Q_{tot,i} = \sqrt{Q_{inf,i}^2 + \left(Q_{l,i} - Q_{s,i}\right)^2} + Q_{s,i} \qquad \textbf{Equation (A3)}$$

where:

$Q_{inf,i}$ = Infiltration airflow rate (air changes per hour [ACH])

Q_{li} = Larger of the mechanical ventilation airflow rates (air changes per hour [ACH])

Q_{si} = Smaller of the mechanical ventilation airflow rates (air changes per hour [ACH])

Equation A3 differs from the analogous superposition equation that is presented in Section 4.4 of ASHRAE Standard 136 (ASHRAE 1993). The equation used here is assumed to provide better estimates for the combination of infiltration with unbalanced and balanced ventilation flows (Sherman 1992). The resulting hour-by-hour rates $Q_{tot,i}$ are provided as an input to DOE 2.1E to calculate the infiltration and ventilation-related component of the annual building energy consumption. These hour-by-hour rates are also used to calculate annual effective ventilation rates. The ASHRAE 2001 Handbook of Fundamentals (ASHRAE 2001) further discusses effective ventilation. The annual effective ventilation rates, as calculated using the ASHRAE 136 calculation method, and the ASHRAE Standard 62.2P target rates are shown in Table A-7. For the existing and new houses, values are reported for the two audit case normalized leakage values (typical and poor). The advanced poor and typical audit cases have the same normalized leakage value. As the ventilation system hourly ventilation airflows are dependent on the amount of time the HVAC system runs, ventilation values are provided based on the poor and typical cases.

Table A-7: Annual Effective Ventilation Rates

		Normalized Leakage (NL)	Air Change Rates (ACH)	
			Standard 136 Based	Standard 62.2P Required
El Toro				
Existing	Audit – Poor	1.4	0.82	
	Audit – Typical	1.2	0.71	0.38
	Commissioning & Opportunity	0.65	0.39	
New	Audit – Poor	1.0	0.58	
	Audit – Typical	0.75	0.44	0.34
	Commissioning & Opportunity	0.50	0.30	
Advanced	Audit – Typical	0.25	0.40	0.34
	Audit – Poor	0.25	0.40	0.34
	Commissioning	0.17	0.39	
Pasadena				
Existing	Audit – Poor	1.4	0.95	
	Audit – Typical	1.2	0.82	0.38
	Commissioning & Opportunity	0.56	0.39	
New	Audit – Poor	1.0	0.67	
	Audit – Typical	0.75	0.51	0.34
	Commissioning & Opportunity	0.50	0.34	
Advanced	Audit – Typical	0.25	0.41	0.34
	Audit – Poor	0.25	0.41	0.34
	Commissioning	0.17	0.39	
Sacramento				
Existing	Audit – Poor	1.4	1.08	
	Audit – Typical	1.2	0.93	0.38
	Commissioning & Opportunity	0.49	0.39	
New	Audit – Poor	1.0	0.76	
	Audit – Typical	0.75	0.57	0.34
	Commissioning & Opportunity	0.50	0.39	
Advanced	Audit – Typical	0.25	0.40	0.34
	Audit – Poor ed	0.25	0.41	
	Commissioning	0.17	0.39	
Fresno				
Existing	Audit – Poor	1.4	1.00	
	Audit – Typical	1.2	0.85	0.38
	Commissioning & Opportunity	0.54	0.39	
New	Audit – Poor	1.0	0.70	
	Audit – Typical	0.75	0.53	0.34
	Commissioning & Opportunity	0.50	0.36	
Advanced	Audit – Typical	0.25	0.41	0.34
	Audit – Poor	0.25	0.41	
	Commissioning	0.17	0.40	

* The advanced house effective air change rates are a function of HVAC central fan runtimes and thus are presented based on the typical and poor cases.

Attic Leakage Values – DOE 2.1E Inputs

The DOE 2.1E Sherman-Grimsrud infiltration subroutine calculated attic infiltration airflow rates. Attic airtightness is specified for this subroutine as a dimensionless fractional leakage value (the effective leakage area divided by the attic floor area).

The existing and new cases have unconditioned attics with the insulation located at the ceiling level. The leakage factor for these attics was assumed to be 1/400th of the attic floor area or a fractional leakage value of 0.0025.

The attics of the advanced houses are insulated at the roof level. As such, the attics in these houses are more closely coupled to the conditioned space than in the existing and new houses. In our field studies of Pulte Building America houses in Las Vegas, NV, we found that the attics had approximately 75% of the house total leakage to outside. Consequently, we used fractional leakage values of 0.00015 and 0.00010 respectively for the attics in the audit and commissioning cases.

Duct Leakage Reduction

Space-conditioning duct systems in un-retrofitted existing houses have 28% total duct leakage to outside on average (Jump et al. 1996). For new California houses, Title 24 assumes a default of 22% total duct leakage to outside (CEC 1999). Our field studies in Pulte Las Vegas Building America Houses measured 11% total duct leakage to outside. We used these rates respectively for the existing, new, and advanced houses.

The total duct leakage percentage and duct location, along with the heating, cooling, and annual thermal distribution system efficiency factors are shown in Table A-8. We assumed ducts are outside the conditioned space for the existing and new houses (63% in the attic) and inside the conditioned space for the advanced houses (10% in the attic due to the attic-outdoor temperature difference being 10% of that found in the control houses, as measured in the Las Vegas Pulte houses). In all cases, the duct leakage is split evenly between the supply and return ducts.

Through quality duct installation and sealing (including mastic and/or aerosol sealing methods), these duct leakage values can be reduced significantly, resulting in significant space conditioning energy savings and better comfort conditions. We assume that the thermal distribution system ducts are sealed as part of the commissioning process. In particular, we assume that the total duct leakage to outside can be reduced to 6% in the existing and new houses. This is the duct tightness level required in order to take the corresponding Title 24 compliance credit (CEC 1999). Building Science Corporation (Ueno 2000) specifies a total duct leakage to outside value of 4% for the Tracy, CA Building America houses. We assume that this leakage value is achieved when commissioning the advanced cases.

Table A-8: Thermal Distribution System Efficiencies

				Thermal Distribution System Efficiencies*					
				Typical			Poor		
		Total Duct Leakage to Outside	Duct Location	Heat	Cool	Avg.	Heat	Cool	Avg.
El Toro									
Existing	Audit	28%	Attic	0.85	0.80	0.83	0.80	0.75	0.78
	Commissioning	6%		0.91	0.86	0.88	0.92	0.86	0.89
	Opportunity	6%		0.90	0.84	0.87	0.90	0.84	0.87
New	Audit	22%	Attic	0.85	0.81	0.83	0.84	0.78	0.81
	Commissioning	6%		0.88	0.84	0.86	0.88	0.84	0.86
	Opportunity	6%		0.89	0.84	0.86	0.89	0.84	0.86
Advanced	Audit	11%	Conditioned	0.95	0.88	0.91	0.93	0.86	0.90
	Commissioning	4%	Attic	0.96	0.89	0.93	0.96	0.89	0.93
Pasadena									
Existing	Audit	28%	Attic	0.85	0.86	0.85	0.81	0.84	0.82
	Commissioning	6%		0.91	0.88	0.90	0.92	0.88	0.90
	Opportunity	6%		0.89	0.87	0.88	0.89	0.87	0.88
New	Audit	22%	Attic	0.85	0.86	0.85	0.84	0.85	0.85
	Commissioning	6%		0.88	0.87	0.87	0.88	0.86	0.87
	Opportunity	6%		0.89	0.86	0.87	0.89	0.86	0.87
Advanced	Audit	11%	Conditioned	0.95	0.90	0.92	0.93	0.90	0.91
	Commissioning	4%	Attic	0.96	0.91	0.94	0.96	0.91	0.94
Sacramento									
Existing	Audit	28%	Attic	0.83	0.85	0.84	0.78	0.83	0.81
	Commissioning	6%		0.90	0.88	0.89	0.91	0.88	0.89
	Opportunity	6%		0.87	0.86	0.86	0.87	0.86	0.86
New	Audit	22%	Attic	0.85	0.85	0.85	0.82	0.85	0.83
	Commissioning	6%		0.88	0.86	0.87	0.88	0.86	0.87
	Opportunity	6%		0.87	0.86	0.87	0.87	0.86	0.87
Advanced	Audit	11%	Conditioned	0.94	0.90	0.92	0.92	0.89	0.91
	Commissioning	4%	Attic	0.96	0.91	0.93	0.96	0.91	0.93
Fresno									
Existing	Audit	28%	Attic	0.84	0.83	0.83	0.79	0.80	0.79
	Commissioning	6%		0.90	0.86	0.88	0.91	0.87	0.89
	Opportunity	6%		0.87	0.85	0.86	0.87	0.85	0.86
New	Audit	22%	Attic	0.85	0.83	0.84	0.83	0.82	0.82
	Commissioning	6%		0.88	0.85	0.87	0.88	0.85	0.87
	Opportunity	6%		0.87	0.85	0.86	0.87	0.85	0.86
Advanced	Audit	11%	Conditioned	0.94	0.89	0.91	0.92	0.88	0.90
	Commissioning	4%	Attic	0.96	0.90	0.93	0.96	0.90	0.93

*The thermal distribution system efficiencies are aggregated based on the thermal distribution system efficiencies of the individual typical case component runs.

Modeling Duct Leakage in DOE 2.1E

The DOE 2.1E RESYS and RESYS-2 -heating and cooling subroutines use a single annual DUCT-LOSS variable to account for the amount of heating and cooling energy lost through duct leakage. For simplicity, we calculated the annual duct loss factor to be the average of the heating and cooling seasonal duct efficiencies. We calculated the heating and cooling seasonal duct efficiencies, or thermal distribution system efficiencies, for each case using ASHRAE Standard 152P (ASHRAE 1999). The thermal distribution system efficiency is the amount of heating or cooling delivered to the space through the modeled duct system compared to the amount that would be delivered to the space via a non-ducted system. Inputs to the 152P model include house characteristics (floor area, number of stories), duct system characteristics (duct system location, surface area, number of registers, duct leakage as a percent of total system airflow), equipment characteristics (heating and cooling capacities and airflows), and climate data. We calculated the duct surface areas and numbers of registers based on the Standard 152P default "per unit floor area" assumptions.

Air Handler Airflow and Refrigerant Charge

We determined the effects of refrigerant charge and system airflow deficiencies on cooling system capacities and efficiencies using charge and airflow degradation algorithms developed by Proctor Engineering Group (Proctor 2001), which are included in the REGCAP model (Siegel 2001). Specifically, we used these algorithms to determine the sensible capacity and efficiency at each of the standard rating points, such as for a 95ºF outdoor air dry-bulb temperature and a 67ºF evaporator entering air wet-bulb temperature. We calculated the corresponding total capacity using a sensible heat ratio of 0.78. We modeled four charge and airflow cases with nominal SEER 10 air conditioners. Full airflow (100%) is 400 cfm/ton and reduced (85%) flow is 340 cfm/ton. We used the resulting data (sensible capacity, total capacity, and energy input ratio) to determine air conditioner performance curve fits for use in the DOE 2.1E models.

Thermostat Set-Points

In order to interchange data between our two hourly models (RESVENT and DOE-2) and still obtain a realistic evaluation of temporal ventilation air change rates, we were limited to using a non-setback thermostat approach. 68ºF heating and 78ºF cooling thermostat setpoints were modeled.

HVAC Equipment Sizing

Our analysis quantifies the relative energy and cost savings between cases. To insure that the heating and cooling hourly loads are met by the HVAC systems modeled for each of the analysis cases, the HVAC systems are sized based on DOE 2.1E's recommended equipment capacities for that case. DOE 2.1E uses the peak loads on design days and, in this case, the user-specified equipment performance curves to determine the heating and cooling equipment capacities at standard conditions.

For cooling, we selected the next larger commercially available air conditioning equipment above the DOE 2.1E recommended cooling capacity. For heating, the gas furnace modeled is the next larger commercially available gas furnace that has sufficient heating capacity to provide the DOE 2.1E recommended heating capacity and that has

sufficient airflow for the cooling mode (based on a nominal 400 cfm per ton of air conditioning).

Equipment Sizing for the "Comfort Call Case" Analysis

The "comfort call case" analysis is included in Appendix C. This case assumes that the existing HVAC equipment in the pre-commissioned house may not be able to meet the cooling loads completely. After commissioning, these systems are better able to meet the cooling loads. Because HVAC equipment would not be changed out as part of the commissioning phase, the audit and commissioning cases have the same equipment sizes. Assuming that equipment is sized based on how the house should be in a best-case scenario (good insulation, correct windows, tight envelope and ducts, correct charge and air flow), the equipment used for these cases is what would be required to meet the commissioning case loads. The equipment capacities modeled for the opportunity case are based on the opportunity case loads.

Energy Prices

The California energy industry is going through a volatile time, resulting in uncertainty regarding future rates. In the event of rate increases, the case for commissioning becomes even stronger with higher cost savings and greater benefits to the homeowner and other stakeholders. As such, we have chosen to provide results based on a more conservative level, using the California average energy rates reported by the EIA for 1999. Our analyses are based on an electricity rate of \$0.1071/kWh (EIA 2000) and a natural gas rate of \$6.63/(100 ft^3) or \$0.634/therm (EIA 2001).

Environmental Impact - Carbon Emissions

We can approximate carbon savings achieved based on the level of estimated energy savings. The carbon impact is determined based on data from the EIA State Electricity Profile (EIA 2000). EIA reports that 23% of California in-state utility-generated electricity is produced using carbon-producing fuels (petroleum and natural gas). While out-of-state-generated electricity consumed in California may be produced using a higher percentage mix of carbon producing fuels (coal, petroleum and natural gas) than in-state electricity generation, we are assuming the 23% value for this analysis. Based on Koomey's 1993 emission efficiency data (Koomey 1993), the 1993 California generating fuel mix produces 0.15 kg of carbon per kWh of site electricity consumption. With improvements in generation and emission technologies, the California value could be as low as 0.10 kg/kWh. For the purpose of this analysis, we are using the 0.10 kg/kWh value. For natural gas, we are using a marginal emission rate of 5.2 kg/therm of site energy consumption (ASHRAE 1997).

Summary of Analysis Case Assumptions

The following three tables (Tables A-9 through A-11) summarize our assumptions for the analysis cases (audit cases, commissioning cases, and opportunity cases). Note that for the opportunity cases, we assumed that any improvements that have taken place during the main commissioning activity remain in place for the opportunity cases.

Table A-9: DOE-2 Modeling Assumptions - Existing Houses

	Audit Case	Commissioning Case	Opportunity Case
Insulation	No wall insulation Ceiling Insulation with voids and over-fluffing Ceiling: R30 (D) (all)	No wall insulation Ceiling Insulation with voids and over-fluffing Ceiling: R30 (D) (all)	Walls: R13 (all) Ceiling: R30 (Coastal) R38 (Inland Valley)
Windows	Clear Single-Pane Aluminum-Frame	Clear Single-Pane Aluminum-Frame	Low-E Double-Pane Vinyl-Frame
Envelope Air Tightness	Loose Existing Construction NL = 1.2 (typical) NL = 1.4 (poor)	Tighten to meet 62.2P: El Toro: NL = 0.65 Pasadena: NL = 0.56 Sacramento: NL = 0.49 Fresno: NL = 0.54	Tighten to meet 62.2P El Toro: NL = 0.65 Pasadena: NL = 0.56 Sacramento: NL = 0.49 Fresno: NL = 0.54
Ventilation	Bathroom and kitchen intermittent exhaust fans	Bathroom and kitchen intermittent exhaust fans	Bathroom and kitchen intermittent exhaust fans
Ducts	28% total leakage to outside split evenly between supply and return) No duct insulation	6% total leakage to outside (split evenly between supply and return) R4.2 Duct Insulation	6% total leakage to outside (split evenly between supply and return) R4.2 Duct Insulation
Air Conditioner Refrigerant Charge	15% undercharged Capillary Tube	100% Charge Capillary Tube	100% Charge TXV
Air Handler	15% fan flow reduction Standard motor	100% Airflow Standard motor	100% Airflow ECM Motor
Furnace Efficiency [AFUE]	78%	78%	90%
Nominal SEER	10.00	10.00	10.00

*(D) denotes degraded installation quality. Insulation R-value listed is the nominal R-value for the insulating material. The net R-value used in the model takes into account framing factors and insulation installation quality degradation due to missing, compressed or over-fluffed insulation.

Table A-10: DOE-2 Modeling Assumptions – New House

	Audit Case	Commissioning Case	Opportunity Case
Insulation	Insulation to Title 24 Package D minimums, but with voids and over-fluffing Walls: R13 (D) (Coastal) R19 (D) (Inland Valley) Ceiling: R30 (D) Coastal) R38 (D) (Inland Valley)	Insulation to Title 24 Package D minimums, no voids or over-fluffing Walls: R13 (Coastal) R19 (Inland Valley) Ceiling: R30 (Coastal) R38 (Inland Valley)	Insulation to Title 24 Package D minimums, no voids or over-fluffing Walls: R13 (Coastal) R19 (Inland Valley) Ceiling: R30 (Coastal) R38 (Inland Valley)
Windows	Clear Double-Pane Aluminum-Frame	Low-E Double-Pane Vinyl-Frame	Low-E Double-Pane Vinyl-Frame
Envelope Air Tightness & Ventilation	New construction NL = 0.75 (typical) NL = 1.00 (poor)	Tighter new construction NL = 0.5	Tighter new construction NL = 0.5
Ventilation	Bathroom and Kitchen intermittent exhaust fans	Bathroom and Kitchen intermittent exhaust fans	Bathroom and Kitchen intermittent exhaust fans
Ducts	22% total leakage to outside (split evenly between supply and return) R4.2 Duct Insulation	6% total leakage to outside (split evenly between supply and return) R4.2 Duct Insulation	6% total leakage to outside (split evenly between supply and return) R4.2 Duct Insulation
Air Conditioner Refrigerant Charge	15% undercharged TXV	100% Charge TXV	100% Charge TXV
Air Handler Flow	15% fan flow reduction Standard motor	100% Airflow Standard motor	100% Airflow ECM Motor
Furnace Efficiency	80%	80%	90%
Nominal SEER	10.00	10.00	10.00

*(D) denotes degraded installation quality. Insulation R-value listed is the nominal R-value for the insulating material. The net R-value used in the model takes into account framing factors and insulation installation quality degradation due to missing, compressed or over-fluffed insulation.

Table A-11: DOE-2 Modeling Assumptions – Advanced House

	Audit Case	Commissioning Case
Insulation	Building America Minimum R-Values, blown in and cocooned cellulose, no voids. Walls: R13 (Coastal) R19 (Inland Valley) Roof: (attic inside conditioned space) R22 (all)	Building America Minimum R-Values, blown in and cocooned cellulose, no voids. Walls: R13 (Coastal) R19 (Inland Valley) Roof: (attic inside conditioned space) R22 (all)
Windows	Clear Double-Pane Aluminum-Frame	Low-E Double-Pane Vinyl -Frame
Envelope Air Tightness	Typical tighter new construction NL = 0.25	Typical tight new Building America construction NL = 0.17
Ventilation	Mechanical supply ventilation system, outside air duct to return side of furnace, sized to ASHRAE 62.2P (nominal 62.5 cfm airflow, the ventilation rate can be up to 20% higher when furnace runs for more than 20 minutes per hour)	Mechanical supply ventilation system, outside air duct to return side of furnace, sized to ASHRAE 62.2P (nominal 62.5 cfm airflow, the ventilation rate can be up to 20% higher when furnace runs for more than 20 minutes per hour)
Ducts	11% total leakage to outside (split evenly between supply and return) R4.2 Duct Insulation	4% total leakage to outside (split evenly between supply and return) R4.2 Duct Insulation
Air Conditioner Refrigerant Charge	15% undercharged TXV	100% Charge TXV
Air Handler Flow	15% reduction in fan flow ECM Motor	100% Airflow ECM Motor
Furnace Efficiency	90%	90%
Nominal SEER	10.00	10.00

APPENDIX B: PEAK DEMAND

Most of the electrical loads reduced through commissioning are associated with cooling and will thus have the greatest influence on summer peak demand in California. This reduction will put less strain on generating, transmission, and distribution resources and will allow utilities flexibility in shifting resources and loads to meet peak demand. Houses with reduced peak loads (lower cooling loads) perform better in extreme climates or during power outages than houses with high cooling loads. Table B-1 summarizes the space-conditioning-related peak electrical demands and percent savings predicted by DOE-2 for each of the cases. These results are discussed in terms of actual peak rather than an averaged peak that takes diversity into account.

As expected, the typical advanced houses have the lowest peak demand, followed by the new houses. The existing houses have the highest peak demand. Due to larger cooling loads and equipment sizes, the peak demands for the poor audit cases are higher than for the typical audit cases, ranging from 40% higher for the existing houses to 50 to 75% higher for the new and advanced houses.

Commissioning results in significant peak savings: 22 to 24% (typical) and 34 to 38% (poor) for the existing cases, 15 to 19% (typical) and 50 to 56% (poor) for the new cases, and 6 to 7% (typical) and 38 to 44% (poor) for the advanced cases. Implementing the opportunity phase in the existing houses increases these peak savings to 57 to 59% (typical) and 70 to 71% (poor). Twenty percent of the HVAC system fan peak energy is saved with the installation of the ECM motors in the new houses. This contributes to slightly greater peak savings in the opportunity phase for the new houses.

Table B-1: Space-Conditioning-Related Peak Demand

		Peak Demand Savings (% of Audit Case)							
		Typical				Poor			
		El Toro	Pasadena	Sacramento	Fresno	El Toro	Pasadena	Sacramento	Fresno
Existing	Audit	-	-	-	-	-	-	-	-
	Commissioning	22%	22%	23%	24%	35%	34%	37%	38%
	Opportunity	59%	59%	59%	57%	70%	70%	71%	70%
New Title 24	Audit	-	-	-	-	-	-	-	-
	Commissioning	15%	15%	18%	19%	50%	56%	51%	50%
	Opportunity	18%	24%	19%	18%	51%	56%	51%	50%
Building America	Audit	-	-	-	-	-	-	-	-
	Commissioning	7%	6%	7%	7%	42%	44%	39%	38%

APPENDIX C: COMFORT CALL CASE

The "comfort call" case allows us to look at the effect of commissioning a house where the existing HVAC equipment may not be able to provide sufficient comfort levels. This may result in a "comfort call" to an HVAC contractor.

In selecting the HVAC equipment sizes for the "comfort call" case, we assume that changing out equipment for equipment that can meet the new load would be part of the opportunity phase and not a normal part of the "tuning and tweaking" commissioning package. In this analysis, the cooling equipment sizes are limited to traditional residential sizes (five tons or less). By using the commissioning phase equipment sizes for the audit phase, we can evaluate the assumption that systems are sized assuming that no system induced problems (e.g., duct leakage, low refrigerant charge, and low air handler airflow) impact the amount of space conditioning actually delivered to a home's living space. As the commissioning phase equipment is sized for the commissioning phase loads, the effect of commissioning on thermal comfort with undersized units can be evaluated. As the opportunity cases include installing equipment that meets the load, we have modeled the opportunity phase cases with the HVAC equipment necessary to meet the opportunity phase loads. For specificity, any case with greater than a five ton cooling loads are modeled with five ton cooling equipment. This results in loads not able to be met for all of the audit cases and for the existing commissioning cases in the inland valley (Sacramento and Fresno).

The following summary compares the "comfort call" data in Table C-1 on a house-by-house type basis for each benefit type. Following this summary are more detailed tables and information regarding climate-specific results. As one might except these results show the same general trends as those in the main body, but the size of the savings has been reduced, reflecting the fact that for some hours of the year the commissioning saves no energy, but does improve comfort conditions.

Existing Houses

Electricity. Using the commissioning phase equipment for both the audit and commissioning phases result in 7 to 12% (typical) and 10 to 19% (poor) electricity savings. In the opportunity phase, adding insulation, low-e double pane windows, and equipment with a thermostatic expansion valve (TXV) and an electronically commutated motor (ECM) results in substantial savings compared to the audit case. Within this phase, the overall electricity saving range from 60 to 70% for the typical cases and from 70 to 80% for the poor cases.

Natural Gas. Natural gas savings are about 20% for the typical cases and from 30 to 35% for the poor cases. Implementing the opportunity phase improvements substantially increases natural gas savings to 44 to 54% for the typical cases and from 59 to 67% for the poor cases.

Operating Costs. As the audit cases have cooling equipment with degraded performance and lower capacities than needed to meet the cooling loads, the commissioning phase cost savings range from 10 to 15% (typical) and 17 to 26% (poor). Implementing the opportunity phase measures substantially increases the cost savings, ranging from 56 to 62% (typical) and 66 to 71% (poor).

Table C-1: Commissioning-Related Energy and Operating Cost Savings
Comfort Call Cases

		Electricity Consumption Savings	
		Typical	Poor
Existing	Commissioning	7 to 12%	10 to 19%
	Opportunity	57 to 72%	66 to 78%
New	Commissioning	1 to 9%	49 to 68%
	Opportunity	2 to 10%	50 to 68%
Advanced	Commissioning	6 to 7%	48 to 69%

		Natural Gas Consumption Savings	
		Typical	Poor
Existing	Commissioning	17 to 21%	33 to 36%
	Opportunity	44 to 54%	59 to 67%
New	Commissioning	24 to 25%	17 to 35%
	Opportunity	28 to 31%	21 to 41%
Advanced	Commissioning	2 to 3%	-19 to -15%

		Energy Operating Cost Savings	
		Typical	Poor
Existing	Commissioning	10 to 15%	17 to 26%
	Opportunity	56 to 62%	66 to 71%
New	Commissioning	10 to 17%	45 to 58%
	Opportunity	14 to 22%	47 to 60%
Advanced	Commissioning	5 to 6%	41 to 62%

New Houses

Electricity. The electricity savings in the commissioning phase are up to 10% (typical) and 50 to 70% (poor). In the opportunity phase, adding equipment with a TXV and an ECM increases savings only slightly (one to seven percentage points more).

Natural Gas. Natural gas savings in the commissioning phase are about 25% for the typical cases and from 18 to 35% for the poor cases. In the opportunity phase, installing a higher efficiency furnace (90% instead of 80%) increases natural gas savings slightly to about 30% for the typical cases and from 22 to 41% for the poor cases.

Operating Costs. Operating cost savings in the commissioning phase range from 10 to 17% (typical) and 45 to 58% (poor). In the opportunity phase, installing the HVAC equipment with a TXV, an ECM, and higher furnace efficiency increases cost savings to 14 to 22% (typical) and from 47 to 60% (poor).

Advanced Houses

Because the advanced houses are already engineered and designed to be energy efficient, relative savings for the typical cases are lower than those for the typical existing and new houses. For the advanced houses, the primary difference between the typical and the poor cases is the incorrect installation of clear glazing in place of low-e glazing. Correcting

this problem in the poor cases drives the energy consumption and savings closer to the levels seen with the new houses.

Electricity. The commissioning phase electricity saving range from 6 to 7%. The poor case savings range from 48 to 69%.

Natural Gas. Natural gas savings range from 2 to 3% for the typical cases. Due to a reduction in solar gains when the incorrect clear double pane windows are replaced with low-e double pane windows, the poor advanced commissioning cases have higher gas consumption, resulting in negative gas savings, from –19 to –15%.

Operating Costs. The typical case operating cost savings range from 5 to 6%. The operating cost savings for the poor case are higher, ranging from 41 to 62%.

Electricity Consumption and Savings – Comfort Call Cases – Detailed Results

The annual space conditioning-related annual electricity consumption rates and percent savings are summarized in Table C-2. Electricity consumption values are provided per square foot of conditioned space to provide comparisons between building types. All savings percentages are reported in terms of savings over the audit cases.

To evaluate issues related to undersized HVAC equipment, the "comfort call" cases are modeled with a maximum of five tons cooling capacity. The audit cases have the same equipment as modeled for the commissioning cases. As mentioned earlier, the five-ton limit results in inadequate cooling capacity for all of the audit cases and for the Sacramento and Fresno poor commissioning cases. The lower audit case electricity consumption values and corresponding lower relative savings percentages are a direct result of the undersized equipment modeled for these cases.

Existing Houses: For the existing cases, commissioning results in 7 to 12% electricity consumption savings for the typical cases and 10 to 19% savings for the poor cases. Implementing additional opportunities increases the savings percentages to just under the levels found with the cases. The opportunity phase changes increase savings to 57 to 72% for the typical cases and to 66 to 78% for the poor cases.

New Houses: For the typical cases, new house savings range from to 8 to 9% for the inland valley climates. As the coastal typical cases showed only 1 to 2% savings through commissioning, there are negative savings with the corresponding case due to the audit cases' inadequate cooling capacities. The poor cases; however, have 50 to 68% savings for the commissioning and opportunity phases.

Advanced Houses: The advanced houses' commissioning-related electricity savings range from 6 to 7%. After the opportunity phase, the savings for the poor cases range from 48 to 69%.

Table C-2: Space Conditioning-Related Electricity – Comfort Call Cases

		Electricity Consumption (kWh/ft^2/year)							
		Typical				Poor			
		El Toro	Pasadena	Sacramento	Fresno	El Toro	Pasadena	Sacramento	Fresno
Existing	Audit	1.48	2.04	2.06	3.90	1.88	2.57	2.63	4.96
	Commissioning	1.37	1.89	1.88	3.42	1.69	2.30	2.26	4.01
	Opportunity	0.42	0.69	0.75	1.66	0.42	0.69	0.75	1.66
New Title 24	Audit	0.51	0.77	0.88	1.78	1.57	1.86	1.80	3.19
	Commissioning	0.51	0.75	0.81	1.62	0.51	0.72	0.81	1.62
	Opportunity	0.50	0.71	0.79	1.61	0.50	0.71	0.79	1.61
Building America	Audit	0.65	0.84	0.96	1.78	1.98	2.25	2.13	3.22
	Commissioning	0.61	0.79	0.89	1.67	0.61	0.79	0.89	1.67
		Electricity Savings (% of Audit Case)							
		Typical				Poor			
		El Toro	Pasadena	Sacramento	Fresno	El Toro	Pasadena	Sacramento	Fresno
Existing	Audit	-	-	-	-	-	-	-	-
	Commissioning	8%	7%	9%	12%	10%	11%	14%	19%
	Opportunity	72%	66%	64%	57%	78%	73%	71%	66%
New Title 24	Audit	-	-	-	-	-	-	-	-
	Commissioning	1%	2%	8%	9%	68%	61%	55%	49%
	Opportunity	2%	7%	10%	10%	68%	62%	56%	50%
Building America	Audit	-	-	-	-	-	-	-	-
	Commissioning	7%	6%	7%	6%	69%	65%	58%	48%

Natural Gas Consumption and Savings – Comfort Call Cases – Detailed Results

The annual space-conditioning-related natural gas consumption and savings are summarized in Table C-3. Commissioning savings range from 17 to 21% (typical) and 33 to 36% (poor) for the existing cases, from 24 to 25% (typical) and 17 to 35% (poor) for the new cases, and from 2 to 3% (typical) and –19 to –15% (poor) for the advanced cases. The opportunity measures increase the gas savings to 44 to 54% (typical) and 59 to 67% (poor) for the existing cases, and from 28 to 31% (typical) and 21 to 41% (poor) for the new cases.

Table C-3: Space-Conditioning-Related Natural Gas – Comfort Call Cases

		Natural Gas Consumption (Therm/ft2/year)							
		Typical				Poor			
		El Toro	Pasadena	Sacramento	Fresno	El Toro	Pasadena	Sacramento	Fresno
Existing	Audit	0.13	0.14	0.35	0.31	0.18	0.19	0.48	0.42
	Commissioning	0.11	0.11	0.28	0.25	0.12	0.13	0.31	0.28
	Opportunity	0.07	0.07	0.16	0.14	0.07	0.07	0.16	0.14
New Title 24	Audit	0.07	0.07	0.18	0.16	0.06	0.06	0.21	0.18
	Commissioning	0.05	0.05	0.14	0.12	0.05	0.05	0.14	0.12
	Opportunity	0.05	0.05	0.12	0.11	0.05	0.05	0.12	0.11
Building America	Audit	0.04	0.04	0.09	0.09	0.03	0.03	0.08	0.07
	Commissioning	0.04	0.04	0.09	0.08	0.04	0.04	0.09	0.08

		Natural Gas Savings (% of Audit Case)							
		Typical				Poor			
		El Toro	Pasadena	Sacramento	Fresno	El Toro	Pasadena	Sacramento	Fresno
Existing	Audit	-	-	-	-	-	-	-	-
	Commissioning	17%	18%	21%	19%	33%	33%	36%	34%
	Opportunity	44%	47%	54%	54%	59%	61%	67%	66%
New Title 24	Audit	-	-	-	-	-	-	-	-
	Commissioning	25%	24%	24%	24%	17%	20%	35%	34%
	Opportunity	29%	28%	31%	31%	21%	24%	41%	40%
Building America	Audit	-	-	-	-	-	-	-	-
	Commissioning	2%	2%	3%	3%	-19%	-18%	-15%	-15%

Annual Operating Costs – Comfort Call Cases – Detailed Results

We calculated annual operating costs based on the annual electricity and natural gas consumption values for each case, using the DOE/EIA 1999 California annual fuel costs of $0.1071/kWh (EIA 2000) and $0.634/therm (EIA 2001). These values provide a base level of comparison. Energy price increases, such as those experienced during the winter 2000/2001 California energy crisis, will further enhance the attractiveness of commissioning California's houses. The annual space-conditioning-related annual operating costs and savings are summarized in Table C-4.

We found that the operating cost savings due to commissioning range from 10 to 15% (typical) and 17 to 26% (poor) for the existing cases, from 10 to 17% (typical) and 45 to 58% (poor) for the new cases, and from 5 to 6% (typical) and 41 to 62% (poor) for the advanced cases.

Correspondingly, the opportunity-related percent operating cost savings range from 56 to 62% (typical) and 66 to 71% (poor) for the existing cases, from 10 to 17% (typical) and 47 to 58% (poor) for the new cases; and from 5 to 6% (typical) and 41 to 62% (poor) for the advanced cases.

Table C-4: Space-Conditioning-Related Operating Costs – Comfort Call Cases

		Operating Costs ($/ft2/year)							
		Typical				Poor			
		El Toro	Pasadena	Sacramento	Fresno	El Toro	Pasadena	Sacramento	Fresno
Existing	Audit	0.24	0.30	0.44	0.60	0.32	0.39	0.59	0.80
	Commissioning	0.21	0.27	0.37	0.51	0.26	0.33	0.44	0.61
	Opportunity	0.09	0.12	0.18	0.26	0.09	0.12	0.18	0.27
New Title 24	Audit	0.10	0.12	0.21	0.28	0.21	0.24	0.32	0.45
	Commissioning	0.08	0.11	0.17	0.24	0.09	0.11	0.17	0.25
	Opportunity	0.08	0.10	0.16	0.24	0.08	0.11	0.16	0.24
Building America	Audit	0.09	0.11	0.16	0.24	0.23	0.26	0.28	0.39
	Commissioning	0.09	0.11	0.15	0.23	0.09	0.11	0.15	0.23

		Operating Cost Savings (% of Audit Case)							
		Typical				Poor			
		El Toro	Pasadena	Sacramento	Fresno	El Toro	Pasadena	Sacramento	Fresno
Existing	Audit	-	-	-	-	-	-	-	-
	Commissioning	11%	10%	15%	15%	18%	17%	26%	24%
	Opportunity	62%	61%	59%	56%	71%	70%	69%	66%
New Title 24	Audit	-	-	-	-	-	-	-	-
	Commissioning	12%	10%	17%	14%	58%	54%	47%	45%
	Opportunity	14%	15%	22%	17%	60%	55%	50%	47%
Building America	Audit	-	-	-	-	-	-	-	-
	Commissioning	6%	5%	5%	5%	62%	58%	45%	41%

Peak Electrical Demand and Savings – Comfort Call Cases – Detailed Results

Table C-5 summarizes the space conditioning-related peak demand savings for the Comfort Call Cases.

Existing Houses: Commissioning existing houses in the inland valley climates results in small or negative peak savings: 0% (typical cases) and -2 to 2% (poor cases). The negative savings are due to the audit cases' inadequate cooling capacities. In contrast, commissioning the existing houses in the coastal climates results in larger peak demand savings: 7 to 8% (typical cases) and 12% (poor cases). Reducing space conditioning loads and improving HVAC equipment efficiency in the opportunity phase for the existing houses results in considerable peak demand savings in all climates: from 39 to 51% (typical cases) and 45 to 60% (poor cases).

New and Advanced Houses: Peak demand savings from commissioning range from 5 to 15% (typical cases) and 16 to 27% (poor cases). For the advanced houses, the peak demand savings in the typical case range from 5 to 6%. The peak demand savings range from 19 to 28% for the poor cases. The ECM motor installed in the new houses in the opportunity phase slightly increases the peak savings.

Table C-5: Space-Conditioning-Related Peak Demand Savings – Comfort Call Cases

		Peak Demand Savings (% of Audit Case)							
		Typical				Poor			
		El Toro	Pasadena	Sacramento	Fresno	El Toro	Pasadena	Sacramento	Fresno
Existing	Audit	-	-	-	-	-	-	-	-
	Commissioning	8%	7%	0%	0%	12%	12%	2%	-2%
	Opportunity	51%	51%	46%	39%	60%	60%	53%	45%
New Title 24	Audit	-	-	-	-	-	-	-	-
	Commissioning	10%	5%	15%	11%	18%	16%	27%	17%
	Opportunity	13%	15%	15%	10%	20%	17%	27%	16%
Building America	Audit	-	-	-	-	-	-	-	-
	Commissioning	6%	5%	6%	6%	22%	19%	28%	22%

Reduced Carbon Emissions – Comfort Call Cases – Detailed Results

Table C-6 summarizes the space conditioning-related carbon emission reductions. As the carbon emissions scale with the amount of electricity and natural gas consumed in a house, the relative amount of carbon emission reductions follows the same general trends seen with electricity, natural gas and operating cost savings. The carbon emission reductions are slightly less than found when the HVAC system capacities meet the cooling loads over all hours.

Table C-6: Space Conditioning System – Related Carbon Emission Reductions
Comfort Call Cases

		Kg/house-year					
		Typical			Poor		
		Electricity Related	Gas Related	Total Fuel Related	Electricity Related	Gas Related	Total Fuel Related
Existing	Commissioning	20 to 70	170 to 540	190 to 570	30 to 140	450 to 1300	480 to 1390
	Opportunity	160 to 330	450 to 1430	610 to 1630	210 to 480	810 – 2460	1020 to 2730
New	Commissioning	0 to 40	210 to 560	220 to 580	250 to 390	140 to 950	400 to 1200
	Opportunity	0 to 40	250 to 720	250 to 740	250 to 400	170 to 1110	430 to 1360
Advanced	Commissioning	10 to 30	10 to 40	20 to 60	310 to 390	-150 to -80	160 to 290

		Percent of Audit Case					
		Typical			Poor		
		Electricity Related	Gas Related	Total Fuel Related	Electricity Related	Gas Related	Total Fuel Related
Existing	Commissioning	7 to 12%	21 to 24%	17 to 22%	10 to 19%	38 to 42%	32 to 39%
	Opportunity	57 to 72%	51 to 63%	55 to 63%	66 to 78%	68 to 78%	70 to 77%
New	Commissioning	1 to 9%	28 to 29%	23 to 26%	49 to 68%	20 to 41%	38 to 43%
	Opportunity	2 to 10%	33 to 36%	28 to 33%	50 to 68%	4 to 21%	41 to 49%
Advanced	Commissioning	6 to 7%	2 to 4%	3 to 4%	48 to 69%	-23 to -17%	11 to 31%

Input Assumptions – Comfort Call Cases

The following tables summarize input assumptions calculated and used when modeling the comfort call cases. The assumptions behind these tables are the same as discussed in Appendix A.

Table C-7: Annual Effective Ventilation Rates - Comfort Call Cases

		Normalized Leakage (NL)	Air Change Rates (ACH)	
			Standard 136 Based	Standard 62.2P Required
El Toro				
Advanced	Audit – Typical	0.25	0.41	0.34
	Audit – Poor	0.25	0.43	
	Commissioning	0.17	0.39	
Pasadena				
Advanced	Audit – Typical	0.25	0.43	0.34
	Audit – Poor	0.25	0.46	
	Commissioning	0.17	0.39	
Sacramento				
Advanced	Audit – Typical	0.25	0.41	0.34
	Audit – Poor	0.25	0.43	
	Commissioning	0.17	0.39	
Fresno				
Advanced	Audit – Typical	0.25	0.43	0.34
	Audit – Poor	0.25	0.45	
	Commissioning	0.17	0.40	

* The advanced house effective air change rates are a function of HVAC central fan runtimes.

Table C-8: Thermal Distribution System Efficiencies – Comfort Call Cases

				Thermal Distribution System Efficiencies*					
				Typical			Poor		
		Total Duct Leakage to Outside	Duct Location	Heat	Cool	Avg.	Heat	Cool	Avg.
El Toro									
Existing	Audit	28%	Attic	0.85	0.80	0.82	0.78	0.74	0.76
	Commissioning	6%		0.92	0.86	0.89	0.92	0.86	0.89
	Opportunity	6%		0.90	0.84	0.87	0.90	0.84	0.87
New	Audit	22%	Attic	0.84	0.80	0.82	0.80	0.77	0.78
	Commissioning	6%		0.88	0.84	0.86	0.88	0.84	0.86
	Opportunity	6%		0.89	0.84	0.86	0.89	0.84	0.86
Advanced	Audit	11%	Conditioned	0.95	0.88	0.91	0.93	0.86	0.89
	Commissioning	4%	Attic	0.96	0.89	0.93	0.96	0.89	0.93
Pasadena									
Existing	Audit	28%	Attic	0.85	0.85	0.85	0.78	0.83	0.80
	Commissioning	6%		0.92	0.88	0.90	0.92	0.88	0.90
	Opportunity	6%		0.89	0.87	0.88	0.89	0.87	0.88
New	Audit	22%	Attic	0.84	0.85	0.85	0.80	0.83	0.82
	Commissioning	6%		0.88	0.87	0.87	0.88	0.86	0.87
	Opportunity	6%		0.89	0.86	0.87	0.89	0.86	0.87
Advanced	Audit	11%	Conditioned	0.95	0.90	0.92	0.93	0.89	0.91
	Commissioning	4%	Attic	0.96	0.91	0.94	0.96	0.91	0.94
Sacramento									
Existing	Audit	28%	Attic	0.83	0.84	0.84	0.75	0.81	0.78
	Commissioning	6%		0.91	0.87	0.89	0.91	0.88	0.89
	Opportunity	6%		0.87	0.86	0.86	0.87	0.86	0.86
New	Audit	22%	Attic	0.84	0.85	0.84	0.79	0.83	0.81
	Commissioning	6%		0.88	0.86	0.87	0.88	0.86	0.87
	Opportunity	6%		0.87	0.86	0.87	0.87	0.86	0.87
Advanced	Audit	11%	Conditioned	0.94	0.90	0.92	0.92	0.89	0.90
	Commissioning	4%	Attic	0.96	0.91	0.93	0.96	0.91	0.93
Fresno									
Existing	Audit	28%	Attic	0.90	0.86	0.88	0.75	0.77	0.76
	Commissioning	6%		0.91	0.86	0.89	0.91	0.86	0.89
	Opportunity	6%		0.91	0.85	0.88	0.87	0.85	0.86
New	Audit	22%	Attic	0.84	0.82	0.83	0.80	0.80	0.80
	Commissioning	6%		0.88	0.85	0.87	0.88	0.85	0.87
	Opportunity	6%		0.87	0.85	0.86	0.87	0.85	0.86
Advanced	Audit	11%	Conditioned	0.92	0.88	0.90	0.92	0.88	0.90
	Commissioning	4%	Attic	0.96	0.90	0.93	0.96	0.90	0.93

*The thermal distribution system efficiencies are aggregated based on the thermal distribution system efficiencies of the individual typical case component runs.

Table C-9: Thermal Distribution System Efficiencies – Comfort Call Cases

	Audit		Commissioning		Opportunity**
	Poor	Typical*	Poor	Typical*	
Existing	76 to 80%	82 to 88%	89 to 90%	89 to 90%	86 to 87%
New	78 to 82%	82 to 85%	86 to 87%	86 to 87%	86 to 87%
Advanced	89 to 91%	90 to 92%	93 to 94%	93 to 94%	n/a

*Thermal distribution systems efficiencies for the typical cases are aggregated based on the individual typical case component runs.

**Smaller, HVAC equipment with the same duct system can result in slightly lower thermal distribution system efficiencies.