

# **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<sup>2</sup> 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  $7 \times 10^{15}$  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<sup>2</sup> 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 than 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<sub>2</sub> 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 is 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.