Joint Committee on Energy and Environmental Policy

Intelligent Green Building Solutions for today's Indoor Environmental Quality

Applicability of Home Energy Rating System (HERS) Programs to Reduce Air Leakage and Energy Consumption in Nonresidential HVAC Systems

Applicability of Home Energy Rating System (HERS) Programs to Reduce Air Leakage and Energy Consumption in Nonresidential HVAC Systems

A White Paper

Prepared for

The California Joint Committee on Energy and Environmental Policy
(California SMACNA and California SMWIA)

By

James E. Woods, Ph.D., P.E.
Executive Director
The Building Diagnostics Research Institute, Inc.
5630 Wisconsin Avenue, Suite 706
Chevy Chase, MD 20815-4455

1 June 2009

Executive Summary

The primary purpose of the 2008 Nonresidential Standards is "to further reduce growth in electrical and natural gas use and demand in nonresidential buildings while providing improved indoor environmental conditions and reducing greenhouse gasses and other emissions." To address this purpose, the objectives of this White Paper are to provide an analysis of the impact that the required but limited air leakage testing and validation procedures have on building energy consumption, and to recommend means and methods to improve the procedures that will reduce energy consumption in nonresidential buildings. To achieve these objectives, the Nonresidential Standards and supporting documents[1] were reviewed, other literature was reviewed, and a thermodynamic analysis was conducted.

These reviews revealed that heating, cooling and ventilation has been reported to account for about 28% of commercial building electricity use in California.[2] The Small HVAC System Design Guide:[3] states that single package DX air conditioners are the most popular HVAC system type in new construction in the state, cooling about 44% of the total floorspace (page 4); the average combined supply and return air leakage in these small systems has been reported as exceeding 35% (page 5); and the "energy benefits from duct tightening are estimated to be about 20% of the annual cooling consumption in buildings where duct systems are located in an unconditioned space" (page 54). Analysis indicates that these statistics are somewhat biased as they do not put in perspective the types and sizes of large HVAC systems that are installed in the residual 56% of the total floor space in new construction in the state, and do not indicate if they include those large buildings that are outside of the scope of the Title 24 2008 Building Energy Efficiency Standards for Nonresidential Buildings. Moreover, literature demonstrates that measured air leakage rates in large HVAC duct systems are also significant, varying from less than 5% to more than 26% of duct inlet airflow for the sections tested, that fan power is a substantial fraction (35 – 50%) of HVAC energy use, and that a leaky system (10% leakage upstream of VAV boxes, and 10% downstream at operating conditions) can use 25 to 35% more fan power than a tight system (2.5% leakage upstream and 2.5% downstream at operating conditions).[4] Reports of measured reductions in building electrical or total building energy consumption rates due to reduced air leakage were not found in the reviewed literature.

For buildings within its scope, the 2008 Nonresidential Standards require compliance with *mandatory measures* in addition to compliance with either a *performance approach* or a *prescriptive approach* to achieve the required "energy budgets." Within both the mandatory measures and the prescriptive approach, quantitative physical tests for duct air leakage and verification by a HERS Rater are required for a small subset of these buildings. If the buildings do not have the conditions that define this subset or if the performance approach is used, these air leakage tests are not required.

---

[1] The 2008 Nonresidential Compliance Manual; the 2008 Nonresidential Appendices, and the Nonresidential Alternative Calculation Manual (ACM) Approval Method.
[2] Source IEQ RFP, December 2002, California Energy Commission No. 500-02-501.
[3] Small HVAC System Design Guide, October, 2003, CEC-500-03-082-A12.
[4] C.P. Wray, R.C. Diamond, and M.H. Sherman. 2005. Rationale for Measuring Duct Leakage Flows in Large Commercial Buildings. Lawrence Berkeley National Laboratories, Report LBNL-58252, July 2005.

For the limited subset of duct systems defined in §144(k)1, 144k(2), 144k(3), 149(b)1D and 149(b)1E, criteria for air leakage in air distribution systems (i.e., ductwork, equipment and terminal devices) are defined as "not to exceed 6% of nominal fan flow[5]" for new systems. For existing buildings, the criteria are "not to exceed 6% of nominal fan flow" for new systems; "not to exceed 15% of nominal fan flow" for combinations of new and existing systems, or more than 60% reduction in leakage prior to replacement; or verification through visual inspection by a HERS rater that the accessible leaks have been sealed. These values are to be tested at a duct pressurization of 25 Pa (0.1 in. w.g.), which does not necessarily represent the actual pressurization of nonresidential systems during operating conditions.

These HERS field verification and diagnostic testing (FV/DT) procedures have evolved from previous editions first published for residential systems, beginning with the Phase I regulations that were established in 1999, and updated on 2005. The first set of Standards for nonresidential buildings, which was also promulgated in 2005, included air leakage procedures and criteria that were nearly identical to those in the 2005 Standards for low-rise residential buildings. Except for editorial and reference updates, the air leakage procedures and criteria in the 2008 Standards for nonresidential buildings are nearly identical to those in the 2005 Standards.

From this review and thermodynamic analysis, the following conclusions and recommendations are highlighted:

1. Air leakage in HVAC distribution systems is an important aspect to the sustainable performance of a building, including health, safety, comfort, system performance, and energy consumption. However, the functional air leakage testing procedures defined in the 2008 Nonresidential Standards, Compliance Manual and Nonresidential Appendix NA2 are limited to only two of five HVAC systems, which are intended for small buildings and areas. For larger buildings and systems, a valid and reliable method of testing for leakage in the entire air distribution systems is not available and should be developed.

2. The use of HERS procedures for nonresidential building systems is limited to those conditions that are defined in the mandatory section of the Standards, §125(a), prescriptive sections §§144(k), 149(b)1D and 149(b)1E, and Appendices NA 7.5.3.2, NA1 and NA2. For all other nonresidential building systems, the HERS procedures are not thermodynamically valid and should not be used to document verification or acceptance of any requirements.

3. Definitions and procedures for functional testing of the more than 56% of the floor area (i.e., larger buildings) in the state are not included in the *Title 24 2008 Building Energy Efficiency Standards for Nonresidential Buildings.* These large buildings are likely to have more occupants and to consume more energy than the 44% of the buildings characterized as "small" in the *2003 Small HVAC System Design Guide*. To meet the stated goals of the 2008 Standards, a concentrated effort is needed to implement a standard set of means and methods to measure and verify the air tightness of air distribution systems together with the corresponding energy consumption for all new and existing nonresidential buildings in the state.

[5] "Fan flow" is determined either by direct measurement or, by default, as Q = (400cfm/Ton) x Rated Tonnage of Equipment. The latter method leads to uncertain results regarding the air leakage criteria.

Table of Contents

Introduction

The Title 24 2008 Building Energy Efficiency Standards for Nonresidential Buildings, together with their Compliance Manual, Reference Appendices, and Alternative Calculation Manual (ACM) Approval Method have been adopted by the California Energy Commission and will become effective on 1 August 2009.

One of the requirements in these 2008 Nonresidential Standards is physical testing of air leakage in duct systems for new and renovation projects, if a certain set of conditions exist. Under these conditions, verification by a certified HERS Rater is also required. If these conditions do not exist, physical testing and verification of duct air leakage is not required by these Standards.

As the primary purpose of the 2008 Nonresidential Standards is "to further reduce growth in electrical and natural gas use and demand in nonresidential buildings while providing improved indoor environmental conditions and reducing greenhouse gasses and other emissions," the objectives of this White Paper are to provide an analysis of the impact that these required but limited air leakage testing and validation procedures have on building energy consumption, and to recommend means and methods to improve the procedures that will reduce energy consumption in nonresidential buildings.

Basis of Consideration

To achieve these objectives, the Nonresidential Standards and supporting documents[6] have been reviewed with particular focus on the required procedures for ascertaining the energy impact of air leakage in the duct systems for new or renovation projects that are within the scope of the Title 24 2008 Building Energy Efficiency Standards. This scope includes all sizes and types of buildings such as offices, retail and wholesale stores, grocery stores, restaurants, assembly and conference areas, industrial work buildings, commercial or industrial storage, schools and churches, theaters, hotels and motels, apartment and multi-family buildings and long-term care facilities with four or more habitable stories. Of particular note, the scope excludes CBC Group I buildings such as hospitals, daycare, nursing homes and prisons or buildings, which are outside of the jurisdiction of the California Building Codes.

For buildings within its scope, the 2008 Nonresidential Standards require compliance with *mandatory measures* in addition to compliance with either a *performance approach* or a *prescriptive approach* to achieve the required "energy budgets." Within both the mandatory measures and the prescriptive approach, quantitative physical tests for duct air leakage and verification by a HERS Rater are required for a small subset of these buildings. If the buildings do not have the conditions that define this subset or if the performance approach is used, these air leakage tests are not required. In the performance approach, an explicit energy consumption rate is calculated and compared to an "energy budget" through computer programs approved by the Energy Commissioner, but an explicit energy impact assessment is not required if the prescriptive approach is used, whether or not the subset

[6] The 2008 Nonresidential Compliance Manual; the 2008 Nonresidential Appendices, and the Nonresidential Alternative Calculation Manual (ACM) Approval Method.

of conditions exists that defines the need for quantitative physical testing and HERS Rater verification.

Through a review of literature and a thermodynamic analysis, this White Paper evaluates these approaches and conditions and provides recommendations for improvements to ascertain reductions in energy consumption through control of duct air leakage in all nonresidential buildings that are within the scope of the Title 24 2008 Building Energy Efficiency Standards.

Review of Literature

Goals and Purpose of the 2008 Nonresidential Standards.

According to its website link,[7] the California Energy Commission adopted the changes in the Title 24 2008 Building Energy Efficiency Standards for the following reasons:

- "To provide California with an adequate, reasonably-priced, and environmentally-sound supply of energy.
- To respond to Assembly Bill 32, the Global Warming Solutions Act of 2006, which mandates that California must reduce its greenhouse gas emissions to 1990 levels by 2020.
- To pursue California energy policy that energy efficiency is the resource of first choice for meeting California's energy needs.
- To act on the findings of California's Integrated Energy Policy Report (IEPR) that Standards are the most cost effective means to achieve energy efficiency, expects the Building Energy Efficiency Standards to continue to be upgraded over time to reduce electricity and peak demand, and recognizes the role of the Standards in reducing energy related to meeting California's water needs and in reducing greenhouse gas emissions.
- To meet the West Coast Governors' Global Warming Initiative commitment to include aggressive energy efficiency measures into updates of state building codes.
- To meet the Executive Order in the Green Building Initiative to improve the energy efficiency of nonresidential buildings through aggressive standards."

The Introduction to the 2008 Nonresidential Compliance Manual (page 1-3) describes these goals more specifically[8]:

- "The 2008 Standards [for residential and nonresidential buildings] are expected to reduce the growth in electricity use by 561 gigawatt-hours per year (GWh/y) and reduce the growth in gas use by 19.0 million therms per year (therms/y). The savings attributable to new nonresidential buildings are 459 GWh/y of electricity savings and 11.5 million therms."… "Savings from the application of the

7 http://www.easytitle24.com/help/what_you_need_to_know_commercial.pdf.

8 2008 Building Energy Efficiency Standards Nonresidential Compliance Manual (Commission Draft Manual) – Final Draft for approval 14 January 2009, CEC-400-2008-017-CMD.

Standards on building alterations accounts for 270 GWh/y and 8.2 million therms. These savings are cumulative, doubling in two years, tripling in three, etc."[9]

- "Since the California electricity crisis, the Energy Commission has placed more emphasis on demand reduction. The 2001 and 2005 standards resulted in 330 megawatts (MW) of demand reduction. The 2008 Standards are expected to reduce electric demand by another 132 MW each year. Nonresidential buildings account for 95 MW of these savings. Like energy savings, demand savings accumulate each year."[10]
- "Comfort is an important benefit of energy efficient buildings. Energy efficient buildings include properly designed HVAC systems, which provide improved air circulation, and high performance windows and/or shading to reduce solar gains and heat loss."
- "The Standards [are] expected to have a significant impact on reducing greenhouse gas and other air emissions: carbon dioxide would be reduced by 473,000 tons first year of construction, cumulative each year thereafter."

Compliance Requirements.

As indicated in several sections of the 2008 Nonresidential Compliance Manual, the Standards focus on performance and prescriptive methods to reduce envelope, lighting, and ventilation loads and on methods to improve energy efficiencies for transporting air and water to provide the required thermal conditions in occupied spaces:

- Chapters 3 and 5-7 describe mandatory measures and prescriptive requirements that affect envelope and lighting loads. Although these loads are not the focus of this White Paper, they are strong determinants in designing the types and sizes of HVAC systems and associated air distribution systems.
- Chapter 4 describes mandatory measures and prescriptive requirements that affect ventilation loads and energy efficiencies of HVAC and water heating systems, which are the focus of this White Paper. This chapter also recognizes a performance method, which allows the designer to increase the efficiency or effectiveness of selected mandatory and prescriptive measures while decreasing the efficiency of other prescriptive measures in order to achieve a site-specific energy budget.
- Chapter 9 describes a "whole building" performance approach to compliance. "The basic procedure is to show that the Time Dependent Valuation (TDV) energy of the *proposed design* is less than or equal to the TDV energy of the *standard design*, where the standard design is a building like the proposed design, but one that complies exactly with both the mandatory measures and prescriptive requirements." Compliance with this method is demonstrated through the use of an Energy Commission-approved public domain computer program or by Energy Commission-approved privately developed alternative calculation methods.[11]

---

9 The source of these statistics was not referenced in the Compliance Manual. The bases are not defined from which the 2008 values are claimed.

10 Ibid.

11 2008 Nonresidential Alternative Calculation Manual (ACM) Approval Method. December 2008. CEC-400-2008-003-CMF.

Of the two methods with which to achieve the nonresidential energy budgets, the performance approach[12] allows compliance through a wide variety of design strategies and provides greater flexibility than the prescriptive approach. It is based on energy simulation models of the buildings. The performance approach requires an approved computer software program that models the proposed building, determines its allowed TDV energy budget, calculates its energy use, and determines when it complies with the TDV energy budget. The performance requirements for HVAC and water heating systems are defined in Section 141 of the Standards.[13]

- "If the performance method is utilized for the entire building, a compiled set of Certificate of Compliance documentation pages is prepared utilizing one of the compliance software applications approved by the Energy Commission. Certificate of Compliance documentation requirements are specified in §10-103(a)1 and §10-103(a)2"[14] in the 2008 Building Energy Efficiency Standards.
- In accordance with §10-103(a)3B in the 2008 Building Energy Efficiency Standards: "For all new nonresidential buildings, high-rise residential buildings and hotels and motels designated to allow use of an occupancy group or type regulated by Part 6, the applicant shall submit a Certificate(s) of Acceptance to the enforcement agency prior to receiving a final occupancy permit. This Certificate of Acceptance is to include a "statement indicating that the applicant has demonstrated compliance with the acceptance requirements as indicated in the plans and specifications submitted under Section 10-103(a) and in accordance with applicable acceptance requirements and procedures specified in the Reference Nonresidential Appendix NA7."
- According to Section NA7.1 of Appendix NA7-2008[15] the purpose of these acceptance tests is to assure: "(1) The presence of equipment or building components according to the specifications in the compliance documents, and (2) Installation quality and proper functioning of the controls and equipment to meet the intent of the design and the Standards." Section NA7.5.3 defines acceptance tests for air distribution systems:
    - Section NA7.5.3.1 defines construction (i.e., qualitative) inspection that is to be conducted for all air distribution systems.
    - Section NA7.5.3.2 defines functional (i.e., quantitative) testing that is to be conducted in accordance with the procedures in Appendix NA2 for the subset of systems that is defined in §144(k), §149(b)1D or §149(b)1E; these tests are to be field-verified by a HERS Rater in accordance with Appendix NA1.

The prescriptive approach[16] is the simpler approach but offers relatively little design flexibility. Each individual energy component of the proposed building must meet a prescribed minimum efficiency. The prescriptive requirements for HVAC and water heating

---

[12] Chapter 9, Nonresidential Compliance Manual.
[13] See Table 100-A, 2008 Building Energy Efficiency Standards, page 22.
[14] Chapter 2, 2008 Nonresidential Compliance Manual, Section 2.2.2.
[15] Appendix NA7-2008: Acceptance Requirements for Nonresidential Buildings, in 2008 Reference Appendices, CEC 400-2008-004-CMF.
[16] See prescriptive requirements in Chapters 3 through 8 in the Nonresidential Compliance Manual.

systems are defined in Sections 144 and 149 of the Standards.[17] "If the design fails to meet even one of the requirements, then the system does not comply with the prescriptive approach."[18] The HERS field verification and diagnostic test (FV/DT) procedures are established in these sections through reference to Nonresidential Reference Appendix NA1.[19]

HVAC Systems and Duct Air Leakage

According to the Nonresidential Compliance Manual: "Mechanical systems are the second largest consumer of energy in most buildings, exceeded only by lighting. The proportion of energy consumed for space-conditioning by various mechanical components varies according to system design and climate. For most buildings in non-mountainous California climates, fans and cooling equipment may be the largest consumers of energy. Energy consumed for space heating is usually less than for fans and cooling, followed by service water heating."[20]

Heating, cooling and ventilation account for about 28% of commercial building electricity use in California.[21] The Small HVAC System Design Guide:[22] states that single package DX air conditioners are the most popular HVAC system type in new construction in the state, cooling about 44% of the total floorspace (page 4); the most popular size is 5 tons, with units between 1-10 tons representing 90% of the total unit sales in new buildings in California in 2002 (page 5); the average combined supply and return leakage in these small systems has been reported as exceeding 35% (page 5); and the "energy benefits from duct tightening are estimated to be about 20% of the annual cooling consumption in buildings where duct systems are located in an unconditioned space" (page 54).

These statistics are somewhat biased as they do not put in perspective the types and sizes of HVAC systems that are installed in the residual 56% of the total floor space in new construction in the state, which include large buildings (e.g., some with floor areas more than 500,000 square feet), and do not indicate if they include those buildings that are outside of the scope of the Title 24 2008 Building Energy Efficiency Standards for Nonresidential Buildings. Moreover, measured air leakage rates in large HVAC duct systems are also significant. It has been reported that they vary from less than 5% to more than 26% of duct inlet flow for the sections tested, that fan power is a substantial fraction (35 – 50%) of HVAC energy use, and that a leaky system (10% leakage upstream of VAV boxes, and 10% downstream at operating conditions) can use 25 to 35% more fan power than a tight system (2.5% leakage upstream and 2.5% downstream at operating conditions).[23] Reports of measured reductions in building electrical or total building energy consumption rates due to reduced air leakage were not found in the reviewed literature.

[17] See Table 100-A, Standards, page 22.
[18] Section 1.6.2, Nonresidential Compliance Manual, page 1-7.
[19] Nonresidential HERS Verification, Testing, and Documentation Procedures, NA1, in 2008 Reference Appendices, CEC-40002008-004-CMF..
[20] Section 4.1.1, Nonresidential Compliance Manual, page 4-2.
[21] Source IEQ RFP, December 2002, California Energy Commission No. 500-02-501.
[22] Small HVAC System Design Guide, October, 2003, CEC-500-03-082-A12.
[23] C.P. Wray, R.C. Diamond, and M.H. Sherman. 2005. Rationale for Measuring Duct Leakage Flows in Large Commercial Buildings. Lawrence Berkeley National Laboratories, Report LBNL-58252, July 2005.

Mandatory Measures, Performance Requirements, and Prescriptive Requirements

The mandatory measures that affect air distribution effectiveness and air leakage in all nonresidential buildings include compliance with requirements for ventilation (Subsections 121(a) through (e)), controls (Subsections 122(a) through (h)), and construction of air distribution system ducts and plenums (Section 124). The mandatory measures also require that a Certificate of Acceptance be submitted to the enforcement agency that certifies the equipment and systems in all nonresidential buildings meet the acceptance requirements (Section 125(a)). Additionally, for a limited subset of duct systems defined in the prescriptive requirements (Sections 144(k)1, 144k(2), 144k(3), 149(b)1D, and 149(b)1E), acceptance also requires passing specific functional tests in accordance with Appendix NA2, and field verification and diagnostic tests (FV/DT) by HERS raters in accordance with Appendix NA1 for air leakage in air distribution systems. These tests are nearly identical to those required by the Standards for low-rise residential buildings.

After the mandatory measures are met, the 2008 Standards allow mechanical system compliance to be demonstrated through performance or prescriptive “approaches.” The performance approach requires the use of a computer program, which has been certified by the Energy Commission, and may only be used to model the performance of mechanical systems that are covered under the building permit application.[24]

The performance approach (§141) is intended to allow the designer to increase the efficiency or effectiveness of selected mandatory and prescriptive measures, and to decrease the efficiency of other prescriptive measures. In this approach, the proposed building’s use of Time Dependent Valuation (TDV) energy, which is calculated as described in Subsection 141(b), must be no greater than the TDV energy budget calculated under Subsection 141(a). Approved compliance software is required for these calculations as specified in the Alternative Calculation Manual (ACM).

- Of the five HVAC systems that comprise the approved models in Section 2.5.2.4 of the ACM, only System Types 1 and 2 require explicit calculation of “duct (system) efficiency.”[25] For these systems, Section 2.5.2.4 states: “ducts installed in unconditioned buffer spaces or outdoors as specified in §144(k), the duct system efficiency shall be as described in Section 2.5.3.18.” No explicit definitions or criteria are provided for duct efficiencies for these systems, and no other requirements are defined for the other three System Types.
- Section 2.3 of Appendix NA2[26] identifies input values for the computer model of a building with small HVAC systems (including ducts) using either default or diagnostic information to calculate duct efficiency. [27]

The performance approach may be used for all building sizes and HVAC system types. For the special cases defined by §125(a), HERS FV/DT is required if all of the conditions in §144(k), 149(b)1D or 149(b)1E exist. However, the performance approach may be used to

---

[24] See §141(c)1 in 2008 Standards.

[25] Section 2.5.2.4: Standard Design Systems, in the Nonresidential ACM, CEC-400-2008-003-CMF. However, the term “duct efficiency” or “duct system efficiency” is not explicitly defined in the reviewed documents.

[26] Section 2.3 in Appendix NA2-Nonresidential Field Verification and Diagnostic Test Procedures, in 2008 Reference Appendices, CEC 400-2008-004-CMF.,

[27] This is an important section as it indicates that the HERS obtained data are only used to input the energy model as the “Duct Leakage Factor.”

evaluate modifications that would preclude the requirement for HERS FV/DT, such as relocation of the ductwork, use of VAV in lieu of CAV systems, or increasing the number of thermostatic zones.

The prescriptive approach in the 2008 Nonresidential Standards is used as an alternative to the performance approach. While it is sometimes considered simpler than the performance approach, it offers little design flexibility. Requirements in the prescriptive approach are used to qualify components and systems on an individual basis and are contained in Sections 144 and 149 of the Standards. The prescriptive requirements that affect air distribution effectiveness or air leakage for all nonresidential buildings within the scope of the Standards include: §144(a) – Sizing and Equipment Selection; §144(c) – Power Consumption of Fans; §144(d) – Space-conditioning Zone Controls; §144(e)1 – Economizers; and §144(f) – Supply Air Temperature Reset Controls.

For the limited subset of duct systems defined in §144(k)1, 144k(2), 144k(3), 149(b)1D and 149(b)1E, criteria for air leakage in air distribution systems (i.e., ductwork, equipment and terminal devices) are defined as "not to exceed 6% of nominal fan flow[28]" for new systems. For existing buildings, the criteria are "not to exceed 6% of nominal fan flow" for new systems; "not to exceed 15% of nominal fan flow" for combinations of new and existing systems, or more than 60% reduction in leakage prior to replacement; or verification through visual inspection by a HERS rater that the accessible leaks have been sealed. These values are to be tested at a duct pressurization of 25 Pa (0.1 in. w.g.), which does not necessarily represent the actual pressurization of nonresidential systems during operating conditions. The limitations in §144(k) are that the duct system:

1. Is connected to a constant volume, single zone, air conditioners, heat pumps or furnaces; *and*

2 Serving less than 5,000 square feet of floor area; *and*

3 Having more than 25 percent duct surface area located in one or more of the following spaces:

   A. Outdoors; or

   B. In a space directly under a roof where the U-factor of the roof is greater than the U-factor of the ceiling; or

      EXCEPTION to Section 144(k)3B: Where the roof meets the requirements of 143(a)1C.

   C. In a space directly under a roof with fixed vents or openings to the outside or unconditioned spaces; or

   D. In an unconditioned crawlspace; or

   E. In other unconditioned spaces.

Additional limitations for duct systems that are installed in existing buildings are stated in §149(b)1D and §149(b)1E.

[28] "Fan flow" is determined either by direct measurement or, by default, as Q = (400cf/Ton) x Rated Tonnage of Equipment. The latter method leads to uncertain results regarding the air leakage criteria.

The procedure for determining the air leakage rates is specified in the 2008 Nonresidential Appendix NA2. The use of these values is given in NA2.3.7, which gives *leakage factors* to be used in the computer simulations. The default value of 0.82 is based on an assumed leakage rate for the Standard Design. The "tested" values of 0.96 and 0.925 are given in Table NA2.1 for new and existing systems. These leakage factors are to be used in the approved computer model to calculate the *delivery effectiveness*, which is defined in NA2.4 as "the ratio of the thermal energy delivered to the conditioned space and the thermal energy entering the distribution system at the equipment heat exchanger." Neither criteria nor methods of calculation for acceptable values of delivery effectiveness are provided in the ACM or in NA2.

Alternatives to the requirement for compliance with the air leakage criteria defined in §144(k)1, 144k(2), 144k(3), 149(b)1D and 149(b)1E are described in , criteria for air leakage in air distribution systems in Section 4.4.2 in the Nonresidential Compliance Manual:

1. "Sealing the ducts can be avoided by insulating the roof and sealing the attic vents as part of a larger remodel, thereby creating a conditioned space within which the ducts are located, and no longer meets the criteria of §144(k)."
2. "If one or more applicable prescriptive requirements cannot be met, the performance method may be used as explained in Chapter 9."

HERS Programs for Nonresidential Buildings

As stated in the 2008 Reference Appendix NA1: [29] "Compliance for duct sealing of HVAC systems covered by §144(k), §149(b)1D, and §149(b)1E requires field verification and diagnostic testing of as-constructed duct systems by a certified HERS rater, using the testing procedures in the Reference Nonresidential Appendix NA2."[30] Appendix NA1 also states: "When field verification and diagnostic testing of specific energy efficiency improvements are a condition for those improvements to qualify for Title 24 compliance credit, an approved HERS provider and certified HERS rater shall be used to conduct the field verification and diagnostic testing."

These HERS field verification and diagnostic testing (FV/DT) procedures have evolved from previous editions first published for residential systems, beginning with the Phase I regulations that were established in 1999, and updated on 2005. The first set of Standards for nonresidential buildings, which was also promulgated in 2005, included air leakage procedures and criteria that were nearly identical to those in the 2005 Standards for low-rise residential buildings. Except for editorial and reference updates, the air leakage procedures and criteria in the 2008 Standards for nonresidential buildings are identical to those in the 2005 Standards. However, a significant change occurred in the scope of NA2 compared to 2005 Nonresidential Appendix NG1: in section NA 2.1.1, the purpose and scope has eliminated the requirement for "calculating the annual and hourly duct system efficiency for energy calculations." It has also changed the word "calculations" to

[29] 2008 Reference Appendix NA1.1, page NA 1-1.
[30] 2008 Reference Appendix NA2: Nonresidential Field Verifications and Diagnostic Test Procedures. NA2.1: Air Distribution Diagnostic Measurement and Field Verification. "Diagnostic inputs are used for the calculation of improved duct efficiency."

"procedures." The terms "duct efficiency" or "duct system efficiency" are not defined in the 2008 Energy Efficiency Standards, Compliance Methods, or Reference Appendices.

Thermodynamic Analysis

Fundamentally, the processes that provide acceptable thermal and ventilation conditions for occupant health, comfort and well-being are similar for residential and nonresidential buildings: electricity, natural gas and other depletable resources are converted to energy forms that heat, cool, and clean the air in the HVAC equipment, which is then transported to and from the occupied spaces through the air distribution system. The thermodynamic objective is also similar for residential and nonresidential buildings: to provide for the functional requirements of the facility while consuming the least amount of the depletable resources. While the thermodynamic objective and processes are similar, significant differences exist between residential and nonresidential applications in the configurations of the HVAC and air distribution systems required to meet this objective. These differences include:

- Function and size of the facility;
- Indoor environmental criteria for thermal, lighting, acoustic, and air quality;
- External (i.e., envelope) and internal (i.e., lighting, ventilation, process) loads that must be dissipated from the various spaces, zones, and schedules in the building;
- Capacity, controllability and reliability of the HVAC systems to dissipate the peak and partial loads;
- Power and energy consumption.

Function and Size of Facility.

Low-rise Residential Facilities. The primary function of a low-rise residential facility is to provide for the health, safety, security, and comfort of a *single family or multiple families*. In the Title 2008 Residential Standards, low-rise single-family residences are less than four-stories and multifamily residences are less than three stories. Low-rise residential facilities are normally dominated by envelope loads but may also have significant electrical power requirements that contribute to the thermal loads. HVAC systems for low-rise residential facilities typically consist of single-zone, CAV packaged DX and gas furnace or heat pump units with ducted supply and return air that serve up to approximately 2,000 ft^2 of floor area; multiple systems may be required for larger residential facilities.

Nonresidential Facilities. The primary function of a nonresidential facility is to provide for the health, safety, security, and comfort of the *total population of occupants*, which requires consideration of the diversity and occupancy periods within the facilities (e.g., staff, visitors, customers, patients, students). Additionally, these facilities must provide for the special conditions required to achieve functional performance and productivity objectives including office, educational, acute and chronic health care, security, sales and services, entertainment, high-rise residential, and hotel/motel and kitchen/restaurant. High-rise residential and nonresidential facilities range in sizes to more than 2,000,000 square feet of floor area. The size and function of these facilities have significant impact on the dominance of the thermal loads: buildings with floor plates larger than approximately 15,000 square feet are more likely to be dominated by internal and ventilation loads, whereas the smaller buildings are more likely to be dominated by the envelope loads. The HVAC systems may be packaged or built-up with central chilled and hot water plants, have single or multiple zones, deliver CAV or VAV air through ducted supply and plenum or ducted return air that serve zones that vary from less than 100 to more than 2,000 ft^2 of floor area; multiple systems may be required for larger nonresidential facilities.

As revealed in this review, the HERS Programs for nonresidential buildings are limited to low-rise nonresidential buildings of three or fewer stories above grade that are served by two types of packaged single-zone systems: Type 1, which have gas furnaces and electric air conditioning; and Type 2, which are electric heat pumps.[31] According to §144(k), these HERS Programs are further limited to air duct systems that serve less than 5,000 ft^2 floor area with single zone CAV, and that more than 25% of the duct surface area located either outdoors or in a semi-conditioned buffer area.

According to the Small HVAC Design Guide, approximately 44% of the total commercial floorspace in California was serviced by single package DX air conditioners, that 90% of these were between 1-10 tons, and that the most common size was 5 tons, which represented about 24% of the sales in 2002. At a nominal supply airflow rate of 1 cfm/ft^2 and an average capacity of 325 cfm/ton,[32] a 15 ton unit would be required to service 5,000 ft^2 and a 5 ton unit would service approximately 1,625 ft^2. These small, single zone CAV units are typically not installed for buildings with more than four stories and are typically not used in buildings that provide critical functions.

Data were not available that indicated how many of these small systems were installed with 25% of the duct surface area located outdoors or in a semi-conditioned buffer area. The number of small HVAC systems with 25% or more of its ductwork in these locations is critical to the assessment of the impact that the HERS Programs will have, as a reasonable alternative is to redesign the HVAC system to reduce the amount of this exposed ductwork. This redesign would eliminate the need for mandatory and prescriptive testing in accordance with §125(a) and 144(k), but would still require the sealing of the ductwork in accordance with §124.

Indoor Environmental Quality.

The thermal and air quality within occupied spaces can be enhanced by many energy efficiency opportunities; but can also be adversely affected by air leakage in the supply and in the exhaust air distribution systems. The Small HVAC System Design Guide reports that the average combined supply and return leakage in these small systems can exceed 35% (page 5), but is not explicit with regard to the reference air flow (e.g., design airflow of the system?). As revealed in the review, Wray et al[33] have documented that significant air leakage of more than 26% of duct inlet flow rate can also occur in large HVAC systems.

- Air leakage in the supply air distribution of all sizes of HVAC systems causes air to bypass the occupied space, which can result in insufficient amounts of supply air available to dissipate sensible and latent loads in the occupied zone(s). This leakage can also result in loss of pressurization control and can exacerbate infiltration of heat, moisture, and other contaminants into the occupied zone(s).

---

[31] See Tables N2-13 and N2-14 in 2008 Nonresidential ACM, page 2-61, CEC-400-2008-003-CMF.
[32] See Fig. 19, page 48, Small HVAC System Design Guide, October, 2003, CEC-500-03-082-A12
[33] Op cit (see Footnote 18).

- Air leakage in negatively pressurized exhaust air distribution of all sizes of HVAC systems results in air infiltration from the shafts or other spaces surrounding the ductwork, which diminishes the capture and removal of contaminants at the local or room inlets to the exhaust air system.
- Testing to assure the tightness of supply and exhaust air of any size HVAC system can result in improved thermal and indoor air quality. However, the HERS FV/DT Programs do not provide for testing, diagnosing, or verifying the impact of duct leakage on thermal and indoor air quality exposures, human responses, or occupant performances.

Thermal and Ventilation Loads.

Thermal and ventilation loads in occupied spaces (i.e., room loads) are independent of air leakage rates in supply and exhaust air ducts, as they are determined by the characteristics of the envelope, lighting and power requirements, and occupant density. However, system or "block" loads are affected by air leakage, as the bypass air from supply duct leakage can inadvertently cool or heat the recirculated air to the air handling units, especially if the ducts are located outdoors or in an uncontrolled buffer area. Also, air leakage in the exhaust ducts can waste the return air and impose incremental loads on the cooling and heating coils. The HERS FV/DT requirements for duct leakage do not address methods of measurement or evaluation of the impact that air leakage has on thermal and ventilation loads. However, the performance approach has the capability of providing calculated results to indicate the impact of air leakage on the system block loads.

HVAC System Capacities and Controls.

Capacities. The design capacities of all sizes of HVAC systems are affected by the assumed and actual air leakage rates in the supply and exhaust air ductwork. Typically, these leakage rates are assumed as minimal and specifications are written to provide the required sealing and testing, as required in §124 of the 2008 Building Energy Efficiency Standards. In larger systems, however, methods of air leakage testing to assure compliance with air leakage criteria are not addressed in the references cited in §§124-125. As a minimum, the SMACNA test methods should be referenced in this Section for all sizes of ductwork. The methods used by Wray et al[34] also provide a solid foundation for developing procedures for air leakage testing in large HVAC systems.

Nonresidential Appendix NA2.3.8.1 extends the method of testing from ductwork to air distribution systems, including the housings for the air handling units and the terminal units. However, the method in Appendix NA2.3.8.1 is limited to small systems and conditions defined in §§144(k), 149(b)1D and 149(b)1E. The likely reason for this limitation is that a protocol for air distribution leakage testing of larger systems has not been developed or validated.[35]

Controls. Control strategies and sequences, which are not addressed by the HERS FV/DT Programs, are significantly affected by air distribution leakage rates. Air leakage in the exhaust air distribution systems will result in reduced effectiveness of capture velocities at exhaust air inlets. Air leakage in the supply air distribution system can result in:

---

[34] Op cit. (See Footnote 18).

[35] From personal communication with Eli Howard, Technical Director at SMACNA,

- Unstable VAV control of air handling units by causing a false reduction in the duct static pressure at the sensor for the variable frequency drive (VFD) or variable speed controller for the supply fan.
- Decreased sensitivity of zone thermostatic sensors or controllers for either VAV or CAV systems.
- Increased contamination in occupied spaces, especially if CO_2 or other contaminant control devices are located in the return air system.
- Loss of control in sensitive positive or negative zone pressurization requirements, perimeter zones, and flow-tracking or differential pressure tracking of return air fan speed.
- Unstable reset control of supply air temperature: higher reset temperatures will require increased airflow rates at the same loads, thus exposing the system to increased air leakage caused by the increased static pressure.
- Unstable performance of air-side economizers and sensible or latent heat recovery devices between supply and exhaust air streams.

Power and Energy Consumption.

Changes in the 2008 Nonresidential Standards from 2005 have not been made to the prescriptive requirements in par 144(k) regarding duct air leakage testing. Therefore, the CEC goal of incremental energy savings should not be expected from 144(k). However, some changes in the 2008 performance requirements have occurred so incremental savings may be expected when using §141, the performance approach, especially in the approach to the Time Dependent Valuation of energy consumption.

Time Dependent Valuation. Beginning with the 2005 Standards, the "currency" for assessing building performance is Time Dependent Valuation (TDV) energy.[36] TDV energy replaces source energy, the thermodynamic term that has been the currency since the CEC first adopted standards in 1978. TDV, as the name implies, values energy differently depending on the time it is used. According to the 2008 Nonresidential Compliance Manual, the values "assigned to energy savings through TDV more closely reflect the market for electricity, gas, propane and other energy sources and provides incentives for measures, such as thermal storage or daylighting that are more effective during peak periods." However, *TDV is not a thermodynamic term and it confounds measures of energy and power for economic reasons.*

For the performance approach, the Commission-approved software calculates TDV energy for three main components: the space conditioning energy use, the lighting energy use, and the service water heating energy use. It does not include energy for plug loads from computers (even though default values for the internal gains from plug loads are modeled in the hourly computer simulation), vertical transportation, garage ventilation, outdoor lighting or other miscellaneous energy uses (see Subsection 141(c) 3 – Energy Excluded). This is a major omission as these "nonregulated" loads can account for 25-50% or more of the actual energy consumed by a building. This omission has significant impact on the calculated percentage of energy wasted by air distribution leakage, as the omission will result in an inflated value (i.e., percentage). This omission was a customary practice prior

[36] See Section 9.1.3 of the 2008 Nonresidential Compliance Manual, CEC-400-2008-017-CMD.

to publication of ASHRAE Standard 90.1-2004. This omission is now recognized as not providing a valid representation of the energy that is expected to be consumed after the building is delivered and is operational.

Energy Efficiency. One of the goals the CEC expressed in adopting changes in the Title 24 2008 Building *Energy Efficiency* Standards was "to pursue California energy policy that *energy efficiency* is the resource of first choice for meeting California's energy needs." Toward this goal, Section 4.10.1 of the Compliance Manual defines energy efficiency as "a measure of how effectively the energy is converted or regulated. It is expressed as the ratio:

$$\text{Eff} = \text{Output}/\text{Input} \qquad \textit{Equation 4-1.}$$

"The units of measure in which the input and output energy are expressed may be either the same or different, and vary according to the type of equipment. The Standards use several different measures of efficiency." Calculating this energy efficiency in terms of TDVs will provide answers that will be different than the energy efficiency calculated in thermodynamic values of the resources and the results will not be amenable to comparisons with measured or metered energy data collected after occupancy. Analysis of how air leakage rates will affect energy efficiency in these terms is beyond the scope of this White Paper.

Power and Demand. Power is the rate of using energy. Typical measures of power are Watts and Btu/hr and typical measures of energy are Watt-hours and Btu.

Air leakage will directly affect the "total fan system power demand" (see §144(c).) and resultant energy consumption. All air distribution systems should be tested to specified minimum air leakage rates, using standardized methods for ducts, plenums, cavities, and terminal units.

- For smaller systems, the methods specified in Appendices NA7.5.3.2 and NA2 for the subset of systems that is defined in §144(k), §149(b)1D or §149(b)1E has a good thermodynamic basis but also has some deficiencies:
  - These air distribution systems should be tested at design values of total static and external static pressures; not at the arbitrary static pressure of 25 Pa specified for the HERS method.
  - The airflow rate used as a reference should be the actual design or measured value; not the arbitrary value derived from the nominal tonnage and the conversion factor of 400cfm/Ton.
- For larger systems, additional standardization is required. The methods used by Wray et al[37] and those being developed by SMACNA[38] are good foundations. For these systems, the tests should be conducted at the design static pressure and at the inlet airflow rate for the section to be tested.

In determining "total fan system power demand" according to the prescriptive approach §144(c)3 for large and small systems, the additional "power demand" caused solely by air treatment or filtering systems with final pressure drops more than 245 Pascals (1 in. w.c.), the pressure drop over 245 Pa may be excluded from the calculations. This exclusion is

---

[37] Op cit (see Footnote 18).
[38] Op cit (see Footnote 30).

not thermodynamically rational as power is actually required to provide for these functions. Moreover, the location of the filters or process loads may directly affect external static pressures and associated duct air leakage rates.

Energy Impact of Air Distribution Leakage.

The Small HVAC System Design Guide:[39] estimated that the "energy benefits from duct tightening are estimated to be about 20% of the annual cooling consumption in buildings where duct systems are located in an unconditioned space" (page 54). The projected 20% energy reduction is apparently for each small building with ductwork in buffer areas and in which the air leakage has been reduced from 35 to 6%. As the number of buildings in which this condition exists is unknown, the potential state-wide impact of air distribution leakage in small buildings is also unknown.

Comparable information regarding air leakage in larger buildings and HVAC systems was found in one study[40] reviewed for this White Paper, but the energy impact of reducing the air leakage on total energy or electrical consumption was not reported. Although the energy impact of air distribution leakage in larger buildings and HVAC systems is likely to exceed the impact for small buildings, this impact on the larger building is only addressed in the 2008 Building Energy Efficiency Standards through the performance approach. An analysis of this impact on a building, or statewide impact, is beyond the scope of this White Paper.

For small systems, Section NA2.4 provides a definition for *delivery effectiveness*: "The ratio of the thermal energy delivered to the conditioned space and the thermal energy entering the distribution system at the equipment heat exchanger." However, neither criteria nor calculation methods for acceptable values of delivery effectiveness are provided in the ACM or NA2. Although used in the 2008 Nonresidential Building Energy Efficiency Standards and its associated documents, no specific definitions for "duct efficiency," "duct system efficiency" or HVAC distribution efficiency" have been found the reviewed documents. The application of these terms is apparently directed to the performance approach.

Thermodynamically, air leakage in ductwork will not only adversely affect the electrical consumption due to wasted fan power, but it will also impose false loads on the heating and cooling coils and result in additional waste of electricity, natural gas, and other energy resources. The Energy Commission approved software should be capable of ascertaining these wastes if queried appropriately. However, there is a dearth of actual data with which to calibrate these models or to verify that the energy reductions are actually occurring during building operations.

Impact of HERS Procedures.

As stated in the 2008 Reference Appendix NA1:[41] "Compliance for duct sealing of HVAC systems covered by §144(k), §149(b)1D, and §149(b)1E requires field verification and diagnostic testing of as-constructed duct systems by a certified HERS rater, using the

[39] Small HVAC System Design Guide, October, 2003, CEC-500-03-082-A12.
[40] Op cit (see footnote 18).
[41] 2008 Reference Appendix NA1.1, page NA 1-1.

testing procedures in the Reference Nonresidential Appendix NA2.[42]" Therefore, by inference, compliance for duct sealing of larger HVAC systems is not covered by these sections and does not require FV/DT by certified HERS rater.

As stated in Section NA2.1: Air Distribution Diagnostic Measurement and Field Verification, the purpose of these procedures is to obtain "diagnostic inputs [that] are used for the calculation of improved duct efficiency," which are not clearly defined as indicated above.

Section NA2.1.1 limits the scope to procedures for measuring air leakage in "single zone, constant volume heating and air conditioning systems serving zones with 5000 ft^2 of floor area or less, with duct systems located in unconditioned or semi-conditioned buffer spaces or outdoors." The procedures described in NA2.3.8.1 and NA2.3.8.2, for new and altered systems, are thermodynamically valid but may not provide accurate results due to some of the assumed conditions. The results from these procedures are apparently intended to provide inputs to determine "duct leakage factors" as shown in Table NA2-1 and described in Section NA2.3.7. These procedures are limited to small, single-zone, CAV systems with relatively low total and external static pressures and are not thermodynamically valid for larger HVAC systems. Values for "duct leakage factors" for larger air distribution systems were not found in the reviewed literature, but may be imbedded in the Commission-approved software for the performance approach to building energy efficiency evaluations.

Conclusions and Recommendations

1. Air leakage in HVAC distribution systems is an important aspect to the sustainable performance of a building, including health, safety, comfort, system performance, and energy consumption. However, the functional air leakage testing procedures defined in the 2008 Nonresidential Standards, Compliance Manual and Nonresidential Appendix NA2 are limited to only two of five HVAC systems, which are intended for small buildings and areas. For larger buildings and systems, a valid and reliable method of testing for leakage in the entire air distribution systems is not available and should be developed.

2. Acceptance tests in accordance with Appendix NA7-2008 must include targeted inspection checks and functional and performance testing to determine compliance with the 2008 Building Energy Efficiency Standards. Appendix NA7-2008 defines acceptance procedures and tests which must be certified for the building envelope (NA7.4), mechanical systems (NA7.5), indoor lighting control systems (NA7.6), and outdoor lighting (NA7.7). A Certificate of Acceptance must be issued by the licensed responsible party before a final Certificate of Occupancy will be issued.

4. Section NA7.5.3.2: Functional Testing for Air Distribution Systems, is the only requirement that refers to HERS Rater field verification of air distribution leakage, which requires completion in accordance with NA1. In this case, the HERS Rater must submit the field verification to the licensed responsible party who includes it with the package of Certificates of Acceptance.

[42] 2008 Reference Appendix NA2: Nonresidential Field Verifications and Diagnostic Test Procedures. NA2.1: Air Distribution Diagnostic Measurement and Field Verification. "Diagnostic inputs are used for the calculation of improved duct efficiency."

5. The use of HERS procedures for nonresidential building systems is limited to those conditions that are defined in the mandatory section of the Standards, §125(a), prescriptive sections §§144(k), 149(b)1D and 149(b)1E, and Appendices NA 7.5.3.2, NA1 and NA2. For all other nonresidential building systems, the HERS procedures are not thermodynamically valid and should not be used to document verification or acceptance of any requirements.
6. Definitions and procedures for functional testing of the more than 56% of the floor area (i.e., larger buildings) in the state are not included in the *Title 24 2008 Building Energy Efficiency Standards for Nonresidential Buildings.* These large buildings are likely to have more occupants and to consume more energy than the 44% of the buildings characterized as "small" in the *2003 Small HVAC System Design Guide*. To meet the stated goals of the 2008 Standards, a concentrated effort is needed to implement a standard set of means and methods to measure and verify the air tightness of air distribution systems together with the corresponding energy consumption for all new and existing buildings in the state.

END OF REPORT