CALIFORNIA ENERGY
COMMISSION

Small HVAC System Design Guide

DESIGN GUIDELINES

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Preface

The Small HVAC System Design Guide (Design Guide) provides design guidance on how to improve the installed performance of small packaged rooftop HVAC systems in commercial buildings. The document is written for architects, engineers, and design/build contractors involved in the design of small packaged rooftop systems for commercial building applications. It includes information and advice on overall building design practices to minimize HVAC loads, unit selection and sizing, distribution and control system design, commissioning, and operations and maintenance.

Small HVAC systems are installed in about 40 million square feet (ft^2) of new California construction annually. By applying the integrated design principles in this document, the energy consumption and costs of buildings with small HVAC systems can be reduced by 25% to 35%. Impacts on building first costs are minimized through a combination of load avoidance strategies designed to reduce the size and cost of the HVAC system, with simple paybacks of about 0.2 to 2.4 years. Along with integrated design, other design strategies suggested in this document focus on establishing and maintaining efficient operation of systems as they are installed in the field. Problems with equipment and controls (economizers, fan controls, thermostat programming), in-situ air flow and fan power, refrigerant charge, and operation/maintenance practices that can lead to poor system performance are addressed.

Solutions to problems observed in the design of small HVAC systems rest in the hands of market actors up and down the building design, construction and maintenance chain. This Design Guide focuses on specific actions building designers can take to improve the overall performance of small HVAC systems.

The Buildings Program Area within the Public Interest Energy Research (PIER) Program produced this document as part of a multi-project programmatic contract (#400-99-413). The Buildings Program includes new and existing buildings in both the residential and the nonresidential sectors. The program seeks to decrease building energy use through research that will develop or improve energy-efficient technologies, strategies, tools, and building performance evaluation methods.

The Design Guide is Attachment A-12 (product 4.7.5) to the Final Report on *Integrated Energy Systems:Productivity and Building Science* Program (Commission Publication #P500-03-082). For other reports produced within this contract or to obtain more information on the PIER Program, please visit www.energy.ca.gov/pier/buildings or contact the Commission's Publications Unit at 916-654-5200. The Design Guide is also available at www.newbuildings.org.

Abstract

The Small HVAC System Design Guide (Design Guide) provides design guidance on how to improve the installed performance of small packaged rooftop HVAC systems in commercial buildings. The document is targeted at architects, engineers, and design/build contractors involved in the design of small packaged rooftop systems for commercial building applications. It includes information and advice on overall building design practices to minimize HVAC loads, unit selection and sizing, distribution and control system design, commissioning, and operations and maintenance.

Small HVAC systems are installed in about 40 million ft² of new California construction annually. By applying the integrated design principles in this document, the energy consumption and costs of buildings with small HVAC systems can be reduced by 25% to 35%. Impacts on building first costs are minimized through a combination of load avoidance strategies designed to reduce the size and cost of the HVAC system, with simple paybacks of about 0.2 to 2.4 years. Along with integrated design, other design strategies suggested in this document focus on establishing and maintaining efficient operation of systems as they are installed in the field. Problems with equipment and controls (economizers, fan controls, thermostat programming), in-situ air flow and fan power, refrigerant charge, and operation/maintenance practices that can lead to poor system performance are addressed.

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Keywords: HVAC, Roof Top Units, Package Units, Mechanical Design Contractors, Economizers, HVAC Controls, Integrated Design, Energy Savings

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Overview

This Design Guide focuses on packaged heating, ventilation and air conditioning (HVAC) systems up to 10 tons per unit—the most common HVAC systems for small commercial buildings in California. These systems are notorious for consuming more energy than is necessary to properly heat, cool, and dehumidify buildings. The electrical and natural gas energy wasted as a result of poorly integrated and operating small commercial HVAC systems in California is significant. The problems arise because designers do not understand the implications of poor systems integration, do not have proper guidelines for total integration of all building elements for minimum energy consumption, and often do not have the necessary financial and market incentives to implement total integration.

This Design Guide discusses a number of topics relating to the design, installation, operation, commissioning, and maintenance of small HVAC systems. A number of problems documented in the field have their roots traced to one or more of these areas. Suggested design practices are summarized below.

Suggested Design Practices

- Practice load avoidance strategies such as reduced lighting power, high-performance glass and skylights, cool roofs, and improved roof insulation techniques in the overall building design.
- Size units appropriately using ASHRAE-approved methods that account for the load avoidance strategies implemented in the design, and use reasonable assumptions for plug load power and ventilation air quantities when sizing equipment.
- Select unit size and airflow based on calculated sensible loads without oversizing. Consider increasing unit flowrate to improve sensible capacity in dry climates.
- Specify units that meet Tier 2 efficiency standards established by the Consortium for Energy Efficiency; incorporate premium efficiency fan motors, thermostatic expansion valves, and factory-installed and run-tested economizers with differential rather than single-point changeover control.
- Design distribution systems with lower velocities to reduce pressure drop and noise. Seal and insulate duct systems located outside the building's thermal envelope.
- Operate ventilation systems continuously to provide adequate ventilation air. Incorporate demand-controlled ventilation to reduce heating and cooling loads.
- Specify commercial grade two-stage cooling thermostats with the capability to schedule fan operation and heating and cooling setpoints independently.

- Commission the systems prior to occupancy through a combination of checklists and functional testing of equipment control, economizer operation, airflow rate and fan power.
- Develop clear expectations on the services provided by HVAC maintenance personnel.

The typical costs to upgrade a building to improved efficiency with high efficiency lighting, high-performance glass, cool roof, improved roof insulation and an energy-efficient HVAC system ranges from \$2.70 per ft^2 in coastal climates to \$3.50 per ft^2 in desert climates. When employing integrated design, the cooling system credit for reduced system size ranges from \$2.00 per ft^2 in coastal climates to \$3.30 per ft^2 in desert climates, with a net first cost impact of \$0.70 per ft^2 in coastal climates to \$0.20 per ft^2 in desert climates. These first costs are offset by annual energy cost savings on the order of \$0.30 to \$0.70 per ft^2 per year, providing 25% to 35% energy savings with a simple payback period of 2.5 years or less.

Introduction

This Small HVAC System Design Guide (Design Guide) is the result of a three-year project on performance of small package HVAC systems in commercial buildings. The project looked at 215 rooftop units on 75 buildings in California. Through field monitoring and testing of these units, the researchers identified a number of common installation and operation problems. The solutions and recommendations presented in this Design Guide are based on the research results, as well as on contributions from leading experts and on other current research on small package systems.

This project was part of a larger research effort called *Integrated Energy Systems: Productivity and Building Science* Program. As the name suggests, it is not individual building components, equipment, or materials that optimize energy efficiency. Instead, energy efficiency is improved through the integrated design, construction, and operation of building systems.

Following the practices in this Design Guide leads to major improvements in energy efficiency and occupant comfort.

Audience

The Design Guide is written primarily for designers of small HVAC systems in new commercial buildings. These designers include architects, mechanical engineers, and design/build contractors. The technical content, design recommendations and guideline organization is intended to provide this audience with fast and relevant information that applies to almost all projects using small package systems.

There are also sections of interest to installers and service contractors. In addition, planners for energy efficiency and green building programs, real estate developers, and building owners and occupants can benefit from information on the performance and opportunities for improvement of this widely used HVAC system.

The HVAC systems addressed in this Design Guide are primarily single package rooftop air conditioners and heat pumps with a cooling capacity of 10 tons or less. These systems may be small, but the buildings that utilize them are often large, with multiple small systems applied. Although this research focused on units in the state of California, the Design Guide solutions apply to small package HVAC design throughout the country.

Why Small HVAC?

Direct-expansion (DX) air conditioners and heat pumps cool more than half the total commercial new construction floor space in California (Figure 1). Of these systems, single package rooftop air conditioners dominate the market, representing approximately three-quarters of the total DX system capacity.

Figure 1. Floorspace Distribution of HVAC Systems in New Commercial Buildings in California

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. Built-up systems are the second-most popular, conditioning about 17% of the total floorspace. The combined total of single package and split DX air conditioners and heat pumps represents slightly more than half of the total floorspace in the state. Note that a significant portion (about 19%) of the total floorspace is not cooled. Source: AEC, 2002.

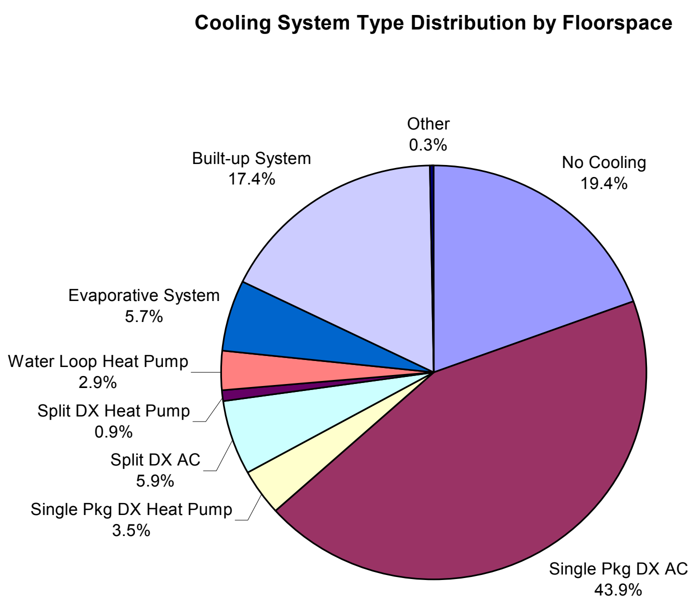
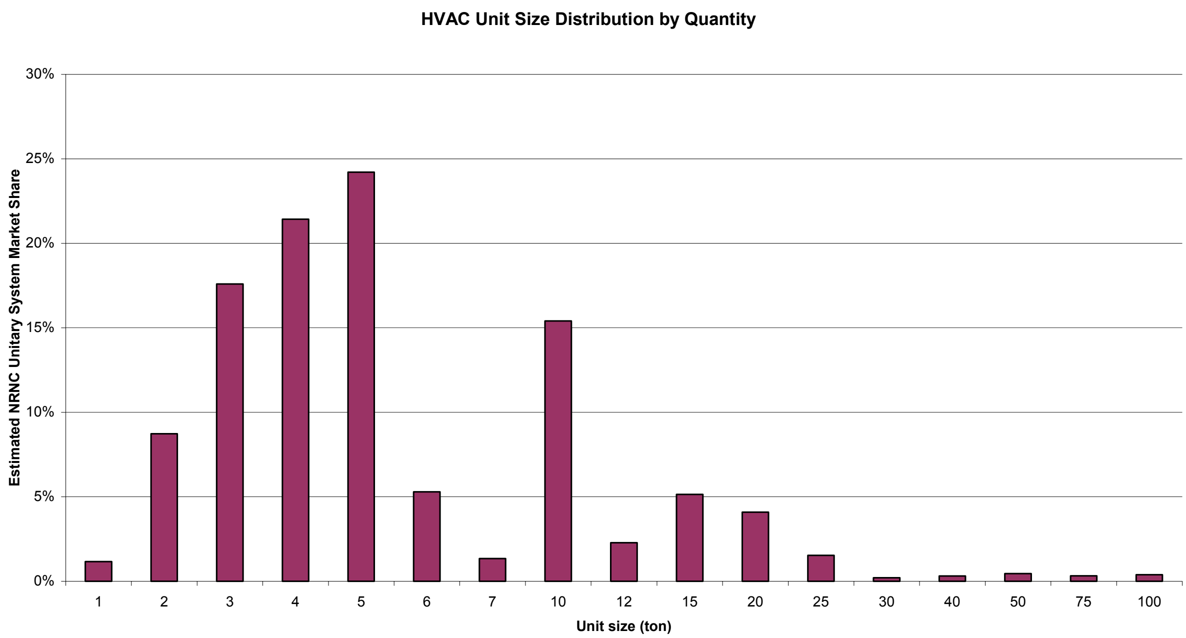


Figure 2. Distribution of Packaged DX System Size

In terms of number of systems installed, the most popular packaged DX system size is 5 tons. Units between 1 and 10 tons represent close to 90% of the total unit sales in new buildings in California. Source: AEC, 2002.



The rooftop air conditioner market is dominated by small systems, defined here as systems 10 tons and smaller, representing almost 60% of the total installed DX cooling capacity. The most popular unit size (in terms of units sold) is 5 tons (Figure 2).

Figure 3. Example of Commercial Building with Small HVAC

This is an example of a small commercial building with packaged rooftop units. This particular building is approximately 5,500 ft² and is conditioned by three 5-ton packaged rooftop units.

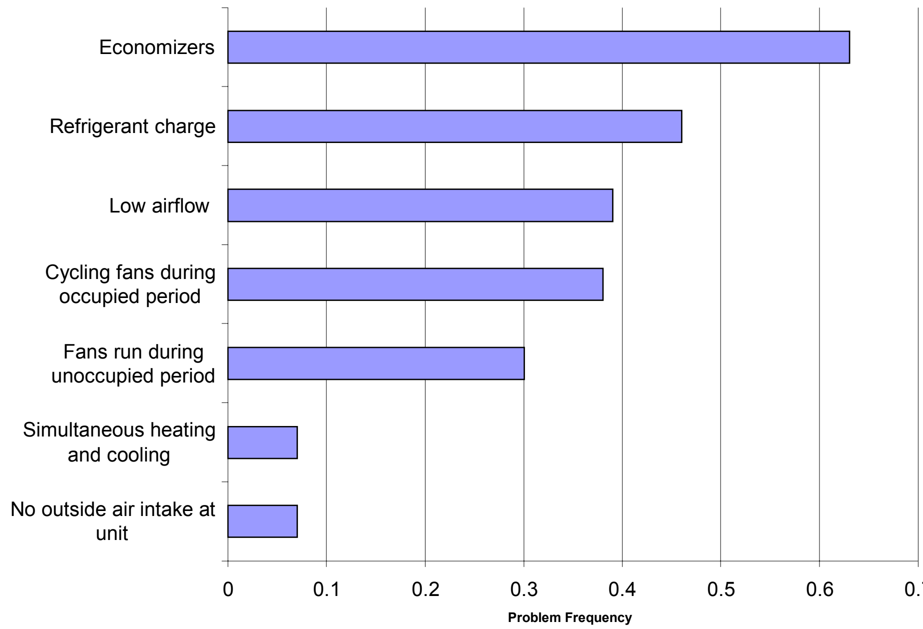
These small rooftop units are the “workhorses” of the commercial building industry, yet many systems fail to reach their full potential due to problems with design, installation, and operation.

FIELD PERFORMANCE

The New Buildings Institute (Institute) PIER project identified a number of problems with HVAC systems as they are installed and operated in the field. Problems identified include broken economizers, improper refrigerant charge, fans running during unoccupied periods, fan that cycle on and off with a call for heating and cooling rather than providing continuous ventilation air, low airflow, inadequate ventilation air, and simultaneous heating and cooling. A summary of findings from the study is shown in Figure 4.

Figure 4. Frequency of Problems Observed in PIER Study

This figure shows the frequency of several of the common problems observed in the PIER study behind this Design Guide.



- ***Economizers.*** Economizers show a high rate of failure in the study. Of the units equipped with economizers, 64%were not operating correctly. Failure modes included dampers that were stuck or inoperable (38%), sensor or control failure (46%), or poor operation (16%). The average energy impact of inoperable economizers is about 37% of the annual cooling energy.
- ***Refrigerant charge.*** A total of 46% of the units tested were improperly charged, resulting in reductions in cooling capacity and/or unit efficiency. The average energy impact of refrigerant charge problems was about 5% of the annual cooling energy.
- ***Low air flow.*** Low air flow was also a common problem. Overall, 39% of the units tested had very low air flowrates (< 300 cfm/ton). The average flowrate of all units tested was 325 cfm/ton, which is about 20% less than the flowrates generally used to rate unit efficiency. Reduced air flow results in reduced unit efficiency and cooling capacity. The annual energy impact of low air flow is about 7% of the annual cooling energy.
- ***Fan power.*** The average fan power measured in the study was about 20% higher than the assumptions used in the Title 24 Energy Standards, causing a commensurate increase in the annual fan energy.

- ***Cycling fans.*** System fans were found to be cycling on and off with a call for heating or cooling in 38% of the units tested. Title 24 Energy Standards require that all buildings not naturally ventilated with operable windows or other openings be mechanically ventilated. The supply of continuous fresh air during occupied hours relies on continuous operation of the HVAC unit supply fan.
- ***Unoccupied fan operation.*** Fans were also observed to run continuously during unoccupied periods in 30% of the systems observed. While this practice improves the ventilation of the space, it represents an opportunity to save energy through thermostat setback and fan cycling during unoccupied periods.
- ***Simultaneous heating and cooling.*** Adjacent units controlled by independent thermostats were observed to provide simultaneous heating and cooling to a space in 8% of the units monitored in the study. This was to largely to occupant errors in the set up and use of the thermostats, and poor thermostat placement during construction.
- ***No outdoor air.*** A physical inspection revealed that about 8% of the units were not capable of supplying any outdoor air to the spaces served. In some cases, outdoor air intakes were not provided or were sealed off at the unit. In other instances, outdoor air dampers were stuck shut, preventing outdoor air intake.

Solutions to these problems rest in the hands of market actors up and down the building design, construction and maintenance chain. This Design Guide focuses on specific actions designers can take to minimize problems and create high-performance commercial buildings through the integrated design and specification of reliable and energy-efficient buildings and mechanical systems.

Energy Impacts

The annual commercial new construction floorspace served by small HVAC units is on the order of 39.6 million ft^2 per year. The potential statewide annual energy savings expected from avoiding problems noted in the study is on the order of 69.4 GWh per year of electricity and 971,000 therms per year of natural gas. Potential demand reductions on the order of 245 MW were also forecast (AEC, 2003). Average savings for commercial buildings are 25-35% of the energy consumption and costs depending on sector type and use patterns.

Design Guide Organization

The Design Guide is organized around eight design areas that help achieve a high-performance HVAC system.

- ***Integrated design*** describes an approach to the design of a small commercial buildings that provides high performance with minimal first cost impacts.
- ***Unit sizing*** provides information on right-sizing HVAC systems to improve efficiency and reduce first costs.

- ***Unit selection*** provides information on features to look for when specifying packaged rooftop equipment.
- ***Distribution systems*** provides information on the design of the HVAC distribution system to minimize fan energy consumption, duct leakage and improve comfort.
- ***Ventilation*** provides information on how to provide adequate ventilation to commercial building spaces without excessive energy costs.
- ***Thermostats and controls*** provides information on control system selection and installation for small rooftop systems.
- ***Commissioning*** provides information on commissioning procedures to ensure the building as constructed meets the intent of the designer.
- ***Operations and maintenance*** provides information on recommended operations and maintenance practices to preserve system efficiency and performance over time.

Integrated Design

Summary

Use load avoidance strategies such as energy-efficient lighting, high-performance glass, cool roofs, and enhanced roof insulation design to reduce the cooling loads imposed on the HVAC system. Reductions in HVAC system size and first cost mitigate the first costs of these energy efficiency strategies.

HVAC systems, like all systems in the building, do not function in isolation, but are part of an interactive system of components. Before addressing the design of the HVAC system, this chapter addresses several aspects of building design that influence the loads imposed on the HVAC system. Many of these advanced design recommendations are being incorporated into efficiency programs and applied by leading designers and developers of high-performance buildings. By including these "load avoidance" strategies in your design, the size and energy consumption of the HVAC system can be reduced. The first costs of the load avoidance strategies are generally offset by reductions in the HVAC and distribution system size and cost (Energy Design Resources, 1998a).

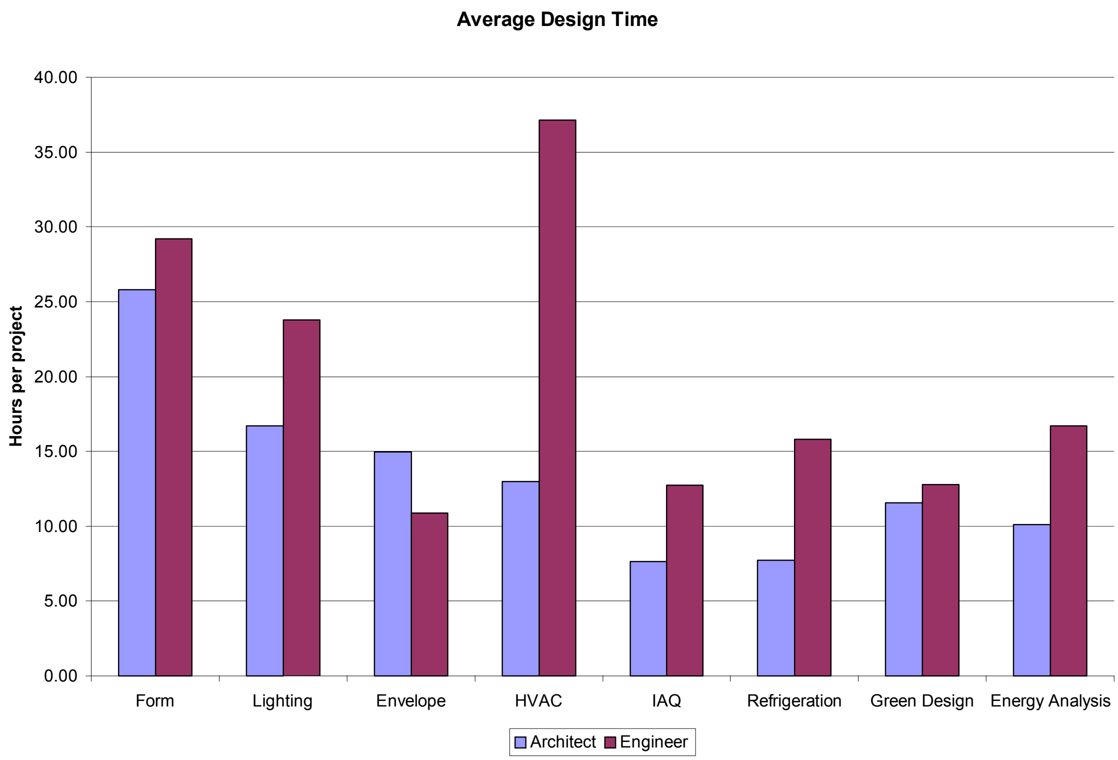
By including these "load avoidance" strategies in your design, the size and energy consumption of the HVAC system can be reduced. The first costs of the load avoidance strategies are generally offset by reductions in the HVAC and distribution system size and cost.

Integrated design in the context of small buildings must be viewed in the context of the design time allocated to small projects. A recent survey of design professionals working on small buildings was conducted to get a sense of the time allotted for various steps in the design process (Jacobs and Henderson, 2002). Figure 5 summarizes the survey results. The average design time for the HVAC system in a small building (defined as 20,000 ft^2 or less) is less than one person-week. Other aspects of the design process, such as building form, lighting and envelope design get even less attention than the HVAC system.

Design projects conducted under these time constraints do not allow for much interaction between architects and their engineering counterparts to optimize the design. However, the load avoidance strategies discussed in this section can be applied prescriptively to most small buildings. Architects and engineers should consider adopting these strategies as part of their office design standards, providing the benefits of the load avoidance strategies without requiring much analysis.

Figure 5. Average Time Spent by Designers of Small Commercial Buildings

This figure shows the average amount of design time spent by architects and engineers during various phases of the design of small commercial buildings. Although HVAC design time allocation is the largest, less than one person-week of engineering time is generally spent on HVAC design. Source: Jacobs and Henderson, 2002.



Reduce Lighting Power

Lighting represents a major opportunity for energy savings in small buildings. Although Title 24 is one of the most stringent energy codes in the country, there is ample opportunity to reduce lighting power below Title 24 allowances. New generation T-8 lamps and electronic ballasts, T-5s, fluorescent high-bay fixtures, task/ambient lighting design, lighting controls, and daylighting represent opportunities to reduce lighting energy and the size of the HVAC system required to remove heat generated by lighting systems.

The Advanced Building Guidelines Energy Benchmark for High Performance Buildings (E-Benchmark), developed by the New Buildings Institute lists recommendations for lighting power density by space type (Institute, 2003). These values are generally 10% lower than the proposed 2005 Title 24 allowances, and are based on the application of state-of-the-art lighting sources and fixtures to lighting designs common in buildings containing these spaces. A list of recommendations by space type is shown in Table 1.

Table 1. Lighting Power Recommendations by Space Type

Tenant Area or Portion of Building	E-Benchmark Lighting Power Density (W/ft²)	Proposed California T24-2005 Lighting Power Density (W/ft²)	Additional allowance for Chandelier
Automotive Facility	0.9	1.1	
Convention Center	1.2	1.4	yes
Court House	1.2	1.4	yes
Dining; Bar Lounge/Leisure	1.3	1.1	yes
Dining: Cafeteria/Fast Food	1.4	1.1	yes
Dining: Family	1.6	1.1	yes
Dormitory	1	1.5	
Exercise Center	1	1	
Grocery Store	1.3	1.6	
Gymnasium	1.1	1	
High End Retail	3.5	5.7	yes
Hospital/Healthcare	1.2	1.2	
Hotel	1	1.4	yes
Library	1.3	1.5	
Manufacturing Facility	1.3	1.3	
Motel	1	1.4	
Motion Picture Theatre	1.2	0.9	
Multi-Family	NA	1	
Museum	1.1	2	
Office	0.9	1.2	
Parking Garage	0.3	N/A	
Penitentiary	1	1	
Performing Arts Theatre	1.6	1.4	yes
Police/Fire Station	1	0.9	yes
Post Office	1.1	1.6	
Religious Building	1.3	1.5	yes
Retail	1.3	1.6	
School/University	1.2	1.2	
Specialty Retail	1.6	1.7	yes
Sports Arena	1.1		
Town, Hall	1.1	1.4	yes
Transportation	1	1.2	

Tenant Area or Portion of Building	E-Benchmark Lighting Power Density (W/ft²)	Proposed California T24-2005 Lighting Power Density (W/ft²)	Additional allowance for Chandelier
Warehouse	0.6	0.6	
Workshop	1.4	1.3	

These guidelines were developed based on the application of a new generation of lighting products that offer increased efficiency over common practice lighting design (Institute, 2002a). For example:

High Efficiency Fluorescent

A new generation of T-8 lamps has been introduced with improved phosphors that provide better color rendering and improved efficacy. These so-called "super" T-8s have color rendering indices in the 80s and provide 34% more light output per watt of input power compared to standard T-8 lamps. The light output over the life of the lamp (lumen depreciation) is also improved in the super T-8 lamp.

T-5 high output (HO) linear fluorescent lamps provide significant improvement in luminaire efficiency and optical control over standard T-8 lamps, emitting up to 1.7 times the lumen output of T-8's. Full size T-5's are also 37.5% smaller in diameter than equivalent T-8's, reducing the size of the luminaire. These lamps are best used in linear indirect/direct luminaires or high ceiling applications as the surface brightness of the T-5 can present visual glare when used in common direct troffers.

Compact Metal Halide

Metal halide lamps are now available in reflector lamp configurations to replace incandescent PAR lamps in down lighting, track lighting, and retail display lighting applications requiring high color rendering. The ceramic metal halide lamp uses a ceramic arc tube, rather than the quartz arc tube commonly found in metal halide lamps, for reduced color shift over the lamp life. Compact metal halide lamps offer efficacy improvements of 100% and longer lamp life relative to incandescent lamps.

Pulse-Start Metal Halide

Pulse-start metal halide lamps offer improved lumen maintenance, color stability, and lamp life over standard metal halide lamps. Initial lamp efficacy remains about the same, but the improved lamp lumen depreciation allows designers to specify about 25% lower wattage when considering maintained lumens These lamps are suitable for high bay warehouses, and retail and industrial applications requiring good color rendering at high efficiency.

Table 2 summarizes the state-of-the-art lighting technologies that can be applied in most building applications.

Table 2. Lamp Efficacies for New Technology Lighting Sources

Measure	Baseline Technology	Efficacy Lumens/W	Improved Technology	Efficacy Lumens/W	% Savings
High efficiency fluorescent	F32T8/7xx NLO	70	F32T8/8xx Super RLO	94	26
	F32T8/7xx NLO	70	F28T5/8xx	103	32
Compact metal halide	PAR 38/IR	30	PAR 30/CMH	60	50
Pulse-start metal halide	MH 400	60	MHP 320	60	0[1]

[1] Efficacy remains constant, but lumen depreciation is reduced by 25%

Use High-Performance Fenestration Systems

High-performance fenestration systems are assemblies consisting of high-performance glazing, frames, and spacers. High-performance fenestration systems also represent a major opportunity for energy efficiency in commercial buildings. High-performance glazings are "spectrally-selective," reducing solar heat gains while transmitting a greater proportion of visible light than non-selective glazings. High performance glazings use a combination of tints (pigments added to molten glass) and coatings (low-e and/or reflective surface treatments). Tinted, low-e glazing systems, available from most glass suppliers, reduce solar heat gain and thermal conduction, thereby reducing the size of the air conditioning system. High-performance fenestration also improves occupant thermal comfort by reducing "hot spots" from direct solar gain, while moderating glass and frame interior surface temperatures. Well-design buildings using high-performance fenestration systems can reduce glare through careful selection of visible light transmittance in "view" or vision glazing and/or incorporating architectural features such as light shelves or louvers to limit occupant views of bright glazing surfaces. Similarly, high-performance skylights are available that reduce solar heat gain and heat conductance, while maintaining sufficient visible light transmission for daylighting applications.

A wide variety of glazing products is available for use in commercial buildings (Institute, 2002b). The glazing systems are characterized by the choice of glazing material (glass, plastic, fiberglass), coatings applied to the glazing, glazing frame design, and the spacer used to separate the glazing layers in insulated sealed units. Tints may be added to the glazing materials to reduce solar heat gain. Green and blue tints provide better overall performance than bronze or gray tints due to their higher visible light transmission. High-performance tints (such as Azurelite and Evergreen) have been developed by several manufacturers that reduce solar heat gain while maintaining good visible light transmission. Glazing layers may be coated with reflective and/or low-emissivity (low-e) coatings to reduce solar heat gains and heat transmission between glazing layers. Several types of low-e coatings are available to tune the solar heat gain, visible light transmission, transmission losses, and glass reflectivity to suit the intended application.

Glazing frames in commercial construction are generally constructed from extruded aluminum. Standard metal frames provide a direct heat conduction path between the outdoors and the building interior. Thermally broken aluminum frames are built in two or more parts, which are connected by a non-metallic bond such as urethane. These frames reduce heat conduction between the outdoors and the building interior, and improve thermal comfort for occupants located near the windows. Standard technology for the spacer that separates the glazing layers in multi-pane glazing systems consists of a hollow aluminum extrusion that also provides a direct conduction path between the glazing layers. Insulated spacers are constructed from a non-metallic material or thin stainless steel to reduce heat conduction around the edge of the glazing unit.

Title 24 requirements exclude single pane glass from most applications, and require double pane, low-e glass in many climate zones. However, glazing systems with higher performance are available in virtually all applications. Table 3 summarizes the standard and high-performance glazing systems suitable for California climates.

Use Cool Roofing Materials

Roofing materials with low solar absorptance and high thermal emittance ("cool" roofs) can reduce peak HVAC loads and energy consumption. Cool roofs work to reflect solar radiation while enhancing radiant heat transfer to the sky, thus reducing the "roof" load of the building. Cool roofs are typically white and have a smooth texture. Commercial roofing products that qualify as cool roofs fall in two categories: single-ply and liquid applied. White single-ply roofing products are made from synthetic materials such as EPDM, PVC, and Hypalon. Liquid-applied products made from elastomeric, polyurethane, and acrylic bases may be used to coat a variety of substrates. Table 4 summarizes cool roof and standard roofing product properties (PG&E, 2002). Note: Asphalt shingles have fairly low reflectance, while white asphalt shingles perform only marginally better than dark asphalt shingles.

Table 3. High-Performance Glazing

Standard practice (Title 24 compliant) and high-performance glazing products for California climate regions. SHGC = solar heat gain coefficient.

Calif. Climate	Standard Practice					High Performance						
	Glazing	Frame	Spacer	SHGC	Total Assembly U-value	Glazing	Frame	Spacer	SHGC	Total Assembly U-value	SHGC % difference	Total Assembly U-value % diff.
Mountains	Tinted double low-e	Standard metal	Standard	0.39	0.57	High perf. tint double low-e	Metal with thermal break	Insulated	0.31	0.42	21%	26%
North Coast	Tinted double low-e	Standard metal	Standard	0.39	0.57	High perf. tint double low-e	Metal with thermal break	Insulated	0.31	0.42	21%	26%
South Coast	Tinted double low-e	Standard metal	Standard	0.39	0.57	High perf. tint double low-e	Metal with thermal break	Insulated	0.31	0.42	21%	26%
Valley	High perf tint double low-e	Metal with thermal break	Standard	0.36	0.49	Reflective high perf. tint double low-e	Metal with thermal break	Insulated	0.19	0.42	47%	14%
Desert	High perf tint double low-e	Metal with thermal break	Standard	0.36	0.49	Reflective high perf. tint double low-e	Metal with thermal break	Insulated	0.19	0.42	47%	14%

Table 4. Reflectance and Emittance of Popular Roofing Products

The reflectance and emittance of popular roofing products is shown below. The most effective products have both a high reflectance and a high emittance. Shaded entries exhibit properties of "cool roofs" (reflectivity greater than 0.70 and an emittance greater than 0.70). Source: PG&E, 2002.

Cool Roof Type	Material	Total Solar Reflectance	Emittance
Reflective coatings	Kool seal elastomeric over asphalt shingle	0.71	0.91
	Aged elastomeric on plywood	0.73	0.86
	Flex-tec elastomeric on shingle	0.65	0.89
	Insultec on metal swatch	0.78	0.90
	Enerchon on metal swatch	0.77	0.91
	Aluminum pigmented roof coating	0.30 – 0.55	0.42 – 0.67
	Lo-mit on asphalt shingle	0.54	0.42
White metal roofing	MBCI Siliconized white	0.59	0.85
	Atlanta Metal products Kynar Snow White	0.67	0.85
Single-ply roof membrane	Black EPDM	0.06	0.86
	Grey EPDM	0.23	0.87
	White EPDM	0.69	0.87
	White T-EPDM	0.81	0.92
	Hypalon	0.76	0.91
Paint	White	0.85	0.96
	Aluminum paint	0.80	0.40
Asphalt shingles	Black	0.03 – 0.05	0.91
	Dark brown	0.08 – 0.10	0.91
	Medium brown	0.12	0.91
	Light brown	0.19 – 0.20	0.91
	Green	0.16 – 0.19	0.91
	Grey	0.08 – 0.12	0.91
	Light grey	0.18 – 0.22	0.91
	White	0.21 – 0.31	0.91

Reductions in heat gains though the roof affects the temperature of the plenum space located between the drop ceiling and the roof, which contains the majority of the ductwork in small commercial buildings. Duct heat gains and air leakage losses (especially on the return side) can increase HVAC loads on the order of 30%, so a cool plenum can reduce energy consumption and improve occupant comfort, especially in commercial buildings where systems run continuously during occupied hours. Cool roofs can also reduce the outdoor air temperature at the roof level. The impact of a cool roof depends on the location and R-value of the roof insulation. Well-insulated roofing systems with the insulation applied to the roof deck or the interior of the roof surface are less affected by cool roofs than poorly insulated buildings or buildings with lay-in insulation (see next section).

Improve Roof Insulation Systems

The roof or ceiling insulation location and R-value can also have a major effect on HVAC system performance (Heschong Mahone, 2003a). Roof insulation can be installed directly on the roof deck or roof interior surface, while ceiling insulation is generally applied on top of the drop ceiling (called "lay-in" insulation). When the insulation is applied to the roof, the plenum space between the roof and the ceiling is located within the thermal envelope of the building and the impacts of duct conductive losses and duct leakage on HVAC system efficiency is substantially less.

Lay-in insulation generally has incomplete coverage due to lighting fixtures, HVAC diffusers, fire sprinklers, and other devices installed into the dropped ceiling grid that interfere with insulation installation. Insulation installed on ceiling tiles inevitably gets displaced as ceiling tiles are moved to gain access to the plenum space for data and telecom wiring, reconfiguring the HVAC diffuser layout, and other maintenance activities (see Figure 6). Although the surface area of the thermal boundary of the building expands due to the inclusion of the plenum walls, overall conductance losses decrease due to improved insulation coverage. Lay-in insulation is allowed under the 2001 Title 24 Standards, but will not be allowed under the 2005 Standards except in special circumstances.

HVAC Unit Location

An HVAC unit's location on the roof can affect its operating efficiency, reliability and serviceability. Site the unit to minimize duct runs consistent with architectural requirements for hiding the unit from view. High parapet walls or unit enclosures can inhibit air flow around the unit and increase local air temperature. Excessively high rooftop temperatures can reduce unit cooling capacity and efficiency.

Provide service access to all units that allows for access panels and doors to be removed without interference. Locate units away from exhaust air outlets to improve indoor air quality. This is especially important in kitchen applications, where grease-laden exhaust from kitchen ventilation systems can enter outdoor air intakes of rooftop units located too close to the exhaust outlet. Entrainment of grease-laden air greatly reduces the service life of filters and can cause premature failure of economizer components.

Figure 6. Lay-in Insulation

Lay-in insulation in a warehouse-to-office conversion. Note the poor insulation coverage and ductwork located in an unconditioned space.

INTEGRATED DESIGN EXAMPLE

These seemingly unrelated aspects of building design can have a profound effect on the size and cost of the HVAC system. Architects and design/build contractors should consider including these load avoidance strategies in their designs to achieve superior performance. The incremental costs of these strategies can be offset by reduced HVAC system size and cost.

To show the interactions between the load avoidance strategies discussed in this section and HVAC system size and costs, a series of computer simulations were done on a simple "box" model of a small commercial office building. Table 5 describes this model.

Table 5. Prototypical Building Model Description

Model Parameter	Standard Building	Improved Building*
Shape	Rectangular, 50ft x 40ft	
Conditioned floor area	2000 ft^2	
Number of floors	1	
Floor-to-ceiling height	9 ft	
Plenum height	3 ft	
Exterior wall construction	8 in. concrete tilt-up construction insulated	
Ext wall R-Value	R-11 (coastal), R-13 (Valley and Desert)	

Model Parameter	Standard Building	Improved Building*
Window type	Coastal Climate (Oakland): Tinted double low-e with standard metal frame and spacer Central Valley (Sacramento) and Desert (Palm Springs): High performance tint double low-e with thermally broken metal frame and standard spacer	Coastal Climate (Oakland): High performance tint double low-e with thermally broken metal frame and insulated spacer Central Valley (Sacramento) and Desert (Palm Springs): Reflective high performance tint double low-e with thermally broken frame and insulated spacer
Window/wall ratio	28%	
Roof construction	Built-up roof over plywood deck	Built-up roof over plywood deck, R-19 insulation
Roof reflectance	Standard roof	Cool roof
Ceiling construction	Acoustic tile with lay-in insulation (R-19) with 80% coverage	Acoustic tile
Lighting power density	Code compliant using standard sources (1.3 W/ft^2)	E-Benchmark compliant using new sources (0.9 W/ft^2).
Equipment power density	0.5 W/ft^2	
Operating schedule	7 am – 6 pm M-F	
Number of people	11	
Outdoor air	15 cfm/person	
HVAC system	Single package rooftop air conditioner with gas furnace	
Size	Varies	
CFM	400 cfm/ton	
SEER	9.7 SEER	13 SEER
Economizer	Differential enthalpy	
Thermostat setpoints	Heating: 70/55; Cooling: 74/85	
Fan power	0.365 W/cfm	
Supply duct surface area	27% of floor area	
Duct leakage	36% total leakage; evenly split between supply and return (18% supply, 18% return)	8% total leakage
Duct insulation R-value	R-4.2.	R-8
Return leak from outside air	0%	
Return system type	Ducted	

* Only changes from the Standard Building are shown.

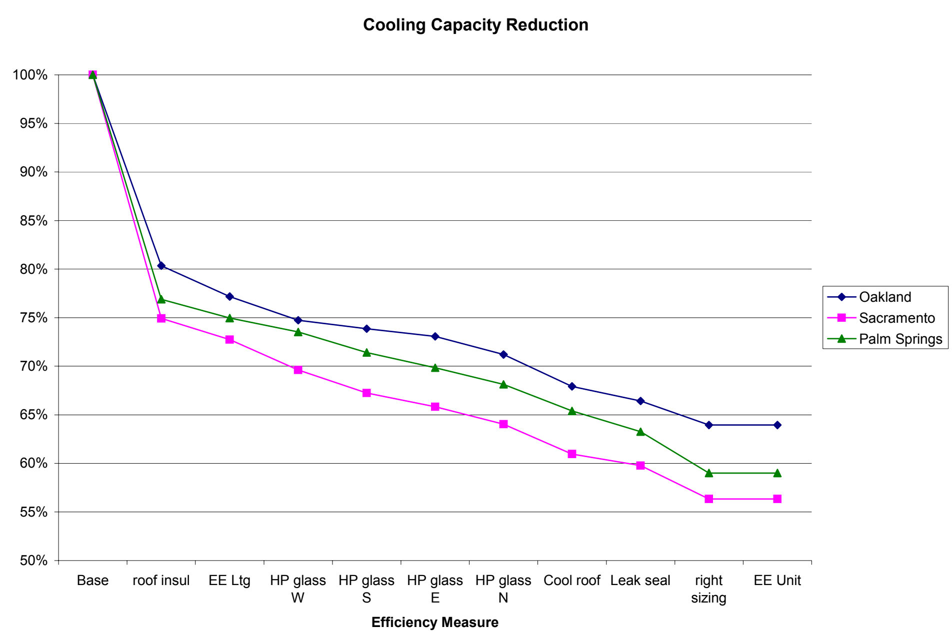
A series of computer simulations were run for Coastal (Oakland), Central Valley (Sacramento), and Desert (Palm Springs) locations. The design changes studied along with the graph legends for Figure 7 are shown in Table 6:

Table 6. Design Changes for Computer Simulations

Design Change	Legend
Insulation location moved from ceiling to roof	Roof insul
Energy-efficient lighting	EE Ltg
High-performance glass on the West orientation	HP glass W
High-performance glass on the South orientation	HP glass S
High-performance glass on the East orientation	HP glass E
High-performance glass on the North orientation	HP glass N
High-reflectivity roofing material	Cool roof
Duct leakage sealing	Leak seal
Reducing HVAC system size to correspond to reduced cooling loads	Right sizing
Energy-efficient rooftop unit	EE unit

Figure 7. Impacts of Integrated Design

The following charts show the impacts of integrated design on HVAC system size and energy cost. In all climates, reductions in system size on the order of 40% and reduction in annual energy costs on the order of 25% to 30% are possible with these simple energy efficiency strategies.



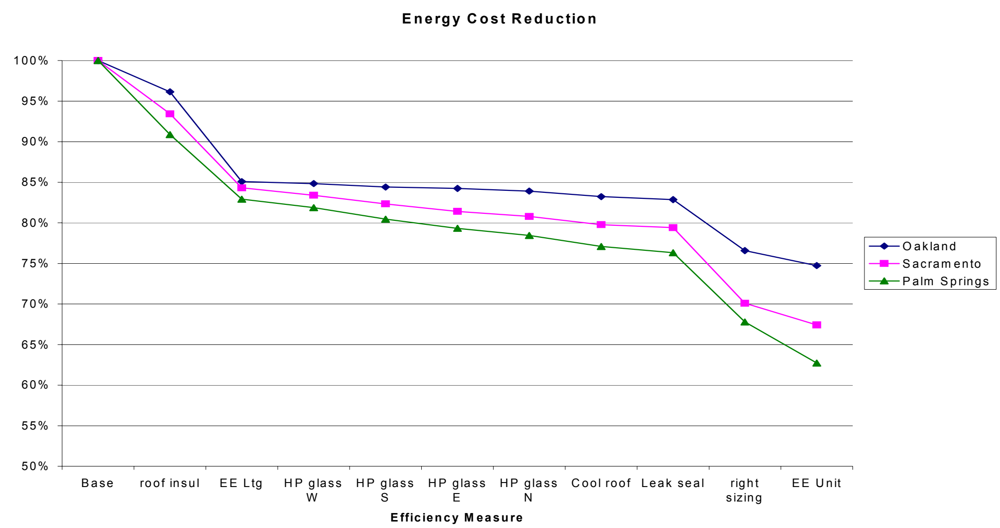


Table 7 summarizes the impacts of these energy efficiency measures on the building's first cost.

Table 7. Cost Estimates

Measure	Description	Incremental unit cost	Total incremental cost*	Source
Insulation location	Climate zone 3 (Oakland)	$0.50 per ft² floor area	$1,003	McHugh et al., 2003
	Climate zone 12 (Sacramento)	$0.52 per ft² floor area	$1,044	
	Climate zone 15 (Palm Springs)	$0.52 per ft² floor area	$1,044	
Energy-efficient lighting	Office occupancy	$0.18 per ft² floor area	$360	Institute, 2002a
High performance glass	Climate zone 3 (Oakland), non-North	$3.50 per ft² glass area	$1,446	DEER database (Xenergy, 2001), CALMAC low volume
	Climate zone 3 (Oakland), North	$7.75 per ft² glass area	$1,232	
	Climate zone 12 (Sacramento), 15 (Palm Springs), non-North	$6.44 per ft² glass area	$2,660	
	Climate zone 12 (Sacramento), 15 (Palm Springs), North	$7.92 per ft² glass area	$1,259	
Cool roof	New construction	$0.30 per ft² roof area	$600	PG&E, 2002
Duct insulation upgrade and leakage sealing	New construction	$600.00 per system	$600	PG&E, 2003
High efficiency HVAC	13 SEER	$270 per ton	$1,350	20% markup per DEER database

* Analysis for 2000 ft² building.

The load avoidance measures in this example reduce the size of the HVAC system and provide annual energy savings, as shown in Figure 7. Note, improving the roof insulation system had the largest effect on HVAC system size, due to reduced roof loads and duct leakage interactions.

The first cost of the HVAC unit is estimated at $1,350 per installed ton. The costs of the duct work and air distribution system components are estimated at an additional $1,350 per installed ton (Means, 2003). The incremental first cost, the value of the capacity credit, the first-year energy savings, and simple payback are summarized in Table 8.

Table 8. Net Costs and Energy Savings

Climate zone	City	Incremental cost	Capacity credit	Net first cost	Annual energy cost savings	Simple payback (yr)
CZ 3	Oakland	$5,448	-$3,987	$1,461	$603	2.4
CZ 12	Sacramento	$6,859	-$6,478	$381	$978	0.4
CZ 15	Palm Springs	$6,976	-$6,621	$356	$1,429	0.2

It is clear from this example that the reduction in HVAC system size nearly covers the incremental first cost of the energy efficiency improvements. The small remaining first costs are covered by the energy savings in a short period of time.

Unit Sizing

Summary

To take full benefit of an integrated design approach, use sizing methods that are responsive to the load avoidance strategies used in the design. Use realistic assumptions on plug loads and ventilation air quantities when calculating unit size. Avoid oversizing equipment to improve energy efficiency.

Many small HVAC systems are significantly oversized, resulting in inefficient operation, reduced reliability due to frequent cycling of compressors, and poor humidity control. Oversized systems also result in wasted capital investment in both the HVAC unit and distribution system. System oversizing also affects the ability of the system to provide simultaneous economizer and compressor operation, and exacerbates problems with distribution system fan power, since larger units are supplied with larger fans.

Use Sizing Methods Responsive to Load Avoidance

A variety of sizing methodologies are used to determine HVAC system size, including “rule of thumb” sizing based on ft^2/ton, manual methods (e.g., ACCA Manual N), and computerized load calculations (Energy Design Resources, 1998a). A recent survey of design practices in the small commercial building market indicated that although computerized load calculations are used more often than manual methods, the assumptions used in the load calculations are based on conservative assumptions about building shell, lighting design, and occupant densities (Jacobs and Henderson, 2002). To reap the first-cost advantages of load avoidance strategies, these strategies should be included in the load calculations.

This survey was conducted nationwide, and may not be representative of design practices in California, where Title 24 compliance drives design practices through the use of compliance software such as Energy Pro. The capabilities of these tools, along with the manufacturers software are summarized in Table 9.

Figure 8. HVAC System Sizing Practices

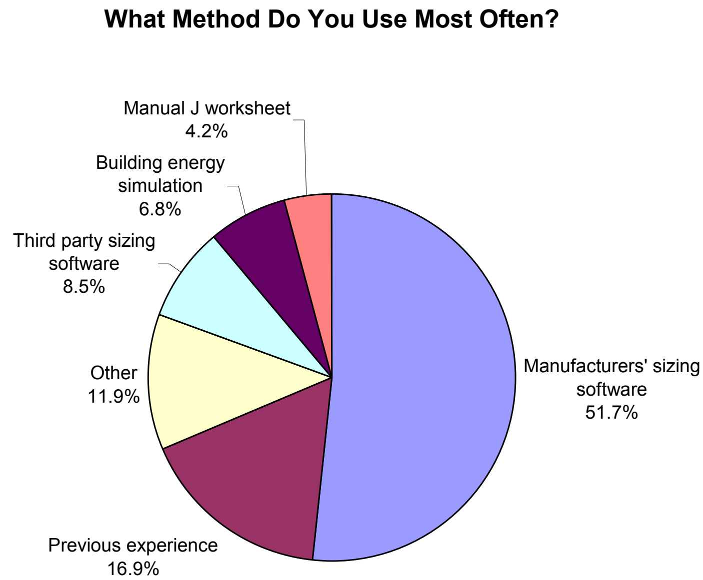


Table 9. Sizing Software Defaults and Capabilities

A recent study conducted by the Air Conditioning Research and Technology Institute (ARTI) investigated the state-of-the-art in computerized design tools for small commercial buildings. The capabilities of popular sizing software to integrate load avoidance features as identified in the study are listed below (Jacobs and Henderson, 2002).

Modeling Parameter	Energy Pro	eQUEST	Carrier HAP	Trane Trace
Default assumptions for lighting power density	Title 24 compliant according to occupancy offices at 1.3 W/ft²	Title 24 compliant according to occupancy offices at 1.3 W/ft²	2.5 W/ft² plus .5 W/ft² task	2.5 W/ft²
Default assumptions for plug load density	Varies by occupancy—offices at 1.5 W/ft²	Varies by occupancy—offices at 1.5 W/ft²	Varies by occupancy—offices at 0.75 W/ft²	0.4 W/ft²
Default assumptions for occupant density	Varies by occupancy—offices at 100 ft²/person	Varies by occupancy—offices at 100 ft²/person	Varies by occupancy—offices at 100 ft²/person	100 ft²/person
Default assumption for ventilation air	15 cfm/person	15 cfm/person	15 cfm/person	20 cfm/person

Modeling Parameter	Energy Pro	eQUEST	Carrier HAP	Trane Trace
Glazing type default	Title 24 compliant	Title 24 compliant	ASHRAE 90.1 compliant	
Cool roof capability	Considers roof absorptance and emittance	Considers roof absorptance and emittance	Considers roof absorptance only	Considers roof absorptance only
Load calculation approach	Design day calculation using ASHRAE method	Design day calculation using DOE 2.2 engine	ASHRAE-endorsed transfer function method	ASHRAE-endorsed transfer function method

Use Reasonable Assumptions for Plug Loads

Engineers often base HVAC sizing decisions on the full nameplate or “connected” load of computers, copiers, printers, and similar equipment, and assume simultaneous operation of such equipment. In fact, most of this equipment operates at a fraction of the nameplate value, and rarely operates simultaneously. The ASHRAE Handbook of Fundamentals (ASHRAE, 2001) lists space heat gain recommendations for computerized office equipment, which shows heat gain recommendations on the order of 55 to 75 continuous watts, compared to power supply input ratings on the order of 300 watts.

Table 10. Recommended Heat Gain from Computer Equipment

Component	Continuous Operation (W)	Energy Saver Mode (W)
Computer		
Average value	55	20
Conservative value	65	25
Highly conservative value	75	30
Monitor		
Small Monitor (13 to 15 in.)	55	0
Medium Monitor (16 to 18 in.)	70	0
Large Monitor (19 to 20 in.)	80	0

1 W/ft² allowance for plug loads is a reasonable upper bound when equipment diversity and reasonable estimates of the true running load are included

Circuit capacity for plug loads approach 5 W/ft² in office spaces, driven in some cases by commercial space lease requirements that dictate a certain level of power availability. An ASHRAE study on plug loads measured equipment load densities in 44 commercial office buildings (Komor, 1997). The measured equipment power ranged between 0.4 and 1.2 W/ft². Values above 1.0 W/ft² occurred in only 5% of the square footage studied. This study indicates that 1 W/ft² is a reasonable upper bound when equipment diversity and reasonable estimates of the true running load are included. The Title 24 default value of 1.5 W/ft² is probably excessive.

Use Reasonable Assumptions for Ventilation Air Quantities

The peak occupant load and the corresponding ventilation load can contribute substantially to equipment capacity in certain spaces such as lobbies and public assembly areas. Often actual occupant loads are substantially less than peak egress loads that building codes frequently defer to. Title 24's references to ventilation air quantities are based on UBC occupant densities, with a 50% adjustment for diversity in densely occupied spaces, defined as ≤ 50 ft² per person (CEC, 2001). Title 24 requires a minimum of 0.15 cfm/ft² for most spaces, which results in higher ventilation than the UBC requirement (including diversity) would dictate. ASHRAE Standard 62 (ASHRAE, 1999) allows the designer to base the design on the actual anticipated occupant density, so long as justification is provided.

Title 24 specifies the minimum outdoor ventilation rate to which the system must be designed. If desired, the designer may elect to take a more conservative approach. For example, the design outdoor ventilation rate may be determined using the procedures described in ASHRAE Standard 62–1999, provided the resulting outdoor air quantities are no less than required by Title 24. Although designers California must comply with Title 24 when setting ventilation rates, designers in other states referencing ASHRAE Standard 62 may be able to take advantage of the anticipated occupant density provision.

Avoid Oversizing

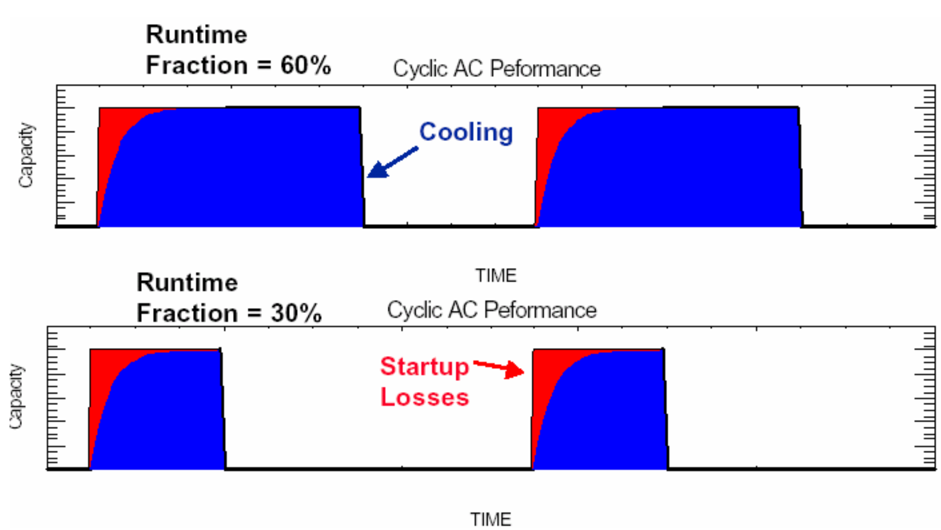
Title 24 limits cooling capacity to 121% of the calculated peak cooling load. Since most sizing methods are based on conservative assumptions, use the calculated load and round up only to the next available unit size to avoid excessive oversizing. Excessive oversizing leads to reduced equipment efficiency and reliability due to frequent cycling (Figure 9). Humidity control is also reduced, though this may not be a problem in most California climates.

Since most sizing methods are based on conservative assumptions, use the calculated load and round up only to the next available unit size to avoid excessive oversizing.

DX air conditioners, once started, take about three minutes to achieve full cooling output. The power draw during this cool-down time is approximately constant, so the efficiency of the unit during the first three minutes of operation is reduced due to startup losses associated with establishing refrigerant pressures and cooling down the evaporator coil.

Figure 9. Impact of Cycling on Efficiency

The impact of on/off cycling on unit performance is shown in the graphs below. Note that each time the unit starts, the input energy is approximately constant, while the unit takes several minutes to reach full output cooling capacity.

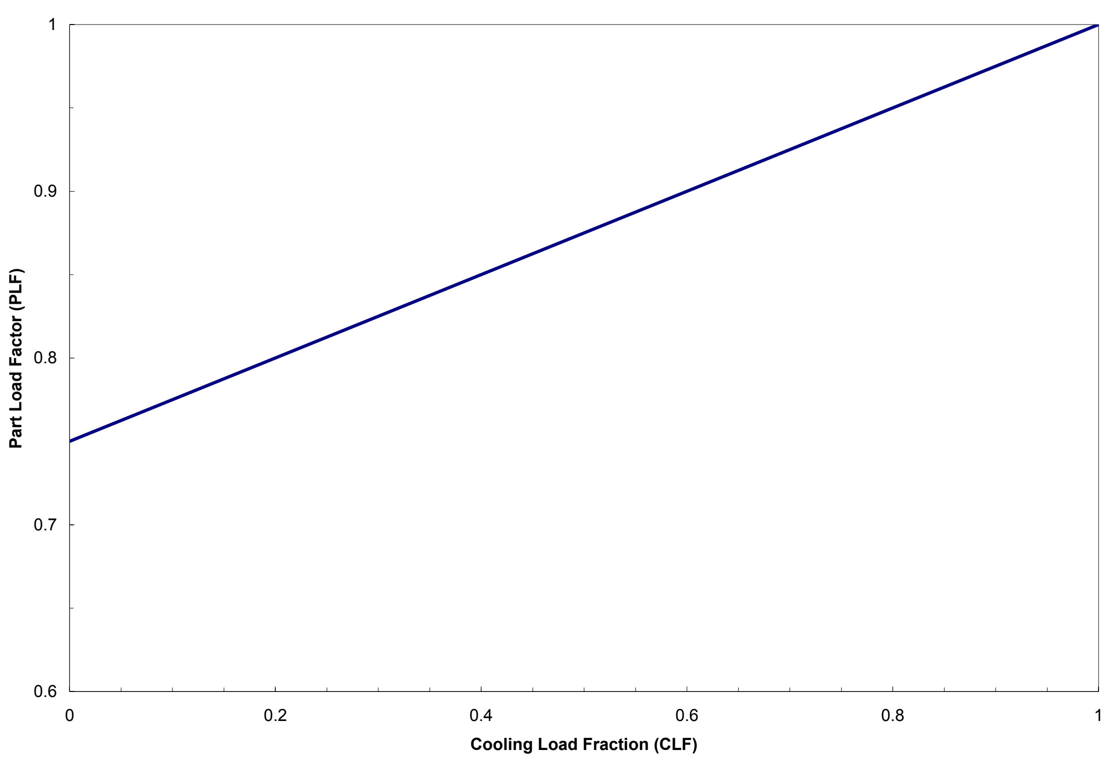


When the unit is oversized, the unit runs for a shorter cycle, and the startup time becomes a greater fraction of the total runtime. The startup losses also become a greater fraction of the total cooling output, reducing overall efficiency. Systems that are properly sized will run longer during each cycle, and the startup losses become small relative to the total cooling output. Figure 10 shows the effect of oversizing on unit efficiency.

In a study of 250 rooftop units conducted for PG&E, the typical runtime under hot conditions was 6 minutes, with an off-time of 16 minutes (Felts, 1998). This represents a 27% runtime fraction, and reduction in unit efficiency of 18%.

Figure 10. Efficiency Loss due to Oversizing

The reduction in system efficiency as the runtime decreases is shown below. Note that when the unit runs continuously (CLF = 1), the part-load factor is 1.0, indicating no degradation due to cycling. When the unit runs 60% of the time, the CLF is 0.6 and the unit efficiency is reduced by about 10%. If the unit runs only 30% of the time, the efficiency is reduced by about 15%. Source: Henderson et al., 1999.



Unit Selection

SUMMARY

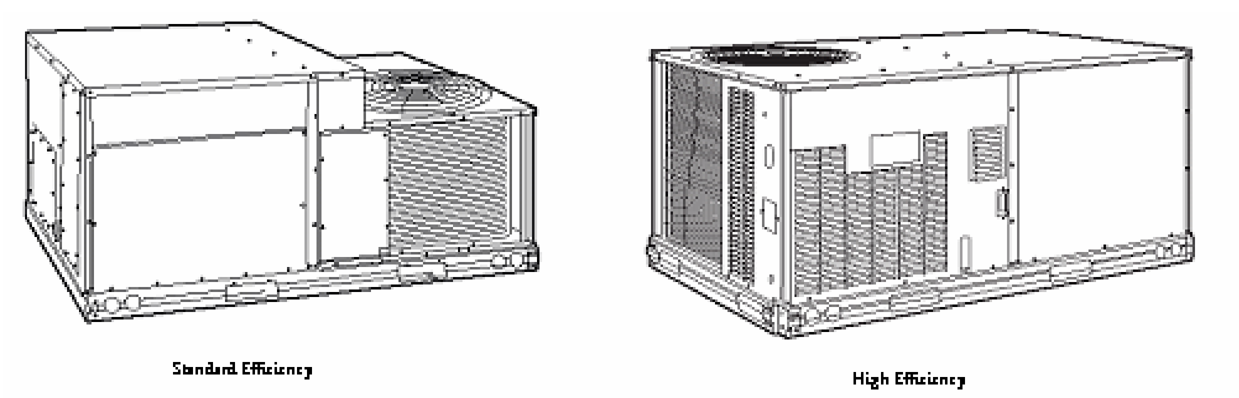
Select rooftop units that meet CEE Tier 2 efficiency standards and employ features that improve the efficiency and reliability of the units, including premium efficiency fan motors, thermostatic expansion valves and factory run-tested economizers. Base unit selection on realistic conditions expected for the building and location.

EFFICIENCY

Energy codes are generally set to correspond to the basic, "standard efficiency" HVAC unit. High efficiency units are available in most size ranges that are up to 30% more efficient than code. These units generally incorporate larger heat exchangers, efficient compressors, improved cabinet insulation, and higher efficiency fans and motors. Consider specifying units that meet the Consortium for Energy Efficiency (CEE) Tier 2 efficiency standards (CEE, 2002).

Figure 11. Form Factor of Standard and High Efficiency Rooftops

The form factors of standard and high efficiency models of the same cooling capacity from the same manufacturer shows the larger condenser coil in the high efficiency unit compared to a standard efficiency unit.



CEE has established efficiency targets for commercial rooftop units through their High Efficiency Commercial Air Conditioning (HECAC) initiative. CEE is a nonprofit, public benefit corporation that actively promotes the use of energy-efficient products and services through its members, including electric and gas utilities, public benefit administrators (such as state energy offices, nonprofit organizations, and regional energy groups), and research and development laboratories. CEE members voluntarily adopt common performance specifications and program strategies with the goal of permanently increasing the supply and demand of energy-efficient products and practices. CEE has established two levels of efficiency for commercial rooftop air conditioners; Tier 2 is the most efficient. Table 11 compares CEE Tier 2 and the efficiency provisions of the California Title 20 Appliance Standards and the Title 24 Non-residential Building Efficiency Standards.

Table 11. Title 20/24 and CEE Tier 2 Efficiency

Cooling capacity	Title 20/24	CEE Tier 2	Efficiency Improvement
< 5.4 ton	9.7 SEER	13 SEER/11.2 EER	34%
5.4 – 11.2 ton	10.3 EER	11 EER	7%

High efficiency units available from several major manufacturers meet or exceed the CEE Tier 2 efficiency specifications. Table 12 shows several examples.

Table 12. Commercially Available Units Exceeding Title 24 and CEE Tier 2 Specifications

Cooling Capacity	Unit Make/Model	Efficiency	% Improvement over Tier 2	% Improvement over Title 24
< 5.4 ton	Carrier 48 HJ	13 SEER	0.0%	34.0%
	Lennox LCA/LGA	13 SEER	0.0%	34.0%
	Trane YCZ	16 SEER	23.1%	64.9%
	York D1NP	13.7 SEER	5.4%	41.2%
5.4 – 11.2 ton	Carrier 48 HJ	11.0 EER	0.0%	6.8%
	Lennox LCA/LGA	11.3 EER	2.7%	9.7%
	Trane THC	11.3 EER	2.7%	9.7%
	York DH	11.5 EER	4.5%	11.7%

Designers should consider both the rated full-load energy efficiency ratio (EER), and the seasonal energy efficiency ratio (SEER) when selecting a unit. Units with high SEER may not perform much better than a standard unit at peak cooling conditions.

Table 13 provides design specifications for 5- and 10-ton standard and high efficiency rooftops from several manufacturers. There are a variety of strategies used to improve unit efficiency, including high efficiency scroll compressors and thermostatic expansion valves (TXV). Consistently, high-performance units have larger condensers and/or evaporators.

Table 13. Design Specifications for Standard and High Efficiency Rooftops

Carrier

Model	Efficiency	Size	SEER	EER	No. comp	Comp type	Meter-ing device	Evap rows	Evap face area	Cond row	Cond face area
48TJ006	Standard	5	10		1	recip	Acutrol	3	5.5	1	13.19
48HJ006	High	5	13		1	scroll	Acutrol	4	5.5	2	16.5
48TJ012	Standard	10		9	2	recip	Acutrol	3	10	2	20.47
48HJ012	High	10		11	2	scroll	Acutrol	4	11.1	2	25

Trane

Model	Efficiency	Size	SEER	EER	No. comp	Comp type	Meter-ing device	Evap rows	Evap face area	Cond row	Cond face area
YSC060	Standard	5	10.2		1	scroll	orifice	3	5	2	8.8
YHC060	High	5	12.2		1	scroll	orifice	3	7.7	3	11
YSC120	Standard	10		10.2	2	scroll	orifice	4	12.4	2	25.9
YHC120	High	10		11.2	2	scroll	orifice	5	12.4	3	27.2

Lennox

Model	Efficiency	Size	SEER	EER	No. comp	Comp type	Meter-ing device	Evap rows	Evap face area	Cond row	Cond face area
LGA060S	Standard	5	10		1	recip	TXV	2	6.3	2	14.6
LGA060H	High	5	13		1	scroll	TXV	3	6.25	2	14.6
LGA120S	Standard	10		9	2	recip	TXV	3	10.5	2	29.3
LGA120H	High	10		11	2	scroll	TXV	4	10.5	2	29.3

York

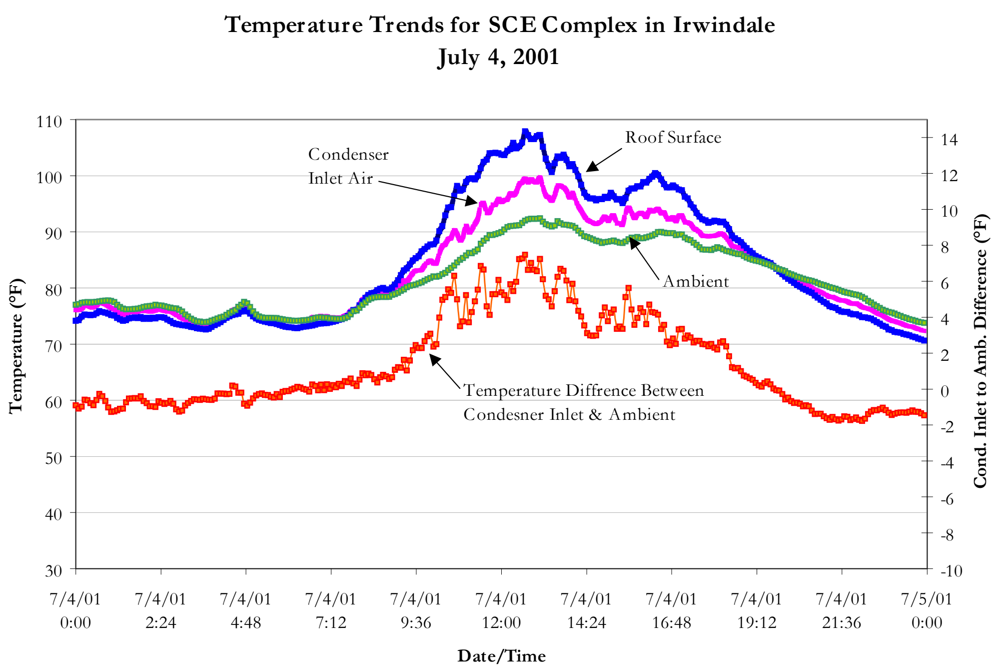
Model	Efficiency	Size	SEER	EER	No. comp	Comp type	Meter-ing device	Evap rows	Evap face area	Cond row	Cond face area
D2NA060	Standard	5	10		1	scroll	orifice	3	4.5	1	14.8
D1H060	High	5	12.2		1	recip	TXV	4	5.1	2	14.8
DM 120	Standard	10		9	2	recip	orifice	2	13.2	1	29
DH 120	High	10		11	2	recip	TXV	4	13.2	2	29

Select Capacity Based on Design Conditions

Consider capacity of unit under actual design conditions, not nominal values. The peak cooling capacity is reduced as outdoor temperatures increase. This can be especially important in desert climates where peak cooling conditions on the roof can exceed the data in manufacturers' standard catalogs. Select the unit to meet the calculated sensible load, and check the latent cooling capacity. High-efficiency equipment generally has reduced latent cooling capacity than standard equipment. Also, energy-efficient buildings have reduced sensible loads but comparable outdoor air requirements compared to standard buildings; thus the sensible heat ratio of an energy-efficient building may be reduced.

In summer of 2001, Southern California Edison (SCE) examined the relationship between measured ambient and condenser inlet air temperatures in Irwindale, California (Faramarzi, et al., 2002). Results of this study revealed condenser inlet air temperature reached as high as 8°F above the ambient, as shown in Figure 12 below.

Figure 12. Correlation Between Measured Ambient and Condenser Inlet Air Temperatures in Irwindale, CA



According to this study, the condenser air inlet temperature is about midway between the outdoor drybulb temperature and the air temperature measured at the roof surface.

Select Airflow Rate to Meet Sensible Loads

Increasing the flowrate can extract extra sensible cooling capacity out of the unit, allowing the selection of a smaller "nominal" unit.

The cooling capacity of most packaged air conditioners is based on a nominal flowrate of 400 cfm/ton of cooling capacity. Nominal flowrates in packaged equipment are selected to provide adequate dehumidification in climates that are more humid than California. Increasing the flowrate can extract extra sensible cooling capacity out of the unit, allowing the selection of a smaller "nominal" unit.

Specify High Efficiency Fan Motors

High efficiency fan motors are important in commercial applications, since fans generally run continuously during occupied periods. In systems equipped with economizers in mild climates such as coastal California, fan energy can be a significant portion of the total HVAC energy consumption (Energy Design Resources, 1998a). Selection of a high efficiency or premium efficiency motor on the supply fan is cost effective in all climates.

Selection of a high efficiency or premium efficiency motor on the supply fan is cost effective in all climates.

Table 14. Cooling Capacity of Standard and High Efficiency Units Under Rated and Hot, Dry Conditions

The effect of climate type and airflow rate on the cooling capacity of standard and high efficiency HVAC units is shown below. Note that many high efficiency units have more cooling capacity at each nominal size than their standard efficiency counterparts. Increasing the airflow rate under hot dry conditions generally increases cooling capacity.

				ARI		Hot/dry		Hot/dry hi flow	
Make	**Model**	**Efficiency**	**Size (ton)**	**Total Capacity (kBtu/hr)**	**Sensible Capacity (kBtu/hr)**	**Total Capacity (kBtu/hr)**	**Sensible Capacity (kBtu/hr)**	**Total Capacity (kBtu/hr)**	**Sensible Capacity (kBtu/hr)**
Carrier	48TJ006	Standard	5	60.9	45.3	47.8	47.8	51.2	51.2
	48HJ006	High	5	63.8	46.7	51.6	51.6	56.1	56.1
	48TJ012	Standard	10	118.9	89.8	93.4	93.4	102.8	102.8
	48HJ012	High	10	125.8	91.5	100.8	100.7	110.1	109.9
Trane	YSC060	Standard	5	63.1	48.2	50.6	50.6	53.9	53.9
	YHC060	High	5	62.1	47.6	48.1	48.1	51.8	51.8
	YSC120	Standard	10	118.0	92.1	95.5	95.2	102.2	102.2
	YHC120	High	10	117.0	92.3	94.3	94.3	101.4	101.4
Lennox	LGA060S	Standard	5	60.6	44.2	52.4	50.8	54.2	54.2
	LGA060H	High	5	63.9	47.3	56.2	54.5	58.3	58.3
	LGA120S	Standard	10	126.0	86.9	107.0	103.8	110.8	110.8
	LGA120H	High	10	128.0	90.9	107.9	95.0	116.4	116.4
York	D2NA060	Standard	5	56.5	44.3	44.6	44.6	45.1	45.1
	D1H060	High	5	60.0	45.0	49.0	49.0	50.0	50.0
	DM 120	Standard	10	124.0	89.0	94.0	94.0	96.0	96.0
	DH 120	High	10	122.0	93.0	94.0	94.0	94.0	94.0

The cooling capacities are based on the following conditions:

Rating condition	Outdoor dry bulb temperature	Entering dry bulb temperature	Entering wet bulb temperature	Airflow cfm/ton
ARI	95	80	67	400
Hot dry	115	80	62	400
Hot dry, high flow	115	80	62	500

Specify Thermostatic Expansion Valves

Refrigerant charge in units degrades over time, due to refrigerant leaks, poor maintenance practices, or both. Specifying units with thermostatic expansion valves (TXV) makes the units more tolerant of refrigerant charge variations by maintaining unit efficiency over a wide range of under-or over-charged conditions. TXVs are available as a factory option in most units.

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Figure 13 shows the distribution of refrigerant charge observed in the study. Note that the charge was correct in 60% of the units tested. About 15% of the units were 5% undercharged. Roughly 8% of the units had severe leaks, rendering them inoperable. Overall, the average loss of efficiency due to improper refrigerant charge was 5%.

The units studied were all four years old or newer, and had hermetically sealed compressors, so one would not expect to see much charge variation. By comparison, data gathered on older units is also plotted in Figure 13 (Proctor, 2000). These data show a much wider variation in refrigerant charge. Overall, less than 40% of the older units tested were appropriately charged, and that variation both above and below the nominal charge was observed. These data indicate that as units age, the incidence of improper charge increases, due to system leakage and improper service techniques.

The variability in unit efficiency as a function of refrigerant charge is shown in the following figures. For units with fixed expansion devices, efficiency degrades by up to 15% as the charge varies from -20% to +20%. Units with thermostatic expansion valves showed much less variation; with essentially no degradation in unit efficiency as long as the charge variations is within -15% to +5%.

Figure 13. Refrigerant Charge Variation in New and Existing Units

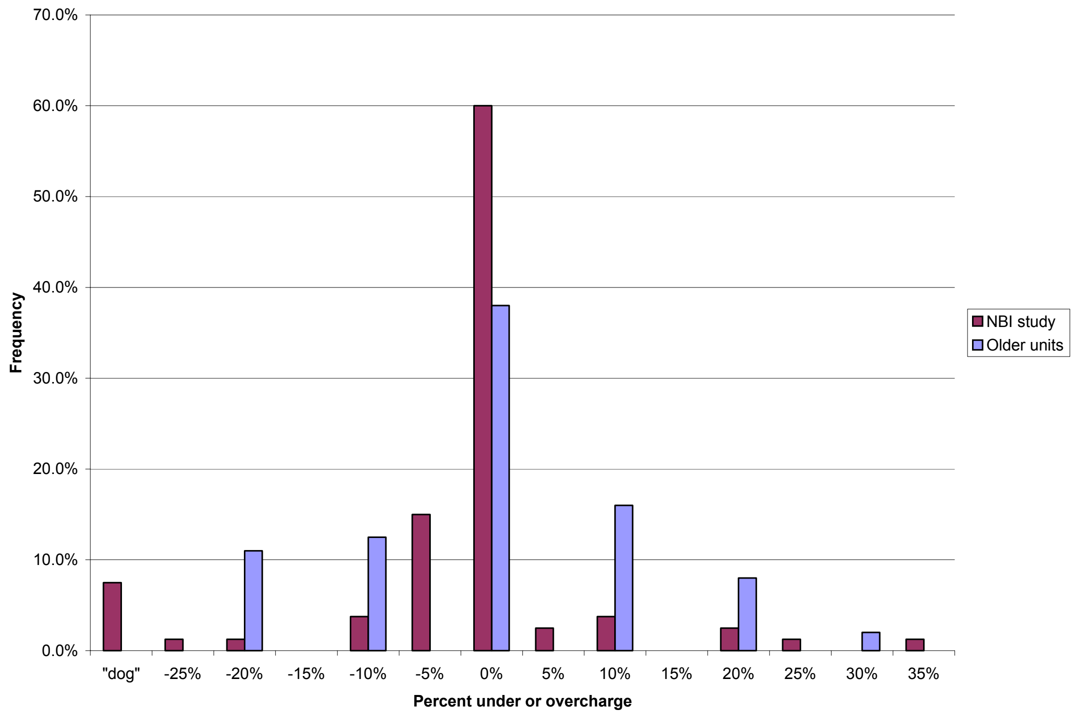
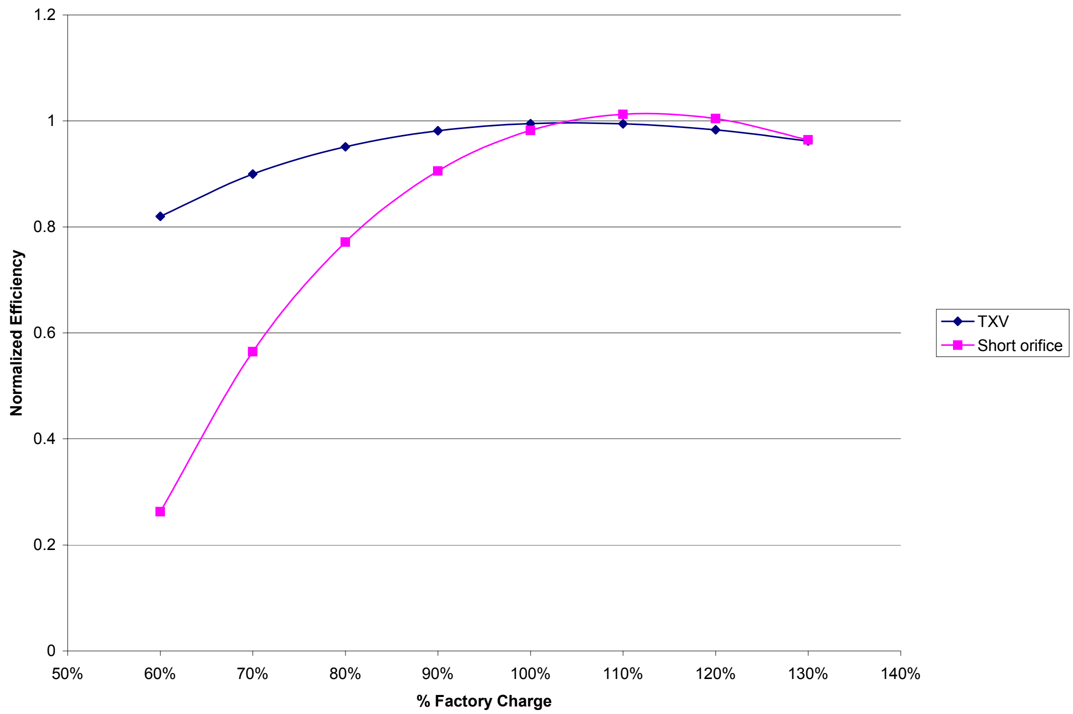


Figure 14. Efficiency Degradation as a Function of Refrigerant Charge



Specify Reliable Economizers

Economizers are required by Title 24 Energy Standards in units exceeding 6.25 tons and used in many smaller units. Energy savings from functioning economizers range can exceed 50% in certain climates and building types, as shown in Figure 15.

__Overall, 63% of the economizers tested did not work properly.__

However, economizers show a high rate of failure in the study. Of the 215 units tested, 123 units were equipped with economizers. Of these, 30 units (24%) would not move at all, and 36 units (29%) did not respond when subjected to simulated economizer operating conditions. Short-term monitoring revealed that an additional 13 (10%) did not respond correctly over a range of operating conditions. Overall, 63% of the economizers tested did not work properly. These findings are consistent with other studies conducted by PG&E (Felts, 1998), Eugene Water and Electric (Davis, et al., 2002), and Portland Energy Conservation Inc. (PECI, 2002a), which show economizer failure rates of 70% or more.

Figure 15. Cooling Energy Savings from Integrated and Non-Integrated Economizers.

Integrated economizer control allows the compressor and economizer to operate simultaneously. Integrated economizers are required by Title 24 in all systems exceeding 75,000 Btu/hr (6.25 ton) cooling capacity. This capacity criterion was selected based on the size of unit commonly using dual cooling compressors. With integrated operation, the economizer reduces the mechanical cooling load, which can cause cycling problems in single compressor systems. Most single compressor HVAC units operate with non-integrated economizer control, where economizer cooling is "all or nothing."

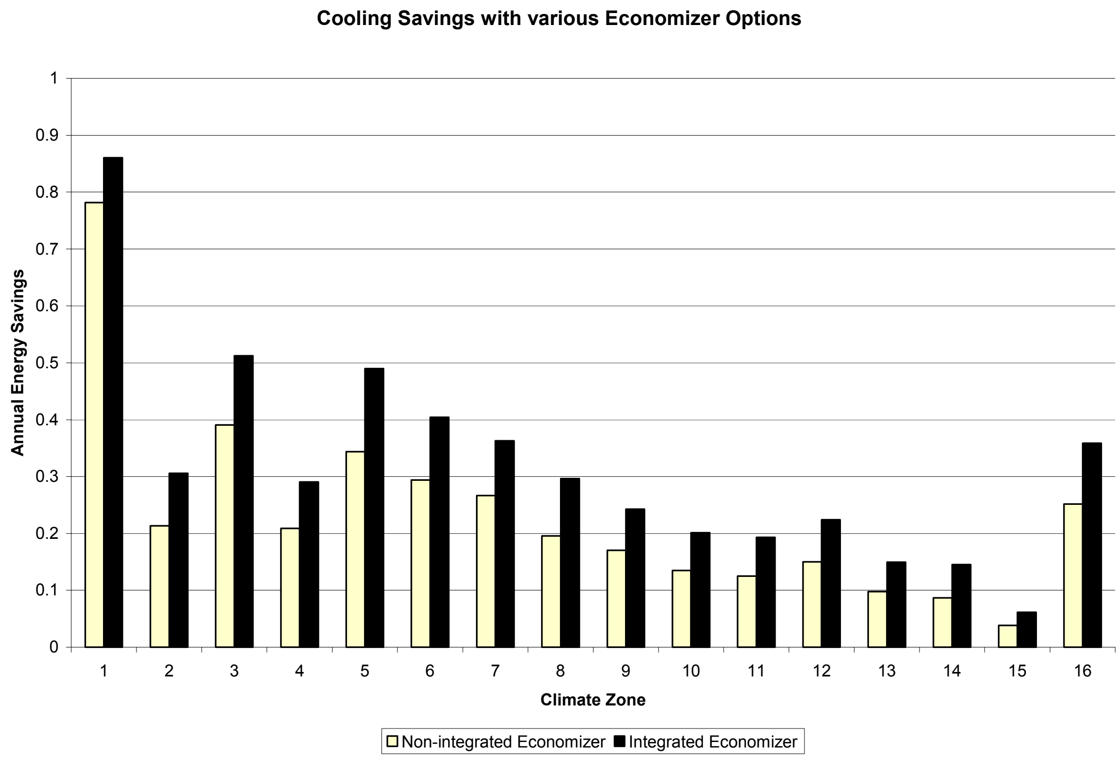
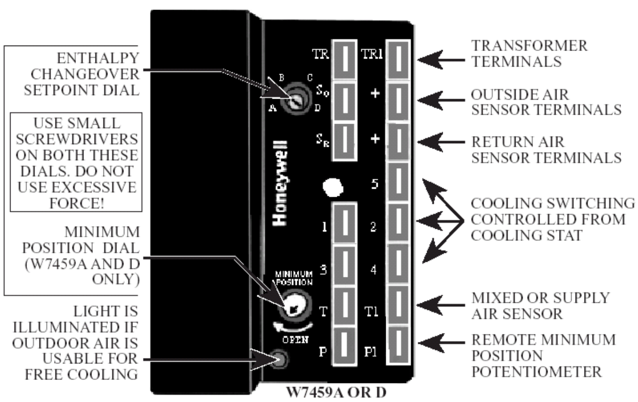


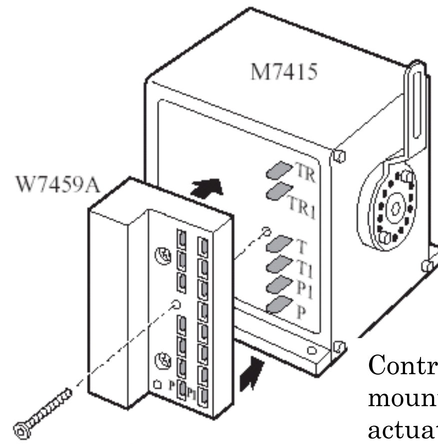
Figure 16 shows the components used in an economizer system for small packaged rooftop units. The economizer controller receive signals from various sensors, and decides when the outdoor air dampers should fully open. The system may include both outdoor air and return air sensors. Systems with outdoor air sensors only are referred to as setpoint systems. Single setpoint systems make control decisions based on a measurement of outdoor air temperature or enthalpy. When the outdoor air conditions are below a preset threshold called the changeover setpoint, the economizer operates. When the outdoor air conditions are above the changeover setpoint, the outdoor air dampers returned to a minimum position.

Figure 16. Common Components in Packaged Rooftop Unit Economizers

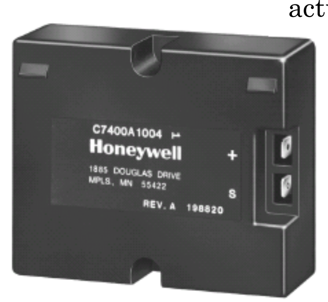
Economizer systems generally consist of an economizer controller, temperature or enthalpy sensors, and a modulating damper actuator. Honeywell manufactures most of the economizer controllers, sensors, and actuators used in small commercial rooftop units. The economizer controller is designed to function with single point or differential temperature for enthalpy logic, depending on the sensors supplied with the unit.



Economizer Controller



Controller mounted on actuator



Enthalpy Sensor

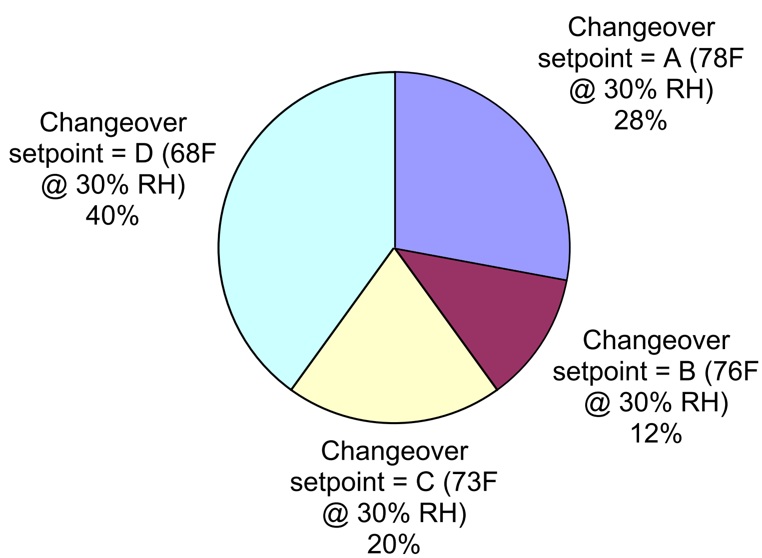
Figure 17. Direct Drive and Linkage Driven Economizer Dampers

Examples of linkage driven (left) and direct drive (right) economizer dampers are shown below. Direct drive systems are inherently more reliable than linkage driven systems due to fewer moving parts and adjustments (PG&E, 2000).

Selection of the changeover setpoint has a major influence on the energy savings potential of the economizer. If the changeover setpoint is set too low, then mechanical cooling will operate exclusively even when the economizer is capable of meeting some or all of the cooling load (Davis, et al., 2002). Single point changeover setpoints are selected on the economizer controller according to an A, B, C or D setting. The selection of the changeover setpoint depends on the climate; humid climates require a lower setpoint than dry climates. According to the Title 24 Energy Standards, the “A” setpoint is appropriate for all climates in California. However, observations of single point changeover setpoint selection in the PIER study behind this Design Guide showed that the “A” setting was rarely used, as shown in Figure 18. Manufacturers may not ship their products with the “A” setting as the default, requiring a field adjustment of the controller setting.

Figure 18. Observed Changeover Setpoints for Single Point Enthalpy Economizers

The distribution of economizer control setpoints observed in the field for single point enthalpy economizers shows only 28% of the systems in the "A" position as required by Title 24. Most systems were set in the "D" position, which results in the fewest hours of economizer operation.



Many of the economizer problems observed in the field can be avoided through careful selection and specification of rooftop unit economizer features. Consider the following when specifying economizers to improve reliability:

- ***Specify factory-installed and run-tested economizers***. Although most manufacturers offer a factory-installed economizer, the majority of economizers are installed by the distributor or in the field. Specifying a factory-installed and fully run-tested economizer can improve reliability.
- ***Specify direct drive actuators.*** Economizers with direct drive actuators and gear driven dampers can reduce problems with damper linkages that can loosen or fail over time.
- ***Specify differential (dual) changeover logic*** Differential temperature or enthalpy changeover logic instead of single point changeover systems eliminates problems with improper setpoint and maximizes economizer operation.

- ***Specify low leakage dampers.*** Low leakage dampers with blade and jamb seals will improve economizer effectiveness by limiting return air leakage during economizer operation and outdoor air infiltration when the unit is switched off. Specify low leakage dampers for outside air and (if available) return air dampers.

Specify Design Features that Improve Serviceability

Maintenance is often made harder or more time consuming because of unit design. Look for design features that will help make unit service easier over the long run. By paying attention to the serviceability of the unit, the likelihood of the unit being serviced properly will likely increase. Here are a few features to look for:

- Compartments requiring regular access for maintenance should have hinged access doors. This includes filter, electrical, economizer and supply fan sections.
- A refrigerant hose access plug should be provided and refrigerant high and low taps should be located so that access panels can be closed completely while hoses are connected to the taps. This allows the unit to be tested with the access door closed. In some units, the technician must hold the access panel in place with the hoses preventing complete closure of the access panel, thus affecting the airflow across the condensing coil.
- Liquid lines on two-stage units should be clearly marked differentiating circuit 1 and circuit 2.

Distribution Systems

Summary

Reduce duct system pressure drop to allow systems to operate at their design flowrate. Base duct system design on 0.05 in W.C. pressure drop per 100 ft of straight duct, and use fittings with low pressure drop characteristics. Limit the use of flex duct, and seal and leak-test distribution systems to improve efficiency and thermal comfort in the space. Size for reduced pressure drop and velocity to also reduce duct system noise.

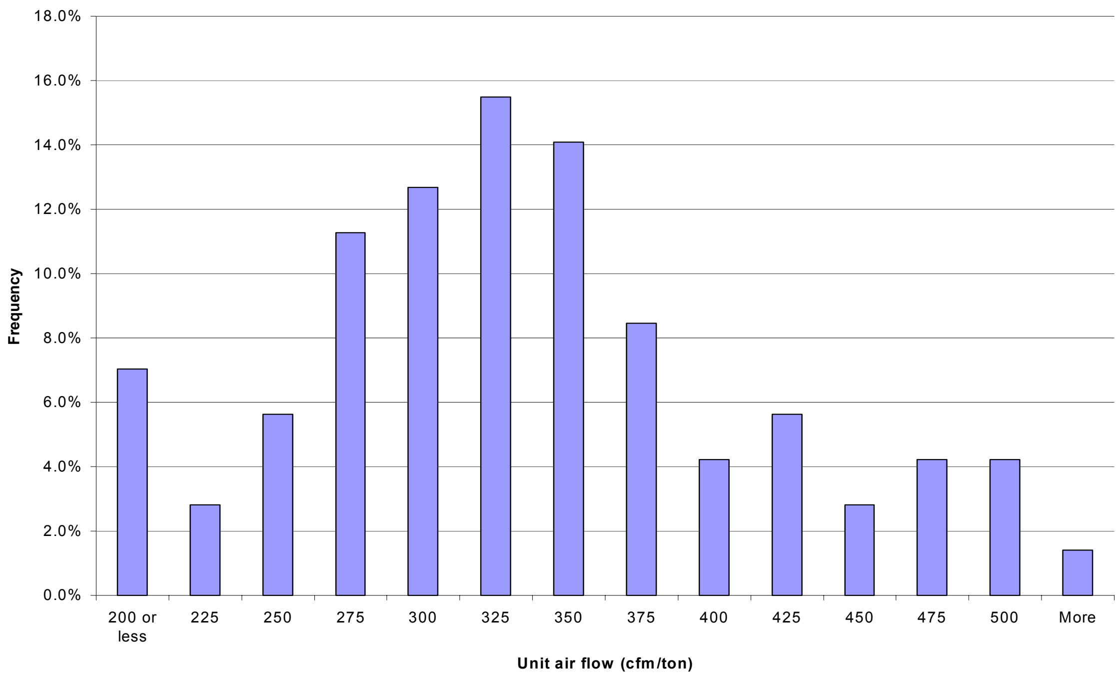
After the HVAC unit, the distribution system (ductwork and diffusers) is the next most important and costly part of the HVAC system. Installed costs for duct systems can approach the cost of the HVAC unit itself, so there is often intense pressure to reduce duct system costs. However, the quality of the duct system can have a profound effect on the efficiency and comfort delivered by the HVAC system. Fan energy in small commercial buildings in mild climates can approach the cooling energy consumption. Duct losses through leakage and conduction can affect the efficiency of the system and the amount of cooling delivered to the space. A poorly balanced and leaky distribution system is one of the leading causes of poor indoor comfort in small systems.

Reduce Duct System Pressure Drop

Poor ductwork design can lead to inadequate HVAC unit airflow and excessive fan power. Tested airflow rates in buildings studied during the PIER study behind this Design Guide averaged about 325 cfm/ton, rather than the nominal 400 cfm/ton used in system efficiency ratings, as shown in Figure 19. Reduced airflow can contribute to coil icing, comfort problems, and a reduction in cooling efficiency on the order of 7% (Proctor, 2002). Maintaining or exceeding the nominal 400 cfm/ton airflow rate improves system efficiency, and increases cooling capacity. Although latent cooling capacity decreases, this is generally not a problem in California’s dry climates. Maintaining design airflow rates without excessive fan power requires close attention to the duct system design and construction practices.

Figure 19. Tested Airflow Distribution in Small Commercial HVAC Systems

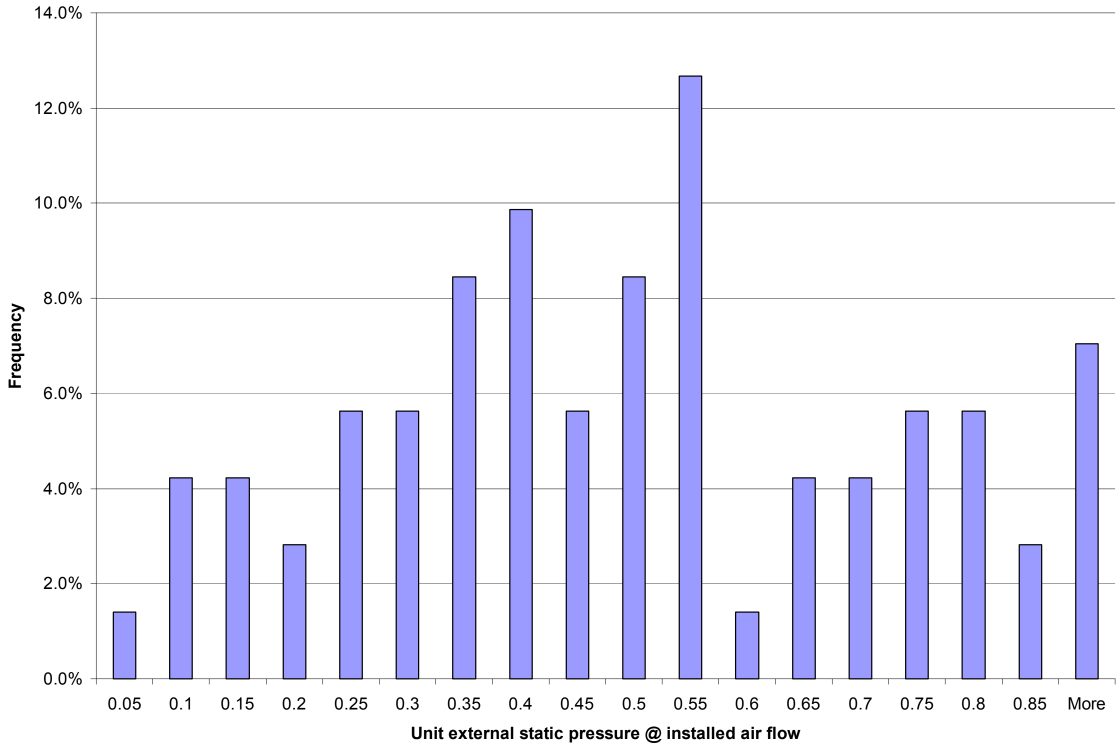
The distribution of the measured airflow is shown below. Overall, of the 79 units tested for airflow, 28 (39%) had airflow less than 300 cfm/ton. The average airflow rate was 325 cfm/ton.



The average measured fan power was 0.18 kW/ton, which is about 20% higher than the nominal fan power assumed in Title 24 energy standards (365 W/cfm or about 0.15 kW/ton). If the fan flow is increased to 400 cfm/ton, the fan power will increase to 0.34 kW/ton. This increase effectively drops the efficiency of a 10.3 EER unit to 9.1.

The combination of high fan power and low flowrate is due largely to excessive pressure drop in the duct systems. The frequency distribution of unit external static pressure at the measured flowrate is shown in Figure 20. The average duct system pressure drop was 0.48 in. W.C. ARI efficiency ratings assume a duct system pressure drop of 0.1 to 0.25 in. W.C., depending on the system size. The average duct system pressure drop corrected to 400 cfm/ton would equal 0.625 in. W.C., which is about 2.5 to 6 times greater than the ARI Standard.

Figure 20. Tested External Static Pressure Distribution in Small Commercial HVAC Systems



Duct Design Methods

Duct systems in small buildings are generally sized using the equal friction or modified equal friction method. The equal friction method, as its name implies, is based on maintaining the same pressure drop per unit of duct length (or friction rate) throughout the system (ACCA, 1990). The duct size is based on the flowrate through a particular section of duct, and design value for the friction rate. Each section is sized using the design friction rate criterion, and the total pressure drop for each run is simply the sum of the pressure drop of each individual section. The duct sections pressure drop includes straight duct friction loss, pressure losses through fittings such as elbows, takeoffs, and registers and/or diffusers. In the sections entering and leaving the HVAC unit, pressure losses associated with the flow transitions entering and leaving the unit (the system effect) are also included. The unit fan speed is selected to provide the design cfm and produce enough pressure difference to overcome pressure losses in the supply and return branches having the greatest pressure drop. Note that duct systems designed using the equal friction method are not self-balancing. Balancing dampers must be installed in lower pressure loss branches to balance the system.

In duct systems with branches having widely varying pressure losses, the modified equal friction method is used to design systems that are closer in balance (ACCA, 1990). Design friction rates for shorter duct runs are increased in an attempt to design each branch with the same total pressure loss. This method provides a design that is better balanced, but balance dampers must still be installed since it is not possible to provide a truly self-balanced system using this method. Also, duct velocities in shorter runs must be checked for noise problems.

Duct size is generally selected using a slide rule or ductilator. The duct section air quantities and design friction rate are matched on the slide rule, and a round duct diameter or several combinations of rectangular duct length and width are displayed. Duct section air velocity is also displayed to check for potential noise problems. Duct dimensions are based on the interior dimensions; if duct liner is used, the thickness of the duct liner must be subtracted. Pressure loss data are based on smooth duct. Adjustment factors must be applied to lined duct, duct board, and flex duct.

Design Values

Principle design variables are the design velocity (chosen for noise control) or the design friction loss (in W.C. per 100 ft). Typical design friction rates are 0.1 in. W.C. per 100 ft in commercial buildings. Reducing the design friction rate to 0.05 in. W.C. per 100 ft increases the duct size and costs by 15%, but cuts the portion of the total pressure drop attributable to the ductwork by 50%, and the overall distribution system pressure drop on the order of 40% when diffuser losses are included. Upsizing the duct can provide fan energy savings on the order of 15% to 20%.

Duct Layout and Fittings

The following guidelines will help provide a duct system with minimum pressure loss and reduced first cost (CEE, 2001):

- Lay out duct system to minimize duct length, turns and fittings. Since air wants to "go straight," energy is lost at each bend. Also, since straight duct is cheaper than fittings, reducing the number of turns reduces system cost.
- Use round spiral duct wherever possible since round duct is less expensive and has better pressure loss characteristics. Round duct also is easier to seal since it does not have any longitudinal joints.
- Use radius or section elbows for all turns greater than 45 degrees. Full radius elbows cost less than square elbows with turning vanes while having similar pressure loss characteristics. Use square elbows with turning vanes only where radius elbows will not fit.
- Turning vanes should be single thickness rather than airfoil. Tests conducted by ASHRAE and SMACNA indicate that fittings with single thickness vanes have reduced pressure losses. Be sure the turning vanes are parallel with the duct centerline at the entrance and exit, as shown in Figure 23.
- Use smooth wye branch fittings instead of right angle fittings at branch takeoffs for a smoother airflow pattern and reduced entrance losses.
- Avoid turns immediately before a supply or return air register to smooth the flow entering these devices. This reduces pressure loss and improves the performance of the diffusers.

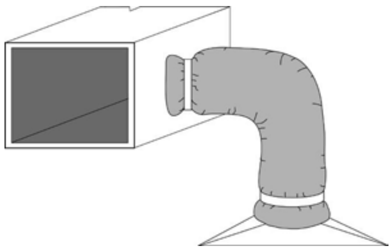
- Avoid duct connection details at the unit that degrade fan performance (called the "fan system effect") by providing at least two feet of straight duct before the first turn. These details are critical to minimize noise and loss of fan capacity. Since rectangular duct is generally used at the unit connection, install turning vanes in supply ducts at the first turn after entering the building.

Use of Flex Duct

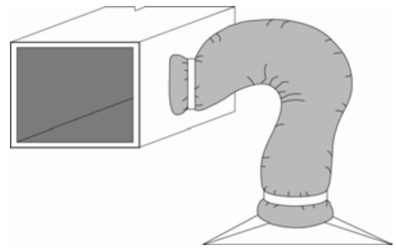
Flex duct, which is used extensively in light commercial construction, has a more than 60% higher pressure drop than galvanized metal duct of the same diameter. Flex duct runs should be limited to six feet or less. When longer runs must be used, make sure the duct is well supported at five-foot intervals to minimize sag. Flex duct should be fully extended to minimize pressure drop. When flex duct is not fully extended, a pressure loss correction factor must be applied to the manufacturer's pressure loss data. The pressure loss correction factor as a function of flex duct extension is shown in Figure 22 (ASHRAE, 2001). Note that a 30% reduction in flex duct extension causes a fourfold increase in pressure drop. The bend radius should be greater than one times the duct diameter to avoid kinking.

Figure 21. Flex Duct Installation Guidelines

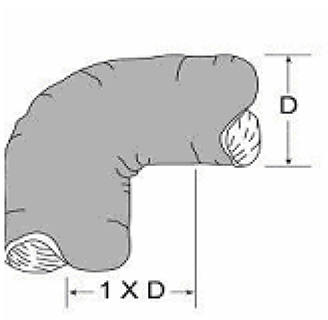
Follow these installation guidelines to ensure adequate airflow is maintained through distribution systems containing flex duct (ADC, 1996).



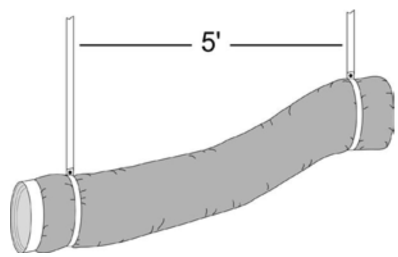
Flex duct connections to a diffuser from a main branch showing smooth duct routing without kinks or compression.



The flex duct used in this connection is too long, resulting in kinking at the branch connection and duct length compression.



To avoid kinking, maintain a bend radius at least equal to the duct diameter.



Support flex duct at minimum 5 ft intervals, with hanging straps at least 2 in. wide.

Figure 22. Pressure Loss from Poorly Extended Flex Duct

Flex duct pressure drop increases dramatically if the duct is not fully extended (ASHRAE, 2001).

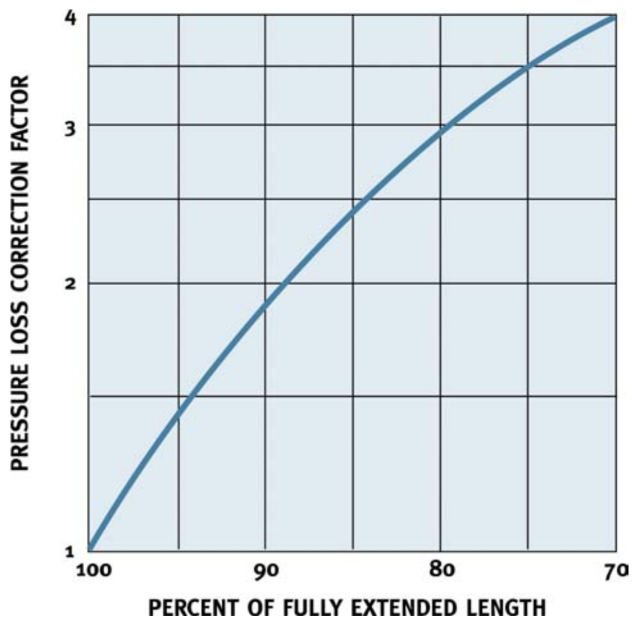
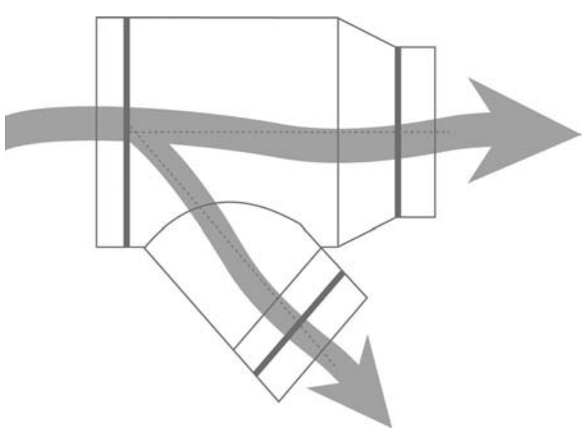
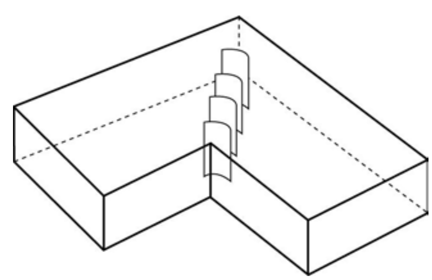


Figure 23. Metal Duct Design Details

Attention paid to metal duct design details, especially at elbows and transitions, can reduce duct system pressure drop.



Wye-branch takeoff for round duct



Turning vanes in rectangular duct elbow reduce pressure drop and turbulence

Seal Duct Leakage

Leaky ductwork is a common problem plaguing small commercial systems. A recent study of 350 small commercial HVAC systems in Southern California found that 85% of the systems tested had excessive duct leakage (Modera and Proctor, 2002). The average combined supply and return leakage in these systems exceeded 35% of the total air volume, causing energy waste and poor thermal comfort. 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. Peak demand savings are greater due to higher ambient temperatures during summer peak hours.

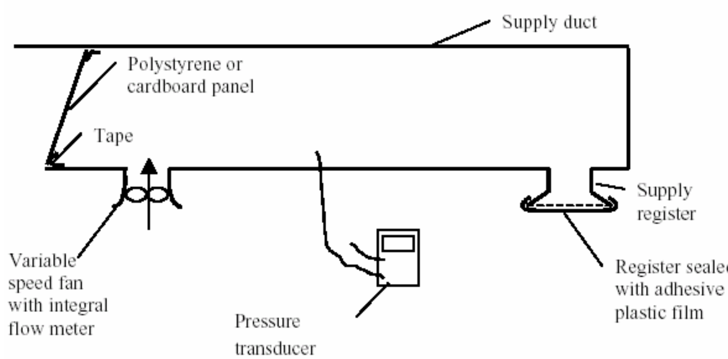
Comfort in buildings with tight ducts is expected to improve, since the HVAC systems will be better able to serve the loads in the space. In commercial buildings, where the HVAC systems supply continuous ventilation air, leaky and poorly insulated duct systems can actually contribute to warming the space during the cooling season by supplying air that is warmer than room temperature. In this case, duct tightening can improve comfort during building ventilation.

Duct leakage testing and sealing should be done prior to installation of a dropped ceiling to maintain good access to the duct system. Duct leakage testing should be conducted using the duct pressurization method, as described in Title 24 Energy Standards and the SMACNA Air Duct Leakage Test Manual (SMACNA, 1985). The duct pressurization test is conducted by pressurizing a sealed duct system to a standard pressure, typically 25 Pa, with a calibrated fan and flow measurement device commonly called a "duct blaster." The duct system is considered to be sealed when the measured leakage rate is less than 6% of the system flowrate.

A schematic diagram of the duct pressurization test is shown in Figure 24. In most applications, the supply registers are sealed with plastic secured by double sided tape, and the duct blaster is connected to the return register. The system is pressurized, and the leakage flow is measured at the duct blaster, as shown in Figure 24. This technique provides a measurement of the combined leakage and in the return and supply duct work, and also includes leakage from the HVAC unit cabinet and outdoor air damper. If the outdoor air damper does not close when the unit is off, the outdoor air intake should be sealed also. Specify sealing materials that meet UL Standard 118, such as mesh tape and mastic. Duct tape should not be used to seal duct leaks, since it tends to degrade over time.

Figure 24. Schematic of Duct Pressurization Test

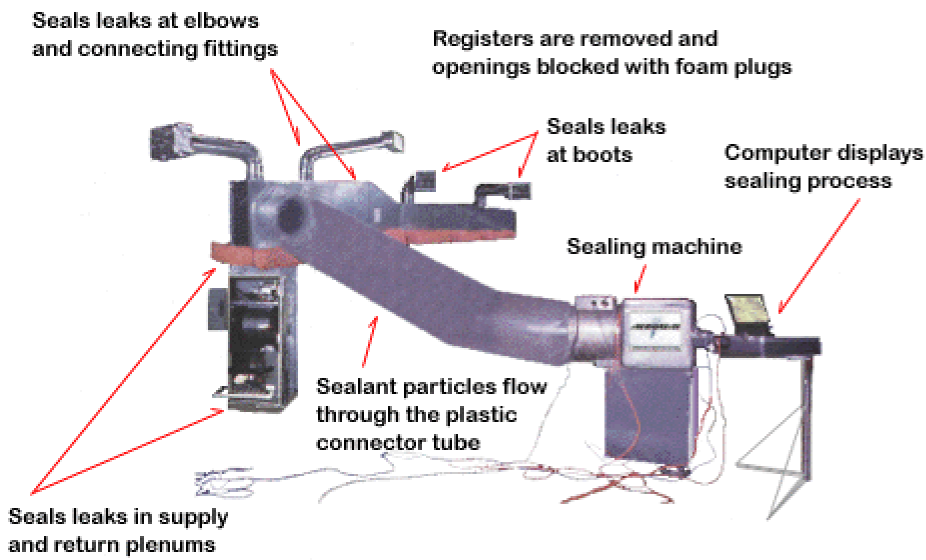
A duct pressurization test is conducted by isolating the section of duct tested, pressurizing the duct with a fan to a pre-determined test pressure, and measuring the duct leakage flowrate (LBNL, 2001). A generic diagram of the setup is shown on the left; a duct blaster connected to an HVAC system return is shown on the right.



Aeroseal is a new technique that combines duct leakage testing and sealing into one operation. A calibrated duct pressurization fan is attached to the duct system, and the leakage flow is measured at a preset duct system pressure. An elastomeric aerosol sealing compound is injected into the duct system until the leakage level is reduced to an acceptable level. A schematic diagrammed of the air sealed system is shown in Figure 25. When required, the duct leakage testing and sealing can be done from the roof to minimize disruption.

Figure 25. Aeroseal System for Duct Sealing and Testing

Aeroseal is a process invented at Lawrence Berkeley National Laboratory for testing and sealing ducts in new and existing buildings. An overview of the process is shown below:



The Aeroseal equipment set up in a commercial building is shown in the photo below:

Increase Duct Insulation Levels to R-8

Most duct systems are insulated with 1 in. of fiberglass insulation (R-4.2). Duct wrap and duct liner 2-in. thick is commonly available, and improves the insulation level to R-8. Increased insulation is cost effective in duct systems run outside the conditioned space, such as attics or plenum spaces with lay-in insulation, or outdoors (PG&E, 2003). Insulate both supply and return duct work to R-8. When using lined duct, be sure to increase the duct size to account for the additional insulation thickness. Also consider the increased friction from lined to smooth duct when calculating duct size. For these reasons, duct wrap rather than lined duct is recommended.

Reduce Duct System Noise

Poorly designed duct systems produce and/or convey noise. Excessive noise can degrade IEQ and productivity in certain spaces, especially classrooms. Research conducted by Heschong Mahone Group under this PIER project listed noise as a leading problem in school HVAC systems (Heschong Mahone, 2003b).

Noise in duct systems is caused by turbulence within the system and transmitted noise from the HVAC unit. Strategies that reduce duct system pressure drop also help reduce noise. The following guidelines will help provide a duct design that is both energy efficient and acoustically acceptable (ACCA, 1990):

- Reducing the design friction rates also reduces duct velocity, which reduces duct noise from turbulence. Fittings designed for reduced pressure losses also have fewer problems from turbulence induced noise.
- Lower duct pressure drop reduces fan speed, which also reduces fan noise. Spiral round duct, which has better pressure drop characteristics is also more rigid than rectangular duct, reducing the “drum effect” from duct vibration.
- Avoid using lined ducts for noise control, since the duct lining increases pressure drop. A common problem is to solve a noise problem related to high duct velocity with duct liner or silencers, which further increases pressure drop.
- Avoid direct line-of-sight layout of duct systems between the HVAC unit and the room. Although minimizing fittings reduces pressure loss, the duct system should have at least two turns between the HVAC unit and the room to reduce noise transmission
- Select diffusers to meet noise ratings that are appropriate for the space served. Provide sufficient straight duct run before the diffusers to minimize turbulence induced noise.
- Locate branch balancing dampers well away from diffusers to minimize noise in case substantial adjustment is required.
- Avoid line-of-sight connections between diffusers serving different spaces to avoid noise transmission (called “cross talk”) from one space to the other.

- Avoid locating the HVAC unit in a space immediately adjacent to the occupied space. Provide vibration isolation and sufficient acoustic insulation for the walls of the mechanical room in situations where this is unavoidable.

Ventilation

Summary

Operate HVAC unit fans continuously during occupied hours to provide adequate ventilation. Use demand-controlled ventilation in spaces with high design occupant density and intermittent occupancy such as auditoria, meeting spaces, and so on.

Providing adequate ventilation is key component of indoor air quality. Strategies to provide adequate ventilation are often at odds with energy efficiency; however, it should the priority of designers and operators of buildings to meet ventilation code requirements first, then meet these requirements in the most energy-efficient manner possible.

Operate Unit Fans Continuously

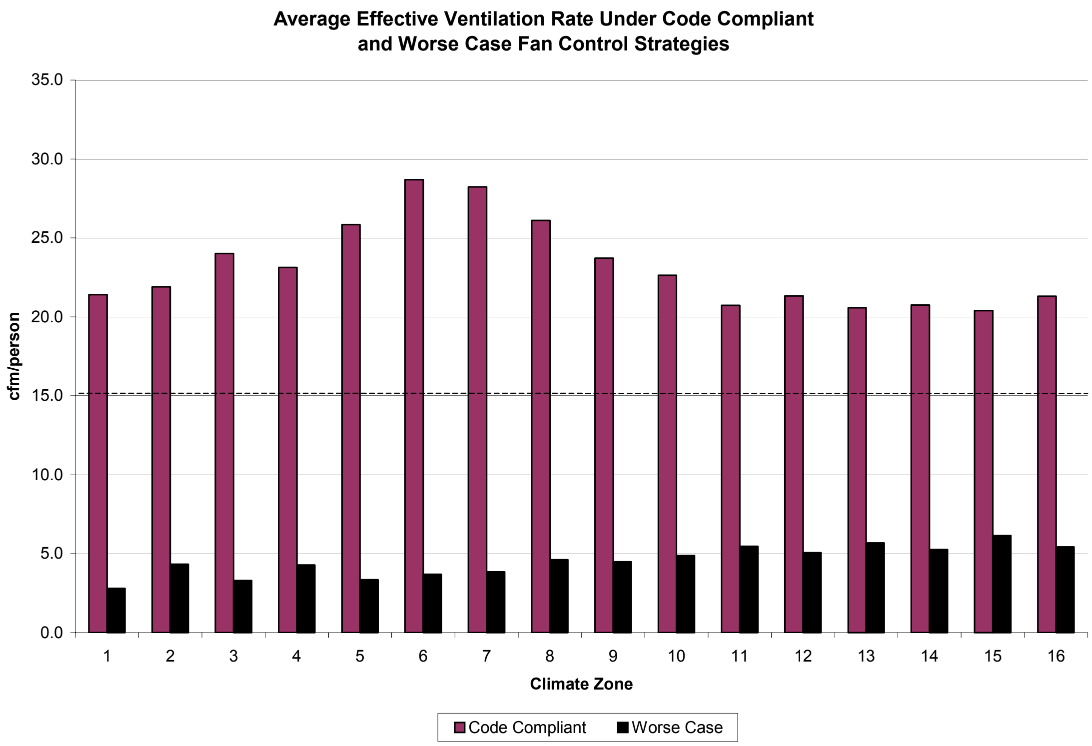
System fans were found to be cycling on and off with a call for heating or cooling in 38% of the units tested in the PIER study behind this Design Guide. Title 24 Energy Standards require that all buildings not naturally ventilated with operable windows or other openings be mechanically ventilated. This is generally accomplished by operating the HVAC unit fan continuously and introducing fresh air at the unit. Mechanical ventilation is required to occur at least 55 minutes out of every hour that the building is occupied. Building outdoor ventilation air is typically supplied during fan operation, with the minimum quantity of outdoor air determined by the outdoor air damper minimum position. The supply of continuous fresh air during occupied hours relies on continuous operation of the HVAC unit supply fan. The Standards further require operation of the ventilation system at least one hour before normal building occupancy in order to purge potential build up of pollutants and outgassing from furniture, carpets, paint and other materials.

The effective ventilation rate for units with cycling fans is on the order of one-third the minimum rate mandated by Title 24 Standards.

When HVAC unit fans are cycled on and off with a call for heating or cooling, the ventilation rates drop dramatically. The effect of cycling fans on effective ventilation rates is shown in Figure 26 (PG&E, 2000). Note that the effective ventilation rate for units with cycling fans is on the order of 5 cfm per person, or about one-third the minimum rate mandated by Title 24 Standards. Continuous fan operation also reduces stuffiness and localized temperature variations that are among the most common complaints in buildings served by small rooftop units.

Figure 26. Effective Ventilation Rate for HVAC units with Continuous and Cycling Fans

In both cases, the minimum outdoor air damper is set to provide 15 cfm/person of outside air. The code compliant case used continuous ventilation and an air side economizer. Economizer operation increased the effective ventilation rate above the nominal 15 cfm/person rate. A unit not equipped with an economizer and operated with cycling fans provided an effective ventilation rate of less than 5 cfm/person in most climate zones. Source: PG&E, 2000.



USE DEMAND-CONTROLLED VENTILATION

Demand-controlled ventilation systems modulate outdoor air quantities based on measured indoor air quality. Indoor CO_2 concentration is commonly used as an indicator of indoor air quality. Many economizer controllers have built-in capability to implement demand-controlled ventilation with the simple addition of a CO_2 sensor. This strategy can reduce outside air requirements during periods of partial occupancy and provide energy savings and reduced humidity.

Figure 27. CO_2 Sensors

CO_2 sensors attached to a standard economizer controller add demand-controlled ventilation to many rooftop units

Wall mounted CO_2 sensor used in demand-controlled ventilation systems

Duct mounted CO_2 sensor used in demand-controlled ventilation systems

Demand-controlled ventilation is commonly used in systems serving spaces with highly variable occupancies, such as auditoria, meeting rooms, and so on. These systems can also save energy in other space types with high design occupant densities to prevent over ventilating the spaces (Eley, 2002).

Alternative Ventilation Strategies

The HVAC unit supply flowrate is generally four times larger than the required outdoor air ventilation rate, requiring excessive fan power during ventilation-only operation. Alternative design strategies for providing ventilation air, such as two speed or variable speed fan systems interlocked with the outside-air (OA) damper and/or a CO_2 sensor can be used to reduce fan power during ventilation only mode. Another strategy is to use a dedicated ventilation fan that brings in a constant supply of fresh air rather than relying on the HVAC unit fan. In this case, the ventilation fan would run continuously during occupied hours, and the HVAC unit fan would cycle on a call for heating or cooling.

Natural ventilation using operable windows can also be used to supply ventilation in lieu of mechanical ventilation. This strategy can be effective in serving perimeter zones in mild climates. Proximity switches installed on operable windows should be used to lock out the HVAC systems when windows are open to prevent energy waste (Energy Design Resources, 2002).

Thermostats and Controls

Summary

Specify two-stage cooling thermostats with the ability to schedule thermostat setpoints, fan schedule, and fan operating mode independently. Locate thermostats where the temperature sensed by the thermostat sensor is representative of the zone served by the HVAC unit.

Controls used in small HVAC systems come from a variety of sources and may not provide the full range of control options required for optimal system performance. A simple room thermostat is used to control most systems, though energy management systems (EMS) are making inroads into the small commercial building market.

Use Two-Stage, Commercial Grade Thermostats

The primary function of the thermostat is to control the heating and cooling output of the unit, but most thermostats also control the operation of the supply fan. Fans are required to run continuously during operating hours, and cycle on and off with a call for heating or cooling during unoccupied hours. Most of the systems we studied have the capability to implement this strategy, yet were not set up correctly. Commercial (not residential) thermostats should be used to provide continuous fan operation/ventilation during occupancy. The thermostat should be programmed for intermittent fan operation during unoccupied hours, and provide a one hour “purge” of the building prior to occupancy.

Designers should specify controls with “default” settings that are appropriate for commercial applications. Gas/electric systems with economizers should use thermostats with two stages of cooling to allow integrated operation of the economizer and mechanical cooling system. When differential temperature or enthalpy economizer control is used, the first stage of cooling is used to initiate economizer operation, and the second stage of cooling is used to start the compressor to maintain space temperature control (EWEB, 2003). Note that heat pumps may require a three-stage cooling thermostat, since the first stage is sometimes used to operate the heat pump reversing valve.

Some programmable thermostats are capable of fully closing the economizer to reduce outdoor air infiltration during unoccupied periods. This sequence of operation is required under Title 24, and can be implemented by selecting a thermostat with this feature even if the economizer controller does not provide this capability.

Location of the thermostat can dramatically affect system loads and occupant comfort. Since the system responds to the air temperature at the thermostat, proper location is key to comfort and energy efficiency. Locating several thermostats in the same general area with conflicting heating and cooling setpoints can invite problems with simultaneous heating and cooling, where adjacent units “fight” each other to maintain selected setpoints.

Figure 28. Thermostat Location

Thermostats controlling three different units serving three different computer labs at a community college are located in the corridor, where they are unable to effectively sense the temperature of the rooms they are controlling.

Controller Options and Interfaces

Modern HVAC units can be configured with a variety of controller options, including standard electromechanical controls, microprocessor controls, and controllers with EMS interface capability. Standard controls allow the use of thermostats from a variety of vendors. In some units with microprocessor control, the thermostat control logic is contained within the unit controller and the zone thermostat is merely a temperature sensor.

Interfaces allow the units to be controlled by one of several energy management systems, including both manufacturer-supplied systems and third-party systems. These interfaces allow the EMS to take over most of the unit control function, including calls for heating and cooling, fan operation and scheduling, and economizer control. Additional digital I/O channels are included to provide alarm capability for fan failure, dirty filters, compressor high- or low-pressure lockout, and economizer status. Supply and return air temperature information can also be transmitted to the EMS console.

These systems are very popular in chain retail and foodservice environments, allowing central control over HVAC system operation and limited unit diagnostic capability. They work best in buildings that are occupied on a Regular schedule; applications in schools have been problematic (Heschong Mahone, 2003b).

Commissioning

Summary

Commission the system to ensure that the intent of the designer is met in the building as constructed. Verify proper unit installation using pre-functional checklists and verify unit operation using functional performance tests of control sequences, fan power, air flowrate, economizer operation, and refrigerant charge.

Commissioning is a quality assurance process that increases the likelihood that a new building will meet the intent of the design team and, ultimately, the client's expectations (Energy Design Resources, 1998b). In large projects, the commissioning process can encompass the entire design and construction process:

- During the design phase, commissioning begins with the selection of a commissioning agent who helps ensure that the project documentation reflects the designer's and owner's intentions.
- Next, the designer incorporates commissioning requirements into the design specifications.
- During construction, the commissioning agent is responsible for inspecting the building to catch construction defects that are difficult to correct after the building is finished.
- When the project is near completion, the commissioning agent and contractors conduct performance tests of the systems to be commissioned.
- At the end of the commissioning process, the designer and vendors train the building operators how to properly operate and maintain the building.

Commissioning of small HVAC systems generally focuses on documentation of the design intent, including commissioning testing in the building plans and specifications, testing the system, correcting deficiencies, and providing operation and maintenance training to the building occupants. Incorporating the commissioning requirements into the specs is very important, since the contractor will base the bid on the plans and specs, and setting the expectation that commissioning will be done will save a lot of trouble during the construction process. The commissioning plan should also include a sample maintenance contract to assist the building owner or operator in obtaining ongoing maintenance services.

Perform Pre-Functional Inspections

Prior to conducting any commissioning tests, the units should be inspected according to a checklist called a pre-functional checklist. Items on the checklist should include:

- Document submittal (spec sheets, operations and maintenance instructions).
- Verification of correct make and model number.

- Installation checks, such as tight curb connections, operable cabinet door(s) with gaskets in place, shipping materials and hold-downs removed; and adequate maintenance access.
- Duct insulation installed and in good condition.
- Filters installed properly.
- Fan motor pulleys aligned and belt tension correct.
- Economizer installation checks for correct configuration (downflow or horizontal) and proper installation of blank-off plates as required to prevent damper bypass
- Economizer linkages tight, with smooth operation.
- Economizer changeover setpoint (for single point controllers) set correctly
- Field-wired controls installed correctly according to installation instructions and/or project design drawings and specifications, including correct wiring of remote outdoor air sensor (if applicable).
- Safety electrical disconnect properly installed.

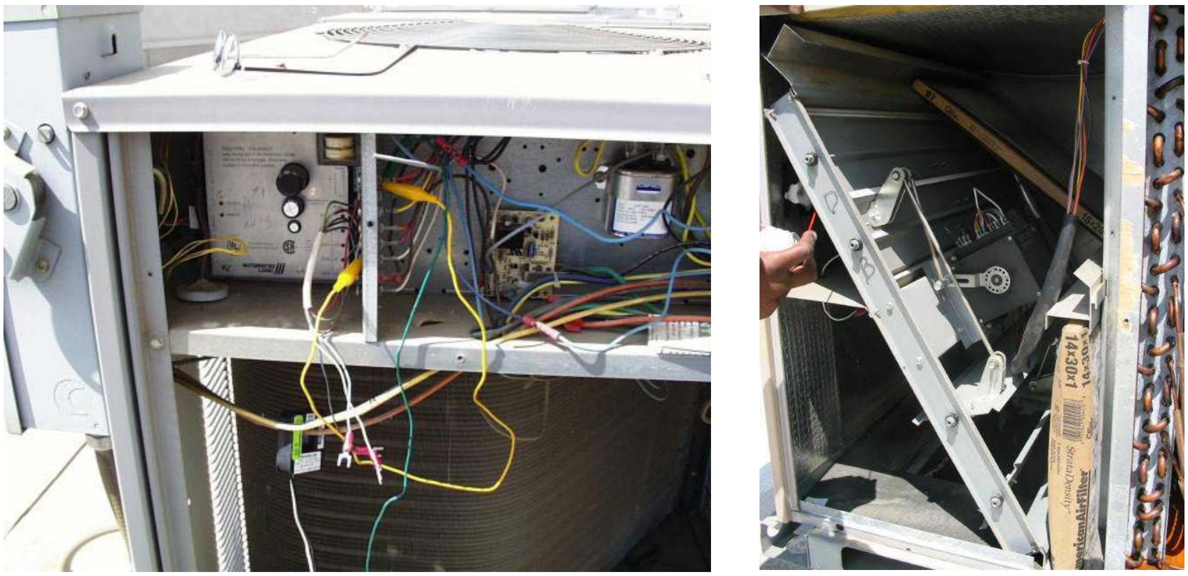
Perform Functional Performance Tests

The heart of the commissioning process is a series of tests called functional performance tests. For small packaged units, perform the following functional performance tests:

- Cycle the unit through its various operating modes and observe unit response relative to the control sequence of operations, as shown in Figure 29. Does the outdoor air damper close when the unit is turned off? Does the second compressor come on as specified?
- Test the economizer. Does the economizer actuator work? Do the dampers move freely over their full range? Are the sensors calibrated? Simulate conditions under which the economizer should operate using one of the methods described in the section below on Economizer Functional Test Procedures. Does the unit respond correctly when subjected to conditions where the economizer should operate?
- Check sensor accuracy. Are the room temperature, outdoor air temperature, return temperature, and/or supply air temperature sensors installed in a reasonable location and providing accurate readings?
- Verify correct rotation of supply and condenser fan motors.
- Check thermostat programming. Are the setpoints and operating schedule correct according to the design documents? Does the fan run continuously during occupied hours?

Figure 29. Functional Performance Tests

The photo on the left shows jumpers being used to simulate various operating modes. The photo on the right shows cool spray being used to simulate economizer cooling conditions.



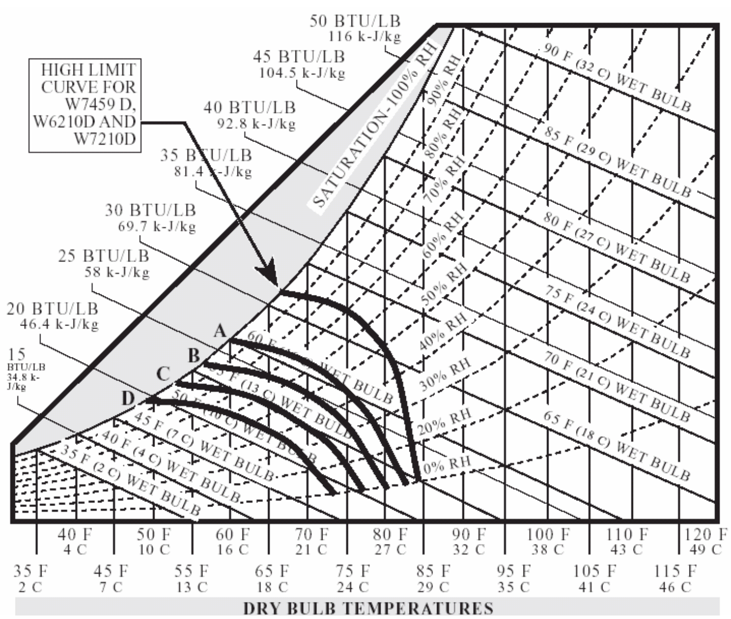
Economizer Functional Test Procedures.

If the unit has a single point economizer and the functional test is conducted during outdoor temperature conditions appropriate for economizer cooling, the following procedures can be used to test the economizer (PECI, 2002a).

- Locate the current outdoor temperature (and wetbulb temperature for enthalpy economizers) on the curves supplied by the manufacturer. Determine which setpoint (A, B, C or D) on the economizer controller should initiate economizer operation and which should initiate compressor operation. A typical changeover curve is shown in Figure 30.
- Adjust the changeover adjustment potentiometer so the setpoint is below and above the current ambient conditions. This should force both economizer and compressor operation.

Figure 30. Typical Economizer Changeover Plot

The chart below shows typical changeover points for single point enthalpy economizer controllers. Locate the outdoor drybulb and wetbulb temperatures on the chart and find the curve corresponding to the controller setting (A–D). The economizer should be open when the ambient conditions are to the left of the control curve.



- Adjust the economizer controller changeover setpoint so the economizer is operable, and jump the unit into first stage call for cooling. Once the economizer is open, jump the unit into a second call for cooling to start the compressor. Confirm that the economizer closes as the supply air temperature approaches the supply air low limit temperature setpoint
- If the unit has a differential temperature or enthalpy economizer, the following procedures can be used to test the economizer.
- Jump the unit into a first stage call for cooling.
- Measure the outdoor and return drybulb air temperature (or wetbulb temperature if the unit has an enthalpy economizer).
- Confirm correct economizer operation by comparing the outdoor and return air conditions; if the outdoor temperature is less than the return air temperature (within the temperature tolerance of the sensors and the controller "deadband," the economizer should be open. If the outdoor temperature is greater than the indoor temperature, the economizer should be closed.

In some cases, the outdoor temperature conditions may not be suitable for the test procedures described above. It is possible to simulate economizer operation by heating up the outdoor temperature sensor using a hair dryer or cooling down the outdoor temperature sensor using a "cool" spray designed for troubleshooting electronic components (See Figure 29). This procedure is fairly quick to implement and provides a qualitative check of the response of the system.

A more quantitative check can be made using a meter called a "loop calibrator." A loop calibrator is a device that can both measure sensor output and generate an arbitrary output signal to observe the response of the control system. The sensor is disconnected from the system and reconnected to the loop calibrator. The output of the loop calibrator is connected to the controller. The sensor output can be compared to the prevailing conditions to verify the accuracy of the sensor. The simulated signal can be used to establish an arbitrary condition on the controller and observe the response.

Additional Functional Tests

Additional functional tests may also be included. These tests can detect less obvious but very important problems with HVAC installations:

- Check unit supply and outdoor ventilation airflow. Measure unit airflow with a flow grid as shown in Figure 32, and verify that the unit supply airflow meets the design specifications.
- Check duct leakage. Use a duct pressurization device to measure duct leakage in the supply and return systems, and verify that the duct leakage rate meets the design specifications.
- Verify correct refrigerant charge. Measure high and/or low side refrigerant pressures and refrigerant line temperatures to verify correct superheat (for fixed throttling devices) or correct sub cooling or approach temperature (for thermostatic expansion valve units), according to instructions furnished by the manufacturer. Also check the superheat on TXV units to verify proper operation of the TXV.
- Conduct short-term monitoring. Use portable, battery-powered data loggers to observe unit operation over a variety of operating conditions. Measure unit current, supply air temperature, return air temperature, outdoor temperature, and mixed air temperature over a period of several weeks if possible. Be sure to shield the outdoor air temperature measurement from direct solar radiation using a radiation shield

Short-term monitored data can be plotted to verify the correct operation of the system. An example of an economizer diagnostic plot resulting from the short-term monitored data is shown in Figure 31 below:

Figure 31. Economizer Diagnostic Plots

The diagnostic software plots short-term monitored data in various formats to help diagnose system problems. Here, the difference between the cooling coil entering (i.e. mixed) air temperature and the return air temperature (Tmix – Treturn) on the vertical (Y) axis is plotted against the difference between the outdoor (ambient) temperature and the return air temperature on the horizontal (X) axis. The slope of the line is equal to the outdoor air fraction. Units with fixed outdoor air (no economizer) have a straight line relationship between these data. Units with functioning economizers show a characteristic change in the slope of the line to the left of the vertical (Y) axis, as shown here. The slope in this region is equal to one, indicating a functioning dry bulb economizer allowing 100% outdoor air.

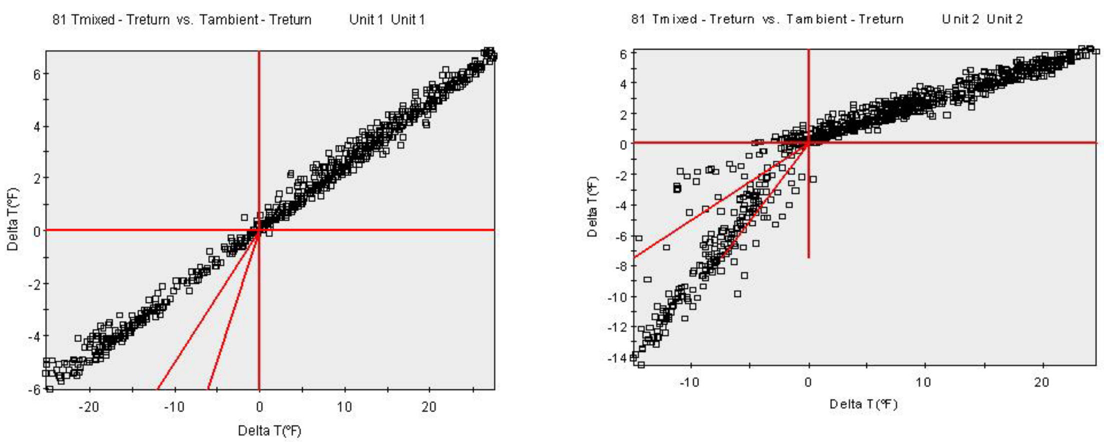


Figure 32. Flow Grid Measures Unit Airflow

A flow grid is used to measure as-installed airflow rate. A series of flow grids are installed in place of the filters; the airflow rate through each flow grid is displayed on a digital manometer.

Figure 33. Short-Term Monitoring with a Portable Data Logger

Short-term monitoring of rooftop unit. Note portable, battery powered data logger in bottom-center of the photo.

Operations and Maintenance

Summary

Provide design details that facilitate good operations and maintenance practices. Provide expectations to the building owner on what a maintenance service contract should include.

Packaged rooftop units are generally designed for a shorter service life than built-up HVAC equipment. They are also exposed to weather elements that can be stressful to the equipment operation. Both can contribute to more frequent maintenance needs. Problems tend to occur during periods of system stress caused by extremely hot or cold weather. This discourages timely inspection and repair. If the problems occur during wet or icy weather, maintenance and repair can actually be hazardous.

Keeping these issues in mind will help you better plan maintenance of units. A little preventive maintenance during nice weather should help optimize operation, energy use, and comfort while minimizing "surprises" during inclement weather.

Provide Reasonable Access to Rooftop

Maintenance of packaged rooftop units is often ignored due to the fact they are on the roof, where they are out of sight and out of mind. Typical access to the roof is by a vertical ladder and roof hatch. Stored items can block access to the ladder, which does not foster frequent inspections. Be sure the roof access is kept free of obstructions, and make sure maintenance personnel have access to the key to the roof hatch padlock. Provide parking for service vehicles in a location close to the roof access if possible.

Routine Maintenance

Regular maintenance is an important component of energy efficiency, comfort, and the prevention of premature equipment failure. Simple routine checks can avoid costly maintenance contractor calls to diagnose or fix simple maintenance problems. A few routine maintenance items include:

- Check fan belts for wear and correct tension.
- Check filters.
- Check economizer damper linkage for tightness and free movement. Be sure the economizer fully closes the return air passage when admitting 100% outside air.
- Test economizer operation as described in the Commissioning chapter.

- Start unit and allow it to run for 15 minutes. Check supply air temperature after units operation has stabilized. Check refrigerant charge using procedures described in the Commissioning chapter. Be sure to replace Schrader valve cores if refrigerant charge is tested. Lubricate moving parts (including dampers and linkage).
- Check access panels for tight fit.
- Inspect electrical wiring/connections.
- Check coils for debris and clean as necessary.

Annual maintenance contracts are common. If you are considering one, make sure the staff has good experience. Maintenance staff in buildings with rooftop units are often under-skilled, with limited training and experience. Routine maintenance tasks should be placed on easy-to-use “cheat sheets.” Post lists in location(s) that encourage pro-active maintenance. Maintenance logs and manufacturer service instructions for all units should be kept in a readily accessible binder. Maintenance contracts should require a log that remains on site.

Maintenance contracts for rooftop units are often selected on the basis of the lowest bid, without adequate consideration for the actual work performed (PECI, 2002b). Advanced maintenance services provide these additional maintenance items, but cost more than the basic low-bid package. Be sure to understand and specify the work to be performed before obtaining bids on service contracts.

Figure 34. Maintenance Hall of Shame

The following photos were taken at a newly constructed restaurant soon ***after*** *a visit by the HVAC service contractor. The roof was littered with old, filthy filters and bent and discarded "bird screens" intended to protect the unit's outdoor air opening.*

A closer inspection revealed several instances of missing filters and filthy cooling coils.

This fan motor fell off its mounting and into the evaporator coil. Although refrigerant wasn't lost, there was no airflow. Comfort complaints that went on for weeks were blamed on a thermostat problem. A simple check of the system would have discovered this problem much earlier.

Summary

Key Recommendations

In this Design Guide we have discussed a number of topics relating to the design, installation, operation, commissioning and maintenance of small HVAC systems. A number of problems documented in the field have their roots traced to one or more of these areas. How can the industry avoid these problems in the future? We see a number of steps that can be taken to improve the overall state-of-the-art in small packaged HVAC systems:

- Practice load avoidance strategies such as reduced lighting power, high-performance glass and skylights, cool roofs, and improved roof insulation techniques in the overall building design.
- Size units appropriately using ASHRAE-approved methods that account for the load avoidance strategies implemented in the design, and use reasonable assumptions on plug load power and ventilation air quantities when sizing equipment.
- Select unit size and airflow based on calculated sensible loads without oversizing. Consider increasing unit flowrate to improve sensible capacity in dry climates.
- Specify units that meet CEE Tier 2 efficiency standards, incorporate premium efficiency fan motors, thermostatic expansion valves, and factory-installed and run-tested economizers with differential rather than single point changeover control.
- Design distribution systems with lower velocities to reduce pressure drop and noise. Seal and insulate duct systems located outside the building thermal envelope.
- Operate ventilation systems continuously to provide adequate ventilation air. Incorporate demand-controlled ventilation to reduce heating and cooling loads.
- Specify commercial grade two-stage cooling thermostats with the capability to schedule fan operation and heating and cooling setpoints independently.
- Commission the systems prior to occupancy through a combination of checklists and functional testing of equipment control, economizer operation, airflow rate and fan power.
- Develop clear expectations on the services provided by HVAC maintenance personnel.

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Additional Resources

New Buildings Institute

New Buildings Institute's website contains additional information about this project and other elements of their PIER research program. For more information, consult:

www.newbuildings.org/pier

California Energy Commission

The California Energy Commission is responsible for conducting Public Interest Energy Research (PIER) on a number of topics. For more information on this and other PIER projects, consult:

www.energy.ca.gov/pier/buildings

Consortium for Energy Efficiency

The Consortium for Energy Efficiency (CEE) is a nonprofit, public benefit corporation that actively promotes the use of energy-efficient products and services through its members, including electric and gas utilities, public benefit administrators (such as state energy offices, nonprofit organizations, and regional energy groups), and research and development laboratories. They have established efficiency guidelines for commercial rooftop units, and have published a small commercial HVAC design guideline. For more information, consult:

www.cee1.org

Energy Design Resources

Energy Design Resources is an information-based nonresidential new construction market transformation program funded by Pacific Gas and Electric, Southern California Edison and Sempra Energy. Energy Design Resources offers a valuable palette of energy design tools and resources that help make it easier to design and build energy-efficient commercial and industrial buildings in California. The goal of this effort is to educate architects, engineers, lighting designers, and developers about techniques and technologies that contribute to energy efficient nonresidential new construction. Design tools that reduce the time spent evaluating the energy use impact of design decisions are also provided at no cost. For more information, consult:

www.energydesignresources.com

Air Conditioning and Refrigeration Technology Institute

The Air Conditioning and Refrigeration Technology Institute (ARTI) conducts the Twenty-First Century Research (21-CR) initiative, which is a privatepublic sector research collaboration of the heating, ventilation, air-conditioning and refrigeration (HVAC/R) industry. ARTI has conducted research into design practices for small commercial HVAC systems. For more information, consult:

www.arti-21cr.org

Northwest Energy Efficiency Alliance

The Northwest Energy Efficiency Alliance (NEEA) along with Portland Energy Conservation Inc. (PECI) is conducting a pilot program to assess the market opportunities for enhanced operation and maintenance services for packaged heating and cooling systems in small commercial buildings. The pilot project is developing and testing an array of diagnostic tools and procedures, training selected contractors, developing marketing materials and documenting the market acceptance of the service in selected markets around the Northwest. For more information, consult:

www.nwalliance.org

Air Conditioning Contractors Association

The Air Conditioning Contractors Association (ACCA) publishes several Manuals on design practices for small commercial HVAC systems. For more information, consult:

www.acca.org

Air Diffusion Council

The Air Diffusion Council publishes an installation guideline for flexible duct systems. For more information, consult:

www.flexibleduct.org

Sheet Metal and Air Conditioning Contractors' National Association

The Sheet Metal and Air Conditioning Contractors' National Association (SMACNA) publishes technical manuals and construction standards relating to the construction and installation of air distribution systems. For more information, consult:

www.smacna.org