INTEGRATED ENERGY SYSTEMS: PRODUCTIVITY & BUILDING SCIENCE

- *Productivity and Interior Environments*
- *Integrated Design of Large Commercial HVAC Systems*
- *Integrated Design of Small Commercial HVAC Systems*
- *Integrated Design of Commercial Building Ceiling Systems*
- *Integrated Design of Residential Ducting & Air Flow Systems*
- *Outdoor Lighting Baseline Assessment*

CONSULTANT REPORT

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Preface

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

The Buildings Program Area within the PIER Program produced this document as part of a multi-project programmatic contract. The Buildings Program includes new and existing buildings in both the residential and the non-residential 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.

What follows is the final report for the PIER Program *Integrated Energy Systems: Productivity and Building Science Program* (the program), Contract Number 400-99-013, conducted by New Buildings Institute, Inc.

This final report and its attachments are intended to provide a complete record of the objectives, methods, findings and accomplishments of the *Integrated Energy Systems: Productivity and Building Science Program.* The report content, and particularly the attachments, is highly applicable to architects, designers, contractors, building owners and operators, manufacturers, researchers, and the energy efficiency community.

The report is organized by the six program research elements: *1) Productivity and Interior Environments, 2) Integrated Design of Large Commercial HVAC Systems, 3) Integrated Design of Small Commercial HVAC Systems, 4) Integrated Design of Commercial Building Ceiling Systems, 5) Integrated Design of Residential Ducting and Air Flow Systems, and 6) California Outdoor Lighting Baseline Assessment.*

The Element sections contain a summary of the Element objectives, followed by the approach and technical outcomes per key project area. Market connections, conclusions, recommendations and statewide energy impact estimates are described at the end of each Element's section. Elements 2 and 5 consisted of a number of separate research projects, each with conclusions specific to those projects. For these two Elements the conclusions section is subdivided by project. Elements 3, 4, 6 and 7 consisted of interrelated research projects that built on each other and led to one final product or set conclusions for the Element.

The key research products in the form of guidelines and technical reports are attachments to this report and are listed and described at the start of the attachment section.

This document is the base component of report P500-03-082. For other reports produced within this contract, attachments to this report, 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. All research products are also available through New Buildings Institute at www.newbuildings.org.

Executive Summary

INTRODUCTION

This report summarizes the work performed between August 2000 and August 2003 as part of the *Integrated Energy Systems: Productivity and Building Science Program.* This research was supported by the California Energy Commission's (Commission) Public Interest Energy Research (PIER) Program.

In addition to a program management/market connections element (Element 1) led by Cathy Higgins of the New Buildings Institute (Institute), the program consisted of six research elements:

- *Productivity and Interior Environments* (Element 2), led by Lisa Heschong, Heschong Mahone Group
- *Integrated Design of Large Commercial HVAC Systems* (Element 3), led by Erik Kolderup, Eley Associates, Inc.
- *Integrated Design of Small Commercial HVAC Systems* (Element 4), led by Pete Jacobs, Architectural Energy Corp.
- *Integrated Design of Commercial Building Ceiling Systems* (Element 5), led by Jon McHugh, Heschong Mahone Group
- *Integrated Design of Residential Ducting and Air Flow Systems* (Element 6), led by Roger Hedrick, GARD Analytics, Inc.
- *California Outdoor Lighting Baseline Assessment* (Element 7), led by Sam Pierce and Matt Brost, RLW Analytics, Inc.

PRODUCTIVITY AND INTERIOR ENVIRONMENTS (ELEMENT 2)

This Element consisted of four research projects addressing the central theme of productivity and interior environments in three different market sectors: schools, retail and offices. Each project is addressed separately below.

Objective

The overall goal was to quantify the impacts of the indoor environment on occupant performance and/or organizational productivity. Specific goals included: 1) establish measurements of the productivity and energy values of daylighting in the operation of commercial buildings, 2) establish and refine a field methodology that can make a compelling association between human performance criteria and building characteristics, and 3) consider how the provision of daylight relates to other indoor environmental quality issues, such as thermal comfort, visual comfort, view, ventilation, and acoustic quality; and consider the potential separate contribution of those conditions to human performance.

Daylighting in Schools: Grade Effect & Teacher Assignment ("Reanalysis Report")

This project was designed to expand the findings of a 1999 study by Heschong Mahone Group that found a compelling statistical correlation between the amount of daylighting provided from windows and skylights in elementary school classrooms and the performance of children on standardized math and reading tests. The project also sought to investigate additional variables and answer questions raised by the previous report by reanalyzing the original data for the Capistrano district with the additional variables.

FINDINGS & CONCLUSIONS

- *The reanalysis study validated the original student learning-rate findings.*

  Based on this study's results, if the average student in the district were moved from a classroom with an average amount of daylight to a classroom with maximum daylight, his or her learning rate would be expected to increase by 11% (or by 21% from no daylight to maximum daylight).

- *There was no teacher assignment in the original results.*
- *The daylighting effect does not vary by grade.*
- *Physical conditions in the classroom do not appear to affect student attendance.*

  When student attendance is used as a proxy measurement of student health, there is not an obvious connection between the physical classroom characteristics considered and student health.

- *There are certain physical classroom characteristics teachers most prefer.*

  Teachers had an almost universal desire for more space, a good location, quiet environment, lots of storage and water in the classroom. Windows, daylight and views were desirable but were not driving preferences. Environmental control was also important.

- *Of many variables studied, only daylighting showed a strong correlation to improved learning.*

  A wide range of factors potentially affect student test scores, but of the physical variables studied (including classroom type, HVAC type, operable windows and daylighting) only daylighting showed a strong and consistent correlation to improved standardized test scores. All these results were observed with 99.9% statistical certainty.

- *Overall, these reanalysis efforts affirm that the effect of daylight on student performance is highly significant.*

  Such consistent results present a powerful argument that there is a valid and predictable effect of daylighting on student performance. The addition of more information to the statistical models did very little to change the predicted impact of daylight on student performance.

OUTCOMES

- *Distribution and publication of findings.* Since publication in February 2001, the full report has been downloaded more than 5,500 times from the Institute's public PIER website, and a summary version has been downloaded more than 4,100 times. In addition, the study's methodology and findings have been widely published in key industry journals, such as *ASHRAE Journal* and *IESNA Journal.*

- *LAUSD/CHPS.* This study's findings contributed to the Los Angeles Unified School District's decision to adopt the Coalition for High Performance Schools (CHPS) guidelines as a standard for their district, which will result in increased use of daylighting in their new schools.
- *California utilities are promoting the project's findings.* PG&E's Pacific Energy Center hosted a training class for design professionals in April 2003, titled "Lighting for Schools" communicated results from Daylighting in Schools Reanalysis study and Healthy Schools study.

Healthy Schools: Daylighting, Lighting, and Ventilation

This project was designed to extend the "Reanalysis Report" described above. The researchers selected the Fresno Unified School District as its study participant, and collected and analyzed data during the 2001–2002 school year from 450 classrooms at 36 school sites; the study included 8,500 children in grades 3 to 6. This study participant was significantly different from the previous participant in several key areas: no skylights resulting in less diversity in daylighting strategies, a valley climate rather than coastal climate, and a larger proportion of lower income and immigrant children within the district.

FINDINGS & CONCLUSIONS

- *The Daylight Code variable used in the previous schools studies was <u>not</u> significant in predicting student performance for Fresno.*

  The holistic Daylight Code had the least explanatory power of the variables considered, and lowest significance level when tested in a model similar to the Capistrano study. Thus, the researchers could not replicate the Capistrano findings based on a similar model structure.

- *The window characteristics have a great deal of explanatory power relative to student performance.*

  Variables describing the physical conditions of classrooms, most notably the window characteristics, were as significant and of equal or greater magnitude as teacher characteristics, number of computers, or attendance rates in predicting student performance. Of all the types of physical characteristics of classrooms considered in the study, the group of window characteristics seemed to be the most consistent and robust in explaining student performance.

- *The visual environment is extremely important for learning.*

  View: The importance of a window view was one of the most consistent findings of all models tested.

  Glare: Sources of glare from windows negatively impact student learning.

  Sun: Direct sun penetration into classrooms, especially through unshaded east or south facing windows, is consistently associated with negative student performance, likely causing both glare and thermal discomfort.

Control: When teachers do not have control of their windows via blinds or curtains, student performance is negatively affected. Blinds or curtains allow teachers to control the intermittent sources of glare or visual distraction through their windows.

- *The acoustic environment is extremely important for learning.*

  Situations that compromise student focus on the lessons at hand, such as reverberant spaces, annoying equipment sounds, or excessive noise from outside the classroom, have measurable association with lower learning rates.

- *Poor ventilation and indoor air quality appear to negatively affect student performance.*

  However, in FUSD these issues are almost hopelessly intertwined with thermal comfort, outdoor air quality and acoustic conditions. Teachers often must choose to improve one while making other aspects of the classroom worse.

- *Some classrooms with a high Daylight Code are performing extremely well in Fresno.*

  Classrooms with a combination of ample view and no window glare or sunlight penetration are associated with 15% to 25% improvement in student learning rates, comparable to the findings of the Capistrano study.

- *Operable windows were not found to be associated with better student performance in Fresno.*

  In many statistical models that we tested operable windows were found to be associated with negative student performance. On the other hand, lack of teacher control of the ventilation was found to be positively associated with student performance. This implies that continuous mechanical ventilation may be preferable to reliance on mechanical or natural ventilation in Fresno, perhaps due to the city's high incidence of air pollution, dust, and asthma**.**

OUTCOMES

- *"Windows and Classrooms: A Study of Student Performance and the Indoor Environment,"* a report describing the project methodology, data collection, analysis, findings and conclusions, and potential energy savings.
- *California utilities are promoting the project's findings.* PG&E's Pacific Energy Center hosted a training class for design professionals in April 2003, titled "Lighting for Schools" communicated results from Daylighting in Schools Reanalysis study and Healthy Schools study.

Daylighting and Retail Sales: Replication Study

A 1998 study by Heschong Mahone Group found that, for the retail chain studied and all other things being equal, stores with skylighting experienced up to a 40% increase in sales over those without skylighting. The objective of this new project was to validate the previous findings by conducting a replication study and to further explore the impacts of daylighting and other indoor environmental characteristics on sales performance. The retail participant in this new project had 74 sites in California appropriate for the study, including 23 daylit sites. The study period was from retail activity 1999 through 2001.

FINDINGS & CONCLUSIONS

- *Daylit stores in this chain experienced an average of 0% to 6% increase in sales compared to non-daylit stores.*

  The replication model did not find that the variable "daylight yes/no" predicted greater sales in daylit stores. However, the more detailed "daylight hours per year" model found that there was a significant dose/response relationship between number of daylight hours per year and the magnitude of the increase in sales, once the size of the parking area for each store was considered.

- *Daylight was found to be as reliable a predictor of sales (as indicated by the partial R^2 for the variables) as other more traditional measures of retail potential, such as parking area, number of local competitors, and neighborhood demographics.*
- *During the California power crisis of 2001, when the chain operated its stores at half lighting power, its daylit stores had an average 5.5% increase in sales relative to its non-daylit stores.*

  The magnitude of the effect varied with the two time periods studied. During the 10-month period of the power crisis, when all stores (both within the chain and competitors' stores) operated their electric lights at about half power, the average daylighting effect was found to be the highest, alternatively estimated at +5.7% (log model) or +5.2% (linear model). During the previous 24-month period, when there was less difference in net illumination levels between daylit and non-daylit stores, the average daylight effect was found to be less, at +1.1% (log model) or –0.3% (linear model).

- *Along with an increase in average monthly sales, the daylit stores were also found to have 1% to 2% increase in the number of transactions per month.*
- *Stores with the most favorable daylighting conditions had a 40% increase in sales compared to non-daylit stores, consistent with the findings of the 1998 study.*

  A bound of a theoretical daylight effect for this chain was detailed. For individual stores in this study with the most favorable daylighting conditions (longest hours of daylight, ample parking areas) the daylighting effect was found to be on the order of 40%. This upper bound is consistent with the previous retail study findings.

- *No seasonal patterns to this daylight effect were observed.*

  The relationship between increased sales and seasonal availability of daylight was examined in models that compared the change in performance between a summer month (July) and a winter month (January). No seasonal variation in the models was detected.

OUTCOMES

- *"Daylight and Retail Sales: Replication Study,"* a report that describes the project methodology, data collection, analysis, findings and conclusions, and potential energy savings.

- *Title 24.* The strength of the original retail study findings helped pave acceptance of the Title 24 code proposal to require skylights with integrated controls in some building types (this code proposal is described in the Element 5 section of this report).
- *National retail chains.* Over a dozen large national retail chains are known to be currently building skylit stores or developing prototypes to investigate how skylighting could best be applied to their format. In addition, in 2003 the head of store planning for a national department store corporation and seven other major retailers have consulted Heschong Mahone Group for advice on including skylighting in their stores. The PIER research greatly facilitates their discussions as a national leader and resource on daylighting with market players considering daylight designs.
- *California utilities are promoting the project's findings.* PG&E's Pacific Energy Center hosted a training class for design professionals, titled "Daylighting Basics for Lighting Designers and Electrical Engineers," which included a presentation of E2's results.

Healthy Offices: Daylighting, Lighting and Ventilation

This project carried forward earlier studies on the interaction of daylighting and productivity by extending those inquiries to office buildings. The basic hypothesis was that daylight has a positive influence on the performance of office workers.

The research team collected information about the environmental conditions in each office workers' cubicle and surrounding areas. They carried out two distinct studies, a Call Center study and a Desktop study. The Call Center study used pre-existing metrics to correlate performance data from 100 employees to indoor environmental conditions. The Desktop study used individual performance data collected from 201 employees via short computerized tests in daylit and non-daylit environments. Both approaches involved collecting environmental data for use in the analysis, including air temperature, ventilation, view, daylight and electric light levels.

FINDINGS & CONCLUSIONS

- *Daylight illumination levels were significant and positive in predicting better performance on a test of mental function and attention.*

  The Backwards Numbers test is widely accepted in psychological research as a valid test of mental function and attention span. An increase in daylight illumination levels from 1 to 20 footcandles resulted in a 13% improvement in performance in the ability to instantly recall strings of numbers.

- *Daylight illumination levels were <u>not</u> significant for the visual acuity tests or long-term memory test.* Daylight illumination levels were found to have an association with a slight decrease in Call Center performance for one of three models.

  Daylight illumination was not found significant in any of the other models considered, with the exception of the November daily model for the Call Center, where an increase in daylight illumination from 1 to 20 footcandles was found to be associated with a 6% decrease in performance, or a 23-second increase in daily average call handling time.

- *An ample and pleasant view was consistently associated with better office worker performance.*

A better view was the most consistent explanatory variable associated with improved office worker performance, in six out of eight outcomes considered. Workers in the Call Center were found to process calls 6% to 12% faster when they had the best possible view versus those with no view. Office workers were found to perform 10% to 25% better on tests of mental function and memory recall when they had the best possible view versus those with no view.

- *Glare from windows was associated with decreased office worker performance.*

  In the Desktop study, the greater the glare potential from windows, the worse the office worker performance was on three mental function tests, decreasing performance by 15% to 21%.

- *Ventilation and indoor air temperature varied in their impacts on worker performance.*

  In the analysis of Call Center performance on an hourly basis, increased outside air delivery to the center was associated with improved performance for the workers. In addition, in both the hourly and the daily Call Center analysis, a fully open floor register, which increases local ventilation rates for individual workers, was found to be associated with 3% to 10% faster performance by those workers than those that had their fully closed. In the Desktop study, workers who left their floor registers full opened performed 17% better on one test of mental function, while their performance was worse for two tests of visual acuity and dexterity. Local ventilation rates in the SMUD Customer Service Center are highly complex, and would require more detailed study to understand the implications of these findings.

  Indoor air temperatures stayed within comfort range throughout both studies, varying by only 6°F to 8°F. Increases in local air temperature by 2°F were found to be associated with improvements in worker performance in the Call Center and on the long term memory test, but a decrease in performance on one test of visual acuity. Indoor air temperature is also a function of ventilation rates, supply air temperatures, and local solar radiation effects, and so is likely to be confounded by interactions with these other variables. Further study would be required to isolate these interactive effects.

- *The natural log of illumination and the daylight illumination level of the previous hour had the best fit in predicting performance.*

  In various models tested, the natural log of both daylight and electric light illumination levels was found to have the best fit in the models of both Call Center and office worker performance. In addition, for the Call Center November hourly models, a one-hour time lag of daylight illumination levels was found to provide the best model fit, even though this explanatory variable was not found significant in the final model. This implies that illumination levels can be expected to have dimensioning effects as they increase in intensity, and that any effects on human performance are likely to have a physiological component (delayed effect) in addition to a visual component (instantaneous effect).

- *Physical comfort conditions were an important component of models predicting office worker performance.*

  The physical comfort conditions measured at employees' workstations were found to provide important explanatory information about their performance. The combination of physical comfort conditions considered—illumination, view, ventilation and temperature—typically provided one-eighth to one-third of the explanatory power of the models, while demographic information provided the remaining two-thirds to seven-eighths of the models' explanatory power.

- *Office worker self reports of better health conditions were strongly associated with better views.*

  Those workers in the Desktop study with the best views were the least likely to report negative health symptoms. Reports of increased fatigue were most strongly associated with a lack of view.

OUTCOMES

- *"Windows and Offices: A Study of Office Worker Performance and the Indoor Environment,"* a report that describes the project methodology, data collection, analysis, findings and conclusions, and potential energy savings.
- *California utilities are promoting the project's findings.* PG&E's Pacific Energy Center hosted a training class for design professionals, titled "Daylighting Basics for Lighting Designers and Electrical Engineers," which included a presentation of E2's results.

Estimated Statewide Energy Impacts

Based on a 10% first year penetration with an increase of 1% per year over the next 10 years the following savings are achievable from the combination of daylighting and lighting controls:

- *Schools* – first year electricity savings of 330 MWh, 10 year cumulative electricity savings of 23,595 MWh equal to a cumulative cost savings of $3 million.
- *Offices* – first year electricity savings of 2,483 MWh, 10 year cumulative electricity savings of 177,535 MWh equal to a cumulative cost savings of $24 million.
- *Retail* – first year electricity savings of 7,867 MWh, 10 year cumulative electricity savings of 562,467 MWh equal to a cumulative cost savings of $77 million.
- *Total* - total statewide benefits for these three sectors - first year electricity savings of 10,466 MWh, 10 year cumulative electricity savings of 748,397 MWh equal to a cumulative cost savings of $103 million.

INTEGRATED DESIGN OF LARGE COMMERCIAL HVAC SYSTEMS (ELEMENT 3)

This research element focused on building-science solutions to support successful system integration and improved efficiency and performance of HVAC systems in large buildings (100,000 ft^2 and larger).

Objective

The Element's overall objective was to identify opportunities to improve the air-side energy efficiency of large HVAC systems through design solutions and strategies for California buildings over 100,000 ft^2. A specific technical objective was to develop guidelines for design that can improve the overall HVAC efficiency of those facilities by 25%.

Findings & Conclusions

- *Variable-air-volume (VAV) reheat systems serve approximately 50% of the large office commercial construction market.*
- *HVAC electricity savings are estimated to be 25%, corresponding to 12% of total building electricity consumption.* Natural gas heating savings are estimated to be 41% of heating energy.
    - Fan energy represents between 20% to 50% of total HVAC electrical energy use, or 10% to 30% of the total building electrical energy usage, which can be more than the chiller energy use. The Design Guide recommendations can reduce the fan energy by 50% or more, achieving total building electrical energy savings on the order of 12%.
    - Electricity savings of approximately 1.5 kWh/ft^2-yr and natural gas savings of 8.5 kBtu/ft^2-yr are predicted for the measures in the Advanced VAV System Design Guide (Design Guide) compared to current standard practice. The corresponding annual utility cost savings are about \$0.20/ft^2 for electricity and \$0.07/ft^2 for gas, based on 2003 PG&E rates.
    - Fan-only peak day electric demand reaches between 0.5 and 1.0 W/ft^2. Following the Design Guide recommendations could provide a modest reduction in demand due to better duct design and lower overall pressure drop, but most of the measures affect part-load efficiency.
- *Most systems operate at part load the majority of the time.* Systems and controls must be designed to be efficient across the full range of operation. This can be achieved by carefully sizing the system components (e.g., terminal units) to make sure they provide comfort and code-required ventilation while limiting the fan and reheat energy at part load. It also requires integrating the controls at the zone to the controls at the air-handling unit and cooling/heating plants to make the system respond efficiently to changes in demand.
- *Key design principles to achieve energy savings identified in Design Guide:*
    1. Reduce design system static pressure.
    2. Employ demand-based static pressure reset.
    3. Use low-pressure plenum returns with relief fans.
    4. Employ demand-based, supply temperature reset to reduce reheat energy and extend economizer effectiveness.
    5. Design fan systems to turn down and stage efficiently.
    6. Optimally size terminal units to balance the energy impacts of pressure drop and minimum air flow control.
    7. Set terminal unit minimums as low as required for ventilation and use intelligent VAV box control schemes to prevent stratification during heating.
    8. Employ demand-based ventilation controls for high-density occupancies.

9. Design conference rooms and other high-density occupancies to provide ventilation without excessive fan energy or reheat.
10. Design 24/7 loads to allow efficient system turn down and use of economizer cooling.

- *Early design issues are most critical.* Optimal performance of the HVAC system depends on the integration of the design with the other building components during the early phases of building design. The Design Guide focuses on the following early design issues to be addressed: integrated design, simulation, system selection, location and size of air shafts, establishment of the return air path, provisions of auxiliary and 24/7 loads, selection of design air-side supply temperature, determination of code ventilation requirements, determination of actual internal loads, and establishment of performance targets.

Outcomes

- *Advanced VAV System Design Guide (Design Guide).* The researchers found that large savings opportunities exist at the design stage. To promote efficient, practical designs that advance standard practice the project team developed the Design Guide the addresses the following areas: early design issues; zone issues; VAV box; ducts and fittings; fan outlet conditions/air handler design; fan type, size and control; coils and filters; and outside air/return air/exhaust air control.

  The Design Guide is targeted to HVAC designers and summarizes the most important data and design recommendations based on the research results. The Design Guide was written to give them reasonable and credible recommendations for creating systems that capture the energy savings and performance opportunities and at the same time feel comfortable that system results will meet client expectations.

- *California utilities are promoting the project's findings.* Element 3 results and Design Guide will be presented at an October 2003 training session at PG&E's Pacific Energy Center. The utilities are considering the PIER results for future Energy Design Resources Briefs.
- *New fan system performance model and industry publishing.* The team developed a new model that more accurately represents fan system performance than the models in current simulation programs. This model is a good match to manufacturer's data and was used along with the monitored fan data to inform many of the Design Guide recommendations.

  Team members published an article about PIER results and the fan model in the May 2003 issue of *HPAC Engineering Magazine* and will present the model at the national ASHRAE conference in January 2004. There has been considerable excitement about the new fan model within the ASHRAE community. In addition, a researcher working on another PIER project is already using the fan model in his simulations, and an EQuest/DOE2.2 software developer has expressed interest in using the fan model in their simulation engine.

- *Title 24.* PIER findings on static pressure reset, sensor location and fan power sizing modified the prescriptive requirements for space conditioning systems in the California 2005 Building Energy Efficiency Standards (Title 24).

Estimated Statewide Energy Impacts

The California Energy Commission predicts large office building construction volume of about 30 million square feet per year over the next ten years, equal to 20% of new construction in California. A reasonable estimate is that about one-half of those buildings will be served by VAV reheat systems. Therefore, the Design Guide will apply to roughly 150 million square feet of new buildings built in the ten-year period between 2003 and 2012.

The researchers applied annual energy savings estimates of 12% combined with a market penetration of 10% of the large commercial office space with VAV reheat systems over each of the next 10 years. This is equal to 5% penetration of all large commercial office space. If the best practices recommended in the Design Guide were implemented, first-year statewide electricity savings are estimated to be 2,220 MWh/yr for new construction. Savings would reach 22,200 MWh/yr at the end of 10 years, and the cumulative electricity savings over that time would be 122,100 MWh equal to a cumulative cost savings of $16.7 million.

First year natural gas savings would be 127,000 therms resulting in a cumulative gas savings over ten years of 6,980,000 therms equal to a cost savings of $5.8 million. The total net energy benefits over ten years to citizens of California would be $22.5 million.

INTEGRATED DESIGN OF SMALL COMMERCIAL HVAC SYSTEMS (ELEMENT 4)

This research project conducted field surveys and short-term monitoring of packaged heating, ventilation and air conditioning (HVAC) systems up to 10 tons per unit and identified problems with equipment, controls, distribution systems, and operation and maintenance practices that lead to poor system performance.

Objectives

The objective was to establish baseline data on the number and type of small commercial HVAC systems, identify the key problems in the efficiency and performance of these units, and create design solutions to address those problems. The specific technical objective was to increase the energy efficiency and functionality of small commercial HVAC systems by 10%.

Findings & Conclusions

- *Small HVAC Systems in California:*
    - Single package direct expansion (DX) air conditioners are the most popular HVAC system type in new construction in the state, cooling about 44% of the total floor space.
    - 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.
    - Units 10 tons and smaller represent about 58% of the total packaged DX cooling capacity in the state.
- *System performance problems are widespread.* The field study consisted of site inspections, occupant interviews and short-term monitoring at 75 sites, which included a total of 215

HVAC units. In addition, the researchers conducted a series of one-time tests on various aspects of the units' operation. The researchers identified a number of problems (% of units) with the HVAC systems, including economizers not operating properly (64%), improper refrigerant charge (46%), fans running during unoccupied periods (30%), fan that cycle on and off with a call for heating and cooling rather than providing continuous ventilation air (38%), low air flow (39%), no outside air (8%), actual fan power 20% greater than Title 24, and simultaneous heating and cooling (8%).

- *These problems impact building electrical energy performance by an estimated 8 % and building natural gas energy performance by an estimated 30%.*
- *The problem of cycling fans and the impact on ventilation rates was not previously documented per our research reviews.*
- *Numerous opportunities exist for improving efficiency.* Opportunities include improved economizer designs for better reliability and control; design features such as thermostatic expansion devices that maintain unit efficiency over a range of refrigerant charge and air flow rates; improved air-side efficiency; on-board fault detection and diagnostic systems; and the use of thermostats appropriate for commercial applications.
- *Equipment manufacturers can improve performance through product design changes and reliability improvements.* Although many installation problems can be corrected during commissioning, and some reliability problems can be corrected during normal operations and maintenance, it may be more effective to address these problems at the product design level. Improved equipment that is actively promoted by energy-efficiency and market transformation programs could reduce energy costs for end-users and increase sales opportunities for manufacturers of small rooftop systems.
- *Reduction in system size on the order of 40% and reduction in annual energy costs on the order of 25% to 30% are possible with simple integrated design strategies.*
- *Key actions designers can take to improve the performance of small HVAC systems include:*
    - 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 air flow based on calculated sensible loads without oversizing. Consider increasing unit flow rate to improve sensible capacity in dry climates.
    - Specify units that meet CEE Tier 2 efficiency standards and incorporate premium efficiency fan motors, thermostatic expansion valves and factory-installed and run-tested economizers.
    - 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 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, air flow rate, and fan power.
- Develop clear expectations about the services provided by HVAC maintenance personnel.

Outcomes

- *Small Commercial HVAC System Design Guide (Design Guide).* The Design Guide provides solutions and recommendations for improving the performance of small commercial rooftop units. This document focuses on actions architects, engineers, and design/build contractors can take to improve the energy efficiency of small HVAC systems, reduce operating costs, and improve indoor comfort and environmental quality.
- *CEE HECAC Initiative.* Element 4 and the New Buildings Institute collaborated with the Consortium for Energy Efficiency (CEE) and their High Efficiency Commercial Air Conditioning Committee (HECAC) to develop a draft national, next-generation performance specification for small commercial, integrated rooftop HVAC systems. This specification is now the basis of ongoing discussions with efficiency program managers as a possible public benefits or utility program requirement.
- *Air-Conditioning and Refrigeration Institute (ARI) Engagement.* Through the CEE effort the project team began direct discussions with the Air-Conditioning and Refrigeration Institute (ARI) to solicit manufacturer feedback and modifications to the spec and to move toward the design of a more advanced unit. The research team developed a brief report (Manufacturers' White Paper) to encourage manufacturers to address some of the problems identified during the course of this project. The ARI has committed to addressing improved performance opportunities through their technical committee and national meetings in late 2003. Members have also offered to participate in the assessment of an advanced unit in the next phase of PIER work.
- *Title 24 – Acceptance Requirements.* Element 4's field findings contributed to the Institute's Nonresidential Acceptance Requirements proposal to the California 2005 Title 24 Standards.
- *Title 24 – Duct Leakage and Insulation.* Element 4's analysis work supported the Nonresidential Duct Sealing and Insulation proposal through PG&E's Codes and Standards Enhancement (CASE) initiative.
- *California utilities are promoting the project's results.* Energy Design Resources (EDR) funded the project team's development of a design brief—an abbreviated version of the Design Guide—which is now published on the EDR website (www.energydesignresources.com). PG&E's Pacific Energy Center hosted a training session in May 2003 to communicate E4's results to design professionals.

Estimated Statewide Energy Impacts

First year savings of 6,942 MWh are expected based on a 10% market penetration. Using an increase of market penetration of 1% per year over the next ten years, the cumulative savings over the next ten years will be 496,360 MWh equal to a cumulative cost savings of $68 million. These calculations use a figure of 39.7 million square feet per year for commercial buildings using packaged units of less than 10 tons (~25% of new commercial construction).

Natural gas savings are estimated to be 97,107 therms first year savings resulting in a cumulative 10 year savings of 6,980,000 therms and a resulting cost savings of $5.8 million.

The total net energy benefits over ten years to citizens of California would be $73.8 million.

Statewide demand savings are estimated at 1,486 kW per year (1.5 MW) based on a first year market penetration of 10%. With an increase in market penetration of 1% per year, the demand savings in year ten is 21.5 MW.

INTEGRATED DESIGN OF COMMERCIAL BUILDING CEILING SYSTEMS (ELEMENT 5)

This Element was designed to fill research information gaps related to the use of skylights in commercial buildings and to develop design protocols that facilitate ceiling-system integration and minimize energy use.

Objectives

This research program consisted of three related projects with distinct objectives:

1. Determine the energy effectiveness of lay-in insulation used with T-bar ceilings.
2. Conduct comprehensive testing of representative skylight U-factors, SHGC, visible light transmission and photometrics to better understand and provide data on the performance of skylights and light wells in commercial buildings.
3. Develop integrated ceiling-system design guidelines for quality lighting (including daylight) and energy savings.

The findings and outcomes for each of these projects is discussed separately below.

Effectiveness of Lay-In Insulation

The researchers surveyed commercial buildings to identify how many have lay-in insulation and what fraction of the original lay-in insulation remains in place, researched application and cost issues of lay-in insulation versus alternative insulation methods, and calculated the energy and energy-cost impacts of these approaches.

FINDINGS & CONCLUSIONS

T-bar ceilings are ineffective as a pressure or infiltration barrier in a building. Therefore lay-in insulation is less effective compared to insulation at a pressure boundary such as a hard ceiling or roof deck. Most field inspections showed that 10% to 40% of the ceiling area had no lay-in insulation. In most situations, it is cost effective to insulate the roof deck rather than use lay-in insulation.

OUTCOMES

- *Title 24.* The study resulted in a recommendation that the California 2005 Title 24 Standards prohibit use of lay-in insulation over suspended ceilings for thermal insulation, except for small spaces under plenums that are taller than 12 ft. The proposal encountered little resistance; the Commission staff has supported it, and adoption is anticipated.

- *California utilities are promoting project's results.* E5 results were presented at a PG&E Pacific Energy Center (PEC) training session in June 2003 titled "Integrated Skylights and Electric Lighting in Commercial Ceiling Systems," and at a November 2002 general training on skylighting design. Also, in June 2002 the PEC hosted a training session on the use of the PIER photometric files. The project results were also included in spring 2003 and fall 2002 training sessions on the SkyCalc program by Heschong Mahone Group at Southern California Edison's Customer Technology Applications Center (CTAC), and will likely continue to be part of ongoing presentations. The utilities are considering the PIER results for future Energy Design Resources Briefs.

Comprehensive Skylight Testing

The researchers developed new test protocols and conducted tests on various skylight and light-well combinations that are common in commercial construction. There were three separate sets of testing activities for U-factor, SHGC and visible transmittance. The project team also developed photometric data for nine skylights with different light-well geometries.

FINDINGS & CONCLUSIONS

- *NFRC test methods for U-factor need to be updated for projecting skylights.* The current method of using a flat CTS (calibration transfer standard) results in erroneous results. Projecting skylights (domed glazing, arch or compound parabolic glazing, and pyramidal glazing) can be tested using the prior area weighted method for measuring the air film resistances. Also, building simulation algorithms should include the capability to account for the ratio of surface area to projected area. Currently simulation models assume this ratio is always 1.0. Making this change would allow better modeling of the air film heat transfer coefficients on projecting skylights.
- *The research confirmed the benefit of light wells and insulation on light wells for reducing solar heat gain through the skylight system.*
- *The effective visible transmittance (EVT) of projecting (dome) skylights stays nearly constant over a range of solar angles,* whereas the EVT of flat-glass skylights rapidly drops off as solar elevation decreases. This is significant because daylight is most needed at times when the sun angle is low. In DOE-2 and other simulation programs, it would be more accurate to model projecting skylights with a constant transmittance instead of modeling them as if they were flat-glass skylights. The study also determined that the ASTM D1003 test method for haze provides an adequate method for predicting the diffusion of skylight glazing.
- *The proposed National Fenestration Rating Council (NFRC) method of rating the transmittance of tubular skylights overestimates the transmittance of these devices* for most of the year and creates an uneven playing field between tubular skylights and projecting unit skylights.
- *Photometric data can be produced for skylight systems.* This project conducted new photometric tests and created the associated files for 22 skylight/light-well combinations. Almost all electric light fixtures sold in the United States have a

photometric report, which allows one to calculate how the light fixtures distribute light in a room, but until now, measured photometric information was not readily available for skylights.

OUTCOMES

- *Title 24.* These studies led to a proposal for a revised definition of the daylit zone and a proposal for a revised spacing criterion for skylights in the 2005 Title 24 Standards. Adoption of the proposal will result in improved daylighting quality.
- *Improved modeling of projecting skylights.* The EVT of projecting skylights can be measured by the test procedure developed for this project, but cannot be measured by the standard visible transmittance test procedure currently used by the NFRC. The current NFRC method of rating transmittance of skylights can only rate flat skylights; this places projecting skylights at a disadvantage as they cannot quality for an Energy Star rating. This is unfortunate because in many cases the projecting skylights have better visible light transmission characteristics than flat skylights for low sun angles.
- *Skylight rating systems.* Element 5's (E5's) findings have been presented to the NFRC. As a result, NFRC is considering reevaluating their rating system for tubular skylights (also known as tubular daylighting devices, or TDDs). Also, the U-factor results may have some effect on how NFRC rates skylights. E5 staff has also contacted the developers of SkyVision and identified that their product may solve the modeling problem. The project leader also provided Energy Star program staff with the research and modeling results.
- *Photometrics.*
    - *Data for lighting designers.* Lighting designers now have the same predictive tools for designing with skylight/light-well combinations as they do for electric lighting. The team has applied the photometric data to the IESNA's LM63–1995 format that can be easily integrated into existing lighting software tools. Lighting Analysts, a lighting software manufacturer, intends to include the photometric files in their AGI-32 software. Other lighting software manufacturers, including the producers of SkyVision, have indicated interest in incorporating PIER photometric results in their products.
    - *Development of a new cost-effective method and facility for testing the photometrics of skylights that is accurate and repeatable.* Some skylight manufacturers purchased additional photometric testing services and will use the data to market their skylights to major clients. One skylight manufacturer has set up a photometric test facility based upon the design developed in this PIER project. They intend to use the test facility for product development and marketing materials (photometric files).
    - *IESNA Test Standards.* E5 submitted this test methodology to the IESNA Computer Committee for adoption by IESNA as part of their test standards. The IESNA LM63 "standard Format for Electronic Transfer of Photometric data" should be updated to contain predefined keywords so that skylight-specific information is contained in the file header. This allows one to make lighting predictions with the photometric files for other locations and other times of the year than when the test data was collected.

Integrated Ceiling System Design Guidelines

The project team conducted research and analysis to identify best practices for integrating skylight/light-well systems with suspended ceilings. The team built on the findings of the lay-in insulation research and comprehensive skylight testing, and conducted additional research, including visiting manufacturers, analyzing the issues that drive ceiling system specification, researching applicable codes, and investigating likely combinations of building components for existing interconnection protocols and standards.

FINDINGS & CONCLUSIONS

- *Splayed light wells allow skylights to be spaced further apart, thereby reducing installation costs and minimizing risks associated with roof penetrations.*
- *Modular light wells are desirable due to cost and performance predictability and better finish appearance.*
- *Light wells substantially reduce the solar heat gain through the bottom of the light well, but a substantial fraction of heat goes sideways through the light well.*
- *There is a market interest and demand for modular skylight products and design recommendations.*

OUTCOMES

- *Design Guidelines for Skylights with Suspended Ceilings (Design Guidelines).* The Design Guidelines provides designers and project managers with guidelines for incorporating skylights with light wells in commercial buildings. It discusses the design process, implications of different design solutions, and code- and performance-related issues. Following the recommendations of the Design Guidelines will result in the effective installation of skylight systems that provide optimal energy performance and superior lighting quality.

  Designers can use the information in the Design Guidelines to create a custom skylight/light-well system for their projects. In addition, the Design Guidelines' valuable coordination and integration information will help facilitate the designers work with other construction professionals. For the manufacturer, the Design Guidelines communicate system design, component requirements, code and performance metrics, and market information about modular skylight systems and the market benefits of providing such a product.

- *Skylight manufacturers.* As a result of E5's studies, several skylight manufacturers are considering product design modifications, and one manufacturer is building a prototype modular light well.
- *California utilities are promoting project's results.* E5 results were presented at a PG&E Pacific Energy Center (PEC) training session in June 2003 titled "Integrated Skylights and Electric Lighting in Commercial Ceiling Systems," and at a November 2002 general training on skylighting design. Also, in June 2002 the PEC hosted a training session on the use of the PIER photometric files. The project results were also included in spring 2003 and fall 2002 training sessions on the SkyCalc program by Heschong Mahone

Group at Southern California Edison's Customer Technology Applications Center (CTAC), and will likely continue to be part of ongoing presentations.

Estimated Statewide Energy Impacts

Productivity and Interior Environments (Element 2 above) addresses daylight energy savings associated with an increased use of skylighting and lighting controls in California.

The potential market specific to modular skylight-well products includes the building types that can take advantage of daylight benefits and that require the use of suspended ceiling systems. These building types - low-rise commercial buildings such as offices, retail spaces, grocery stores, and schools - make up 54% of all new and retrofit construction in California. With an estimated total annual commercial construction market of 156 million ft^2 in California, this results in a potential market of the target building types of 84.8 million ft^2 a year. Of the potential target buildings, 16.5 million ft^2 a year are constructed with T-bar ceilings located under the roof and could be impacted by the use of the Design Guidelines.

Based on this market size for the Design Guidelines, first year electricity savings of 1,614 MWh are expected based on a 10% market penetration. Using an increase of market penetration of 1% per year over the next ten years, the cumulative electricity savings over the next ten years will be 115,429 MWh equal to a cumulative cost savings of $16 million.

INTEGRATED DESIGN OF RESIDENTIAL DUCTING & AIR FLOW SYSTEMS (ELEMENT 6)

Poorly performing residential duct systems installed in unconditioned space can have a significant effect on energy use and comfort. This research project was designed to develop realistic alternatives that would bring the ductwork within the conditioned building envelope.

Objective

This Element's objective was to provide information sufficient to allow the Commission to evaluate means of including ducts in homes' conditioned space for future revisions of the energy code, and to inform builders about the construction changes needed to build homes with ducts in conditioned space.

Findings & Conclusions

- *Building houses with ducts in conditioned space is technically feasible* and can be done at fairly small cost increments with valuable returns in energy savings and delivered comfort.
- *Three approaches are recommended for constructing California houses with ducts located in conditioned space:* 1) a "Dropped Ceiling" within portions of the house to contain the ductwork; 2) a "Cathedralized Attic" design that moves the insulation to the roof plane and removes attic venting, creating a semi-conditioned space above the ceiling; and 3) the Plenum Truss approach, which uses a modified scissors truss to create space for the ducts between the ceiling and the bottom chord of the truss that is then inside the conditioned space.
- *Cost impact to the builder is 0% to 3% of construction costs.* Of the three recommended approaches, the Dropped Ceiling and Cathedralized Attic designs will result in the lowest construction cost increase, ranging from zero to 1% respectively. The Plenum Truss approach is estimated to add between 1.5% and 3% to construction costs. In

addition, the three approaches may, in some cases, allow the heating and cooling equipment to be downsized, which could offset some of the construction cost increases or even result in an overall decrease in construction costs.

- *Significant energy savings and energy-cost savings can be achieved by building houses with ducts in conditioned space.* The approach used—Cathedralized Attic, Dropped Ceiling, or Plenum Truss—has less of an impact on savings than does the house size or the climate.
    - Estimated annual electric energy savings range from a low of 1% (176 kWh) for a townhouse built with the Plenum Truss design to a high of 19% (5420 kWh) for a single-story detached house built with the Dropped Ceiling design.
    - Annual net energy cost savings per housing unit range from no savings for a townhouse using the Cathedralized Attic approach to a high of $1,285 for a two-story detached house using the Dropped Ceiling approach.
    - Annual savings vary greatly by climate zone and on whether the house uses normal leakage ducting (22% of system airflow) or a low leakage duct system (6% of system airflow).
    - Heating energy increases slightly with the Cathedralized Attic approach and, to a lesser extent, the Plenum Truss approach. This is due to the increase in insulated envelope area that results from moving the insulation up to the roof (Cathedralized Attic) or up to an intermediate location between the attic floor and roof (Plenum Truss).
    - All three approaches are cost effective in almost all housing types and climate zones with normal leakage ducting. For low duct leakage houses, the Dropped Ceiling approach is cost effective in most of the single family and some of the townhouse types, the Cathedralized Attic is only cost effective in some of the single family types, and the Plenum Truss approach is not cost effective.

Outcomes

- *Home Builders Guide to Ducts in Conditioned Space (Builder's Guide).* The Builder's Guide provides builders, contractors and subcontractors with sufficient detail so that they can modify their existing house designs and build them successfully with ducts in conditioned space. The Builder's Guide describes construction techniques, provide technical diagrams, address market barriers, and give summarized cost and savings information.
- *Market barriers report.* The researchers developed a report that identifies barriers to the market acceptance of building homes with ducts in conditioned space, and provides strategies that may be used to overcome these barriers.
- *Code official's guide.* This document provides technical information that builders can present to a code official when requesting a variance to build a house that follows one of the recommended approaches to putting ducts in conditioned space.
- *Homeowners' benefits.* This is a brief marketing piece that explains to homeowners the benefits of placing ducts in conditioned space.

- *Technical information report.* This summarizes the recommended approaches and describes associated costs, savings and market barriers. This report was specifically developed as a resource for the Commission and technical audiences.
- *Industry Distribution.* The Building Industry Institute (BII), a program of the California Building Industry Association, has expressed interest in incorporated E6's findings in a BII protocol on ducts in conditioned space, and may publish E6's Guide for Builders on their website. DOE's Building America program plans to distribute the Guide for Builders through their widely used website on residential construction.

Estimated Statewide Energy Impacts

First year savings of 266 MWh and ten year cumulative savings of 178,768 MWh are expected from the adoption of the ducts in conditioned space building techniques. There is a minor ten year penalty in gas consumption of 364,000 therms. These numbers are based on the California new construction market of 155,000 houses per year and a 0.1% penetration the first year ramping to a 10% penetration in year 10. The savings estimates are based on the current averages of 30% of housing built with low leakage ducts and 70% built with normal leakage ducts. The ten year cumulative electric energy savings is $23.2 million with a small increase in gas use equal to $328,000 resulting in a net energy cumulative savings of $22.9 million.

CALIFORNIA OUTDOOR LIGHTING BASELINE ASSESSMENT (ELEMENT 7)

This research project was the first major study of outdoor lighting in California.

Objective

This Element's objectives were to fill gaps in knowledge about outdoor lighting in California by identifying current design practices and estimating the energy demand and consumption of current statewide practices, providing outdoor lighting baseline information to inform the 2005 Title 24 Standards development, and providing a framework for future investigations into outdoor lighting practices in California.

Findings & Conclusions

- *The statewide commercial and industrial outdoor lighting annual energy consumption is estimated to be 3,067 GWh.* This is roughly 1.35% of the total statewide annual energy consumption of 227,087 GWh reported for 2001 by the California Independent System Operator (ISO).

  Commercial outdoor lighting accounts for 3% of the California nighttime energy use of 101,773 GWh in 2001. The maximum peak demand from commercial outdoor lighting is 809 MW, and occurs in the winter from 7 PM to 8 PM. This winter peak is slightly higher than the summer peak due to the operation of winter resorts (closed during the summer) and due to school recreation areas not in use in the summer.

- *The commercial outdoor lighting peak demand is 2.63% of the total California system load of 30,788 MW for the peak hour, calculated using California ISO data (the peak demand in February 2002, for the hour ending at 8 PM).*
- *This research resulted in extensive data on the types of lamps and fixtures installed at each site.* For example, 57.7% of all outdoor lamps in apartments and condominiums are compact

fluorescent lamps. Incandescent lamps represent 30.8% of all lamps installed across all functional use areas (parking lots, walkways, security areas, etc.). Approximately 48% of parking lots have high pressure sodium lamps. This body of information provides a valuable snapshot of the commercial and industrial outdoor lighting in California, incorporating data from a range of business types and geographic areas.

- *The California Outdoor Lighting Baseline Assessment provides extensive data on lighting power density (LPD) levels by building type, functional use area and lighting zone.* This data is likely to prove valuable to researchers and analysts who wish to evaluate the potential energy savings from improving commercial outdoor lighting design practices.

Outcomes

- *Outdoor lighting assessment method and tool.* The researchers developed an Outdoor Lighting Assessment Tool, which consisted of various modules essential to conducting an effective survey. This included classroom and field training of surveyors; instrumentation including a camera, a light meter and attachments, and a measuring wheel; and an Onsite Survey Manual with luminaire and lamp information, survey procedures, and a luminaire catalog; and an Onsite Survey Instrument that provided a format for recording the required daytime and nighttime onsite data.
- *Informing standards.* The results of this survey will provide information for ongoing discussions of program and code options for addressing outdoor lighting energy use. The research has already influenced nationwide discussions of exterior lighting. Some examples follow.
    - *California outdoor lighting standard.* Work is currently underway to develop a Title 24 outdoor lighting standard for California, informed in part by Element 7's research.
    - *Model Lighting Ordinance.* A consortium of lighting experts and entities, lead by the International Dark-Sky Association (IDA) is developing a Model Lighting Ordinance (MLO). As the Commission develops a scientific basis for outdoor lighting regulation, based in part on Element 7's research, the MLO Task Force will incorporate results as appropriate to the outdoor lighting section of their national model ordinance.
    - *Washington State and City of Seattle outdoor lighting standards.* This project's findings are being reviewed to expand category definitions and characteristics for exterior lighting requirements.
    - *Lighting industry design guidelines and standards.* Team members are involved in IESNA and ASHRAE and will present E7 information for consideration to technical committees regarding outdoor lighting energy baselines and the predominance of specific equipment. This information will provide input to key lighting design guides such as the IESNA handbooks and recommended practice guidelines, the ASHRAE/IESNA 90.1 lighting standards, and the Advanced Lighting Guidelines.
- *Repeatable methodology.* This research has created an excellent foundation for more specific studies by providing a repeatable methodology for targeted data collection and by establishing a set of results from which to design more specific inquiries.

Estimated Statewide Energy Impacts

Statewide energy savings scenarios were not a part of the technical results. Quantifying outdoor lighting's energy consumption and demand provides the state of California and utilities with a foundation for establishing regulatory and voluntary approaches to modifying energy use in this sector.

Abstract

The *Integrated Energy Systems: Productivity and Building Science Program* is comprised of six research projects that focus on integrated design topics to save energy, improve the indoor environment, and reduce operating and maintenance costs. *Productivity and Interior Environments* consists of four studies that examine the impacts of daylighting and other indoor environmental factors on occupant performance and organizational productivity in schools, stores and offices. *Integrated Design of Large Commercial HVAC Systems* quantifies problems and identifies solutions to variable-air-volume HVAC system performance in large commercial buildings. *Integrated Design of Small Commercial HVAC Systems* identifies common system performance problems and their solutions for small packaged rooftop HVAC systems. *Integrated Design of Commercial Building Ceiling Systems* analyzes the effectiveness of lay-in insulation over suspended ceilings, tests skylight performance, and develops an integrated ceiling-system design for using skylights and light wells with suspended ceilings. *Residential Ducting and Air Flow Systems* develops guidelines for building homes with ducts in conditioned space. Finally, *California Outdoor Lighting Baseline Assessment* is the first comprehensive study of outdoor lighting practices in California.

Some of this program's key products are:

- Reports on the effect of daylighting and other indoor environmental factors on human performance and organizational productivity
- Design guidelines for large commercial HVAC systems
- Design guidelines for small commercial HVAC systems
- Guidelines for designing modular skylight/light-well systems for suspended ceilings
- Guidelines for builders and information for code officials and homeowners about placing residential ducts in conditioned space
- An extensive database of outdoor lighting conditions and practices in California

Key words: productivity, energy efficiency, indoor environment, daylight, skylight, outdoor lighting, integrated design, HVAC, residential duct

1.0 Introduction

This report presents the results of research performed between August 2000 and August 2003 as part of the *Integrated Energy Systems: Productivity and Building Science Program.* This research was supported by the California Energy Commission's (Commission) Public Interest Energy Research (PIER) Program.

The *Integrated Energy Systems: Productivity and Building Science Program,* managed by New Buildings Institute (Institute), focused on building-related energy efficiency advances for the public benefit. The six research elements in this program were designed to fill gaps in the existing body of building science knowledge, and address topics that have long been recognized as having untapped potential to save energy, improve the indoor environment for occupants, and reduce operating and maintenance costs for building owners.

1.1. Team

Integrated Energy Systems: Productivity and Building Science Program was managed by Cathy Higgins, Program Director of New Buildings Institute, Inc. The Commission's Contract Manager was Donald Aumann. The research was directed by the people and organizations listed below.

1.2. Elements

In addition to a program management/market connections element (Element 1) managed by New Buildings Institute, the program consisted of six research elements:

- *Productivity and Interior Environments* (Element 2, or E2), led by Lisa Heschong, Heschong Mahone Group
- *Integrated Design of Large Commercial HVAC Systems* (Element 3, or E3), led by Erik Kolderup, Eley Associates, Inc.
- *Integrated Design of Small Commercial HVAC Systems* (Element 4, or E4), led by Pete Jacobs, Architectural Energy Corp.
- *Integrated Design of Commercial Building Ceiling Systems* (Element 5, or E5), led by Jon McHugh, Heschong Mahone Group
- *Integrated Design of Residential Ducting and Air Flow Systems* (Element 6, or E6), led by Roger Hedrick, GARD Analytics, Inc.
- *California Outdoor Lighting Baseline Assessment* (Element 7, or E7), led by Sam Pierce and Matt Brost, RLW Analytics, Inc.

1.3. Organization Chart

The program was managed by a team of top energy efficiency and building science experts and researchers. Figure 1 shows the structure of the research program and responsibilities for major elements and management.

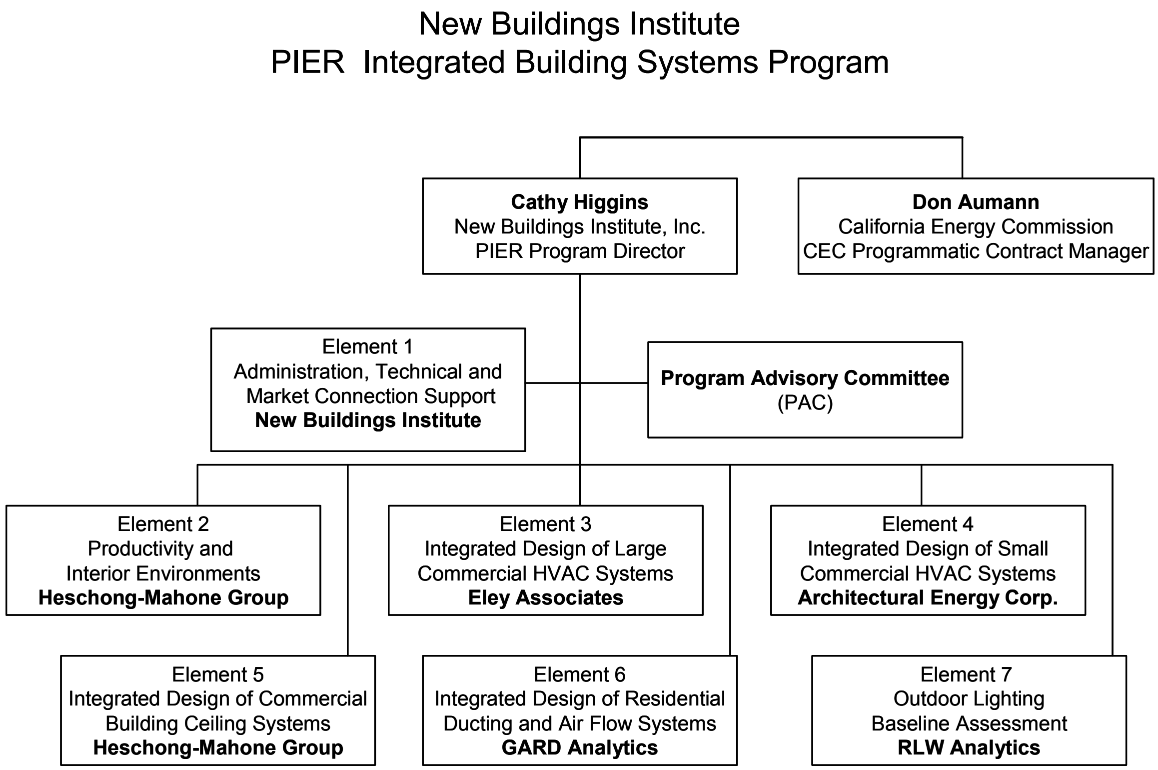

Figure 1: PIER Program Team Organization Chart

1.4. Report Organization

Each Element in this program investigated a distinct topic related to advancing our knowledge of building science. Accordingly, this report is organized in six distinct sections, one for each Element.

The Element sections contain a summary of the Element objectives, followed by the approach and technical outcomes per key project area. Market connections, conclusions, recommendations and statewide energy impact estimates are described at the end of each Element's section. The research results in the form of guidelines and technical reports are attachments to this report.

Elements 2 and 5 consisted of a number of separate research projects, each with conclusions specific to those projects. Therefore, for these two Elements the conclusions section is subdivided by project. Elements 3, 4, 6 and 7 consisted of interrelated research projects that built on each other and led to one final product or set conclusions for the element.

This final report summarizes the key outcomes of this multi-year, multi-project research effort. People who are interested in learning more about specific methodologies, outcomes, conclusions and recommendations are encouraged to read the original documents on which this final report is based. The original documents are listed under "Products" in each project section and in the Attachments section at the end of this report; they are organized into two sections:

- "Summary" attachments, which include final products such as design guidelines and final research reports; and

- “Technical” attachments, which include technical reports, survey methods and databases.

2.0 Productivity and Interior Environments (Element 2)

2.1. Introduction

This Element consisted of four research projects addressing the central theme of productivity and interior environments. The four projects dealt with three market sectors: schools (Projects 2.2 and 2.4), retail (Project 2.3), and offices (Project 2.6). Research into manufacturing (Project 2.5) was cancelled during Program Year 2 because of difficulty in locating an appropriate participant within the timeline.

The overall technical goal was to quantify the impacts of the indoor environment on occupant performance and/or organizational productivity. Specifically, the project sought to:

- Establish actual measurements of the productivity and energy values of daylighting in the operation of commercial buildings.
- Establish and refine a field methodology that can make a compelling association between human performance criteria and building characteristics. Validation and quantification of the productivity value of energy efficiency measures will motivate the inclusion of these measures in buildings.
- Consider how the provision of daylight relates to other indoor environmental quality issues, such as thermal comfort, visual comfort, view, ventilation, and acoustic quality; and consider the potential separate contribution of those conditions to human performance.

The projected outcome from *Productivity and Interior Environments* is a reduction in building lighting energy use due to an increased use of daylighting by establishing and refining a field methodology that successfully links human performance to building characteristics.

2.1.1. Project Team and Technical Advisory Group (TAG)

Element 2 was led by Lisa Heschong of Heschong Mahone Group (HMG) with support from Cynthia Austin, Lynn Benningfield, Jackie Burton, Sean Denniston, Ihab Elzeyadi, Chas Ehrlich, Carey Knecht, Douglas Mahone, Puja Manglani, Jon McHugh, Abhijeet Pande, and Mudit Saxena. Subcontractors were RLW Analytics, Inc., Cascadia Conservation, Northwest Evaluation Association, and Wirtshafter Associates.

Heschong Mahone Group and New Buildings Institute would like to acknowledge the invaluable guidance and advice provided by members of Element 2's TAG, which included:

- Clifford C. Federspiel, Ph.D., Research Specialist, Center for the Built Environment, UC Berkeley
- Judy Heerwagen, Ph.D., LightRight Technical Advisor
- Danny Parker, Senior Research Scientist, Florida Solar Energy Center
- Abby Vogen, Project Director, Energy Center of Wisconsin
- Jed Waldman, Ph.D., Research Scientist, Dept. of Health Services, State of California

In addition, the contributions of many other building science experts and managers at the participating study sites were critical to the success of these studies.

2.2. Daylighting in Schools: Grade Effect and Teacher Assignment (Project 2.2 "Reanalysis Report")

2.2.1. Introduction

Background and Overview

In 1999, Heschong Mahone Group completed a study funded by Pacific Gas & Electric Company that found a compelling statistical correlation between the amount of daylighting in elementary school classrooms and the performance of children on standardized math and reading tests. These findings, which potentially have very important implications for the design of schools and other buildings where people live, work and play, generated significant attention nationally and internationally.

A panel of experts reviewed the original study and was generally satisfied with the soundness of the methodology and rigor of the statistical analysis. The reviewers, however, expressed two primary concerns: Were "better" teachers more likely to be assigned to classrooms with more daylighting, thereby confounding the results? And would the analysis be more accurate if performed by grade level rather than aggregating data from four grade levels?

Project 2.2 was designed to answer these questions and expand this important research by testing additional methodologies.

Project Objectives

The objectives of this project were to:

- Determine if the results are still valid when grade level effects and teacher assignment bias are considered; and
- Identify any impacts of daylighting or natural ventilation on absenteeism.

2.2.2. Approach

The researchers reanalyzed the 1997–1998 school year student-performance data from the Capistrano Unified School District (California) and the Seattle Public School District (Washington) to answer questions from the peer review panel. The reanalysis effort consisted of the following four research tasks:

- *Teacher survey***.** The teacher survey collected information from a sample of teachers in the Capistrano school district about their education, teaching experience and preferences for classroom features. The survey's primary purpose was to inform the subsequent "assignment bias" analysis. The survey also revealed useful information about teacher preferences, attitudes and behaviors in response to classroom conditions.
- *Teacher bias analysis.* The teacher survey data was statistically analyzed to determine if the original study had over-inflated the effect of daylight on student learning by not accounting for a potential "assignment bias" of better teachers to more daylit classrooms.
- *Grade level analysis.* The original student test score data were reanalyzed for both Capistrano and Seattle by separate grade level, instead of aggregating the data across grades 2 to 5.

- *Absenteeism analysis***.** The researchers used absenteeism and tardiness data in the original Capistrano data set as dependent variables and evaluated them against the full set of explanatory variables from the original study, plus the new information on teacher characteristics. These models allowed an assessment of whether daylighting or other classroom physical attributes potentially affected student health, as measured by changes in student attendance.

2.2.3. Technical Outcomes

The following summarizes Project 2.2's technical outcomes. For an in-depth explanation of the project's methodology and results, see "Daylighting in Schools: Reanalysis Report" (deliverable 2.2.5).

- *The reanalysis study validated the original student learning-rate findings.*

  The availability of daylight in classrooms was reliably associated with an increase in student performance and learning rate in the range of 7% to 37%. The central tendency among all the models studied would be a 25% improvement in reading and a 16% improvement in math, or a 21% general improvement between children in classrooms with the most daylight compared to those in classrooms with the least daylight. This is highly consistent with the range of findings in the original study.

  Based on these results, if the average student in the district were moved from a classroom with an average amount of daylight to a classroom with maximum daylight, his or her learning rate would be expected to increase by 11%.

- *There was no teacher assignment in the original results.*

  Better teachers were not significantly more likely to be assigned to classrooms with more daylighting. The researchers conclusively found that there was not an "assignment bias" influencing the results. A few types of teachers, those with more experience or honors, were slightly more likely (1%–5%) to be assigned to classrooms with more windows or some types of skylights. But considering all teacher characteristics together only explained 1% of the variation in assignment to daylit classrooms.

  When the teacher characteristics were added to the original student performance models, the daylight effect was not reduced in significance. Using a variety of models, the researchers identified a central tendency of a 21% improvement in student learning rates in classrooms with the most amount of daylight compared to those with the least.

- *The daylighting effect does not vary by grade.*

  At the grade-school level, there do not seem to be progressive effects as children get older, and younger children do not seem to be more sensitive to daylight than older children. The data showed neither an increase nor decrease in daylight effects by grade level. Looking at aggregated data across elementary school grade levels, the researchers concluded, is a sufficiently accurate methodology.

- *Physical conditions in the classroom do not appear to affect student attendance.*

  When student attendance is used as a proxy measurement of student health, there is not an obvious connection between the physical classroom characteristics considered and student health. This seems to contradict claims that have been made about the health effects of daylight or other environmental conditions, as reflected in absenteeism rates of building occupants.

Student attendance data is certainly not the best indicator of student health. Yet to the extent that attendance data does reflect student health, the findings do not suggest an obvious connection between physical classroom characteristics and student health. Notably, daylighting conditions, operable windows, air conditioning and portable classrooms were not found to be significant in predicting student absences. Absences were found only to be associated with student socioeconomic characteristics outside the scope of this project.

- *There are certain physical classroom characteristics teachers most prefer.*

  Teachers had an almost universal desire for more space, a good location, quiet environment, lots of storage and water in the classroom. Windows, daylight and views were desirable but were not driving preferences.

  While the teachers surveyed generally preferred classrooms with windows, daylight and views, they considered other classroom features—more space, a good location, quiet, lots of storage and water in the classroom—to be far more essential. Environmental control was also important. Teachers expected to be able to control light levels, sun penetration, acoustic conditions, temperature and ventilation in their classrooms as they do in their homes. They made passionate comments about the need for improvement if any of these conditions could not be controlled.

- *Of many variables studied, only daylighting showed a strong correlation to improved learning.*

  A wide range of factors potentially affect student test scores, but of the physical variables studied (classroom type, HVAC type, operable windows, daylighting) only daylighting showed a strong and consistent correlation to improved standardized test scores. All these results were observed with 99.9% statistical certainty.

- *Overall, these reanalysis efforts affirm that the effect of daylight on student performance is highly significant.*

  Such consistent results present a powerful argument that there is a valid and predictable effect of daylighting on student performance. The addition of more information to the statistical models did very little to change the predicted impact of daylight on student performance. Thus, the researchers decided that it would be much more informative to try to replicate this study with a different population, at a different school district and climate, than to continue to refine the models with further details and variables. With funding from this PIER program, the researchers completed a new study with another school district. That study, *Project 2.4— Healthy Schools: Daylighting, Lighting, and Ventilation,* is described later in this report.

Products

- Daylighting in Schools: Reanalysis Report (2.2.5)

2.3. Daylighting and Retail Sales: Replication Study (Project 2.3)

2.3.1. Introduction

Background and Overview

The "Skylighting and Retail Sales" study completed by Heschong Mahone Group in 1998 found that, for the retail chain studied and all other things being equal, stores with skylighting experienced up to a 40% increase in sales over those without skylighting. These findings, however, may have been a function of the particular chain store that participated in the study, or may have included effects from other influences for which the researchers were unable to control. The first study raised many questions that the research team endeavored to address in this project.

Project Objectives

The objectives of this project were to:

- Validate previous findings by conducting a replication study;
- Explore any daylighting effect in greater detail, seeking to better understand the mechanism of any effect;
- Explore the impact of other indoor environmental characteristics on sales performance; and
- Correlate indoor environmental characteristics that are shown to be associated with greater sales with their potential statewide energy impacts.

2.3.2. Approach

The project comprised the following key tasks:

- *Criteria evaluation and site selection (Tasks 2.3.1 and 2.3.2).* Criteria were developed for the retail study, candidate sites were identified, and the research team was able to match a willing participant with the needed research parameters. At the request of the participating retailer, the identity of the company will be kept confidential.

  The selection approach resulted in identification of a single retailer with a total of 74 sites appropriate for the study, which included 23 daylit sites with a variety of daylighting levels. The sites were all located in California, and the study period was from 1999 through 2001.

- *Data collection (Tasks 2.3.3 and 2.3.4).* Data was collected directly from the participant, including sales data and building and operational characteristics. The data was analyzed for reliability and completeness. Site visits were conducted to verify the existing data and collect supplemental data via measuring, monitoring, interviewing and documentation (Task 2.3.4). The "Report on Data Collection: Deliverable 2.3.4b" describes this data collection process in detail.

  The basic hypothesis of this research was that daylight has a positive influence on the sales performance of retail stores. To test this hypothesis, the researchers not only collected information about the daylighting in each store, but also data on other nonskylight-related factors that may have had a significant influence on sales on a site-by-site basis.

During the course of the research, it became clear that the retail study would benefit from a more in-depth analysis than originally proposed. With the cancellation of Project 2.5 (Manufacturing), Element 2 was able to shift some funds to this project and take advantage of additional analysis opportunities from detailed onsite data collection and employee and manager surveys.

- *Analysis (Task 2.3.5).* Statistical analysis was performed, including multivariate regression analysis using the SPSS model. The outcome variable for the statistical models was the average sales per store in one of two time periods: a 10-month period during the California power crisis of 2002 and a 24-month period previous to the power crisis. The electric lighting system was operated differently during these two periods, potentially creating a natural experiment. Both linear and logged variables were considered. In addition, other models examined the number of customer transactions per store in the same two time periods, and differences in seasonal sales performance between daylit and non-daylit stores. Thirty-four explanatory variables were considered, along with additional interaction effects between variables. For testing replication of the previous study, daylight was initially modeled as a yes/no variable. For more detailed analysis of potential daylight effects, a daylight variable was created based on the number of predicted annual hours of daylight illumination per store above the average horizontal electric illumination level.[1]
- *Peer review and final retail report (Tasks 2.3.6 and 2.3.7).* A draft report was developed and submitted for peer review. Two reviewers asked questions about the unusual and highly significant behavior of the parking variable, which led to further analysis of the parking variable and its impact on the findings. An error in the parking data was uncovered and corrected, reducing the magnitude of the effects detected. The report includes a description of the project methodology, data collection, findings, comparison to prior study results, analysis of energy implications of daylighting systems in retail applications, and recommendations for further study.

2.3.3. Technical Outcomes

- *Depending on the type of model and time period considered, daylit stores in this chain experienced an average of 0% to 6% increase in sales compared to non-daylit stores.*

The replication model did not find that the variable "daylight yes/no" predicted greater sales in daylit stores. However, the more detailed "daylight hours per year" model found that there was a significant correlation between increased daylight (more hours of useful daylight in a store) and higher sales, once the size of the parking area for each store was considered. Stores with parking areas at or above mean for the chain were found to have greater sales associated with more hours of daylight per year. Stores with reduced parking area, below mean for the chain, were found to have a negative effect

[1] Prediction of daylight hours per year was done using SkyCalc, a simplified DOE-2 simulation of the store, which uses regional hourly climate data (TMY2) and detailed information about the store and skylight design inputs.

associated with more hours of daylight. Likewise, stores with parking at or above mean also showed a significant increase in number of sales transactions as their hours of daylight per year increased.

Daylight was found to be as reliable a predictor of sales (as indicated by the partial R^2 for the variables) as other more traditional measures of retail potential, such as parking area, number of local competitors, and neighborhood demographics.

A dose/response relationship was found, whereby more hours of useful daylight per year in a store were strongly associated with increased sales.

All models found a dose-response relationship between number of daylight hours per year and the magnitude of the increase in sales: the more hours of daylight per year per store, the higher the percentage increase in sales predicted.

- *During the California power crisis of 2001, when the chain operated its stores at half lighting power, its daylit stores had an average 5.5% increase in sales relative to its non-daylit stores.*

  The magnitude of the effect varied with the two time periods studied. During the 10-month period of the power crisis, when all stores (both within the chain and competitors' stores) operated their electric lights at about half power, the average daylighting effect was found to be the highest, alternatively estimated at +5.7% (log model) or +5.2% (linear model). During the previous 24-month period, when there was less difference in net illumination levels between daylit and non-daylit stores, the average daylight effect was found to be less, at +1.1% (log model) or –0.3% (linear model).

- *Along with an increase in average monthly sales, the daylit stores were also found to have 1% to 2% increase in the number of transactions per month.*

  In the 10-month period of the power crisis, there were 2.1% more customer transactions on average for the daylit stores. In the previous 24-month period, customer transactions were 1.2% higher. The number of transactions per store was also found to be a function of the amount of parking area and annual daylight hours per store. As parking area increases and as daylight hours increases, the magnitude of the predicted daylight effect on number of transactions also increases.

- *Stores with the most favorable daylighting conditions had a 40% increase in sales compared to non-daylit stores, consistent with the findings of the 1998 study.*

  A bound of a theoretical daylight effect for this chain was detailed. For individual stores in this study with the most favorable daylighting conditions (longest hours of daylight, ample parking areas) the daylighting effect was found to be on the order of 40%. This upper bound is consistent with the previous retail study findings.

- *No seasonal patterns to this daylight effect were observed.*

  The relationship between increased sales and seasonal availability of daylight was examined in models that compared the change in performance between a summer month (July) and a winter month (January). No seasonal variation in the models was detected.

Products

- Daylight and Retail Sales: Replication Study (2.3.7)

2.4. Healthy Schools: Daylighting, Lighting, and Ventilation (Project 2.4)

2.4.1. Introduction

Background and Overview

The "Daylighting in Schools" study completed by Heschong Mahone Group in 1999 found that, all other things being equal, students in classrooms with the most daylighting were learning faster—that is, mastering the standard curriculum content more quickly—than students in classrooms with the least daylighting. This Element's Project 2.2 subsequently validated the findings of the original study. Project 2.4 was designed to extend those two studies. This study participant was significantly different from the previous participant in several key areas: no skylights resulting in less diversity in daylighting strategies, a valley climate rather than coastal climate, and a large proportion of lower income within the district.

Project Objectives

This project's objectives were to:

- Conduct a second study to see if the findings of the original "Daylighting in Schools" study could be replicated;
- Develop an efficient data collection and analysis methodology;
- Include additional factors in the analysis, such as thermal comfort, visual comfort, view, ventilation and acoustic quality; and
- Incorporate more information about the operation of systems and about teacher attitudes.

2.4.2. Approach

The project comprised the following key tasks:

- *Evaluation criteria and site selection (Tasks 2.4.1 and 2.4.2).* Criteria for the school study were developed, candidate sites were identified, and the study site was selected. Element 2's top candidate district, the Fresno Unified School District (FUSD), agreed to participate and fully cooperated in helping the researchers collect existing and onsite data. The site selection process is described in detail in deliverable 2.4.1, "Site Selection Report."
- *Collection of existing data (Tasks 2.4.3 and 2.4.4).* An efficient data collection and analysis methodology was developed, and all existing sources of district data were identified and evaluated. The study looked the performance of 8,500 children in grades 3 to 6 at 36 school sites within FUSD during the 2001–2002 school year. It included 450 classrooms, of which 54% are portables. There was less range of daylight conditions than in the previous school study: the schools in this study had no skylights and no photocontrols, and less than 20% of classrooms had appreciable daylight.
- *Onsite data collection (Task 2.4.5).* The data set was supplemented with onsite verification and data collection via measuring, monitoring, interviewing and photo-documentation.

FUSD requested acceleration in the collection of onsite data to avoid conflicts with the start of the fall semester. The survey instrument and methodology used to collect data about the physical conditions of classrooms is detailed in the "Report on Data Collection" (deliverable 2.4.5b).

Since the Fresno schools had no skylights, there was a need to collect sufficient information to differentiate between the daylight, view, ventilation, acoustic and thermal functions of windows.

- *Analysis (Task 2.4.6).* Multivariate statistical regression analysis was performed to test alternative models and the strength of different variables. Twenty-seven student and teacher demographic variables were considered for inclusion in the models, including economic, ethnic and language status, teacher tenure and salary indices. The study also considered 137 physical characteristics of the neighborhoods, school sites and classrooms as explanatory variables in order to control for as many influences on student performance as possible.

  The methodology involved first developing a "base demographic" model that incorporated the most significant student and teacher explanatory variables. Next, a model was created replicating the format of the Capistrano study model using the holistic "Daylight Code," which classified classrooms by their amount and quality of available daylight. Larger groups of detailed physical characteristics were then studied in thematic groups that were used to refine the variables and test for collinearities. Finally, the "full" model was run, which consider all explanatory variables simultaneously.

  It became clear that the Fresno district's preference for neighborhood schools and site-based curriculum standards resulted in less uniformity in district-wide test results. Therefore, the regression models were not able to predict individual student performance on the tests with as much precision as was achieved in the Capistrano study.

- *Additional observations and analysis.* Initial findings were submitted for peer review. During the course of peer review, it became clear that the Healthy Schools study would benefit from a more in-depth analysis than originally proposed. With the cancellation of Project 2.5 (Manufacturing), Element 2 was able to shift some funds to the Healthy Schools study; researchers went back onsite in Year 3 to collect observations while the district was in session. During this Phase II onsite data collection, surveyors observed classrooms in session; interviewed teachers on their operation and experience of classroom physical comfort factors; took acoustic, radiant temperature, air temperature and light measurements; and distributed a teacher survey. A secondary analysis of this information was performed to test for correlations between daylight and other comfort conditions. In addition, radiant comfort models and acoustic reverberation models were developed to compare across classroom types and climate conditions. This analysis allowed the researchers to analyze how daylighting interacts with other indoor environmental quality issues in the Fresno district, and also to compare how the inland climate in Fresno might result in different effects than the coastal climate of Capistrano.

- *Final Report.* A report, "Windows and Classrooms: A Study of Student Performance and the Indoor Environment" was drafted, peer reviewed, and finalized. The report describes the project methodology, data collection, analysis, findings and conclusions, and potential energy savings. (Tasks 2.4.7 through 2.4.10).

2.4.3. Technical Outcomes

- *The researchers did not replicate the Capistrano daylight findings based on a similar model structure using the Daylight Code.*

  When considered in isolation of other window characteristics, the holistic Daylight Code was not significant in predicting student performance in Fresno.

- *The window characteristics of classrooms have a great deal of explanatory power relative to student performance.*

  The research team conducted more detailed statistical analysis of specific physical characteristics of classrooms and school sites. Of all the types of physical characteristics of classrooms considered in the study, the group of window characteristics seemed to be the most consistent and robust in explaining student performance.

- *The visual environment is extremely important for learning.*

  View: The importance of a window view was one of the most consistent findings of all models tested. An ample and pleasant view out of a window, that includes vegetation or human activity and objects in the far distance, was consistently associated with better outcomes of student learning for both reading and math tests. Security bars, louvers or meshes on windows that permanently impeded the view were associated with negative outcomes. After carefully studying the context, the researchers interpreted this to be a view issue, not a security issue.

  Glare: Glare from windows was negatively associated with student learning. This is especially true for math learning, where instruction is often visually demonstrated on the front teaching wall. The researchers observed that when teachers have white marker boards, rather than black or green chalk boards, they are more likely to use them and children perform better in math.

  Sun: Direct sun penetration into classrooms, especially through unshaded east- or south-facing windows, is consistently associated with negative student performance, likely causing both glare and thermal discomfort.

  Control: When teachers do not have control of their windows via blinds or curtains, student performance is negatively affected. Blinds or curtains allow teachers to control the intermittent sources of glare or visual distraction through their windows.

- *Some classrooms with a high Daylight Code are performing extremely well in Fresno.*

  Most finger plan (highest Daylight Code) classrooms in Fresno show higher than average student performance, when considering all aspects of their window and daylight characteristics. However, so do some open plan and portable classrooms (lowest Daylight Code). Classrooms with a combination of ample view with avoidance of glare and sunlight penetration are associated with 15% to 25% improvement in student learning rates, comparable to the findings of the Capistrano study.

- *The acoustic environment is also extremely important for learning.*

  Situations that compromise student focus on the lessons at hand, such as reverberant spaces, annoying equipment sounds, or excessive noise from outside the classroom, have measurable association with learning rates.

- *Poor ventilation and indoor air quality also appear to negatively affect student performance.*

  However, in FUSD these issues are almost hopelessly intertwined with thermal comfort, outdoor air quality and acoustic conditions. Teachers often must choose to improve one while making other aspects of the classroom worse.

- *Some classrooms with a high Daylight Code are performing extremely well in Fresno.*

  Most finger plan (highest Daylight Code) classrooms in Fresno show higher than average student performance, when considering all aspects of their window and daylight characteristics. However, so do some open plan and portable classrooms (lowest Daylight Code). Classrooms with a combination of ample view with avoidance of glare and sunlight penetration are associated with 15% to 25% improvement in student learning rates, comparable to the findings of the Capistrano study.

- *There were suggestions that high Daylight Code classrooms in Fresno might have more acoustic problems than in Capistrano.*

  Classrooms in FUSD with a high Daylight Code were found to be generally more reverberant than those with a low Daylight Code. This was exacerbated by a practice of having teaching assistants provide tutoring within the classroom, causing an increase in human-voice frequency background noise. The high Daylight Code classrooms were also found to have greater operable window area, and teachers reported that they opened these windows more often, primarily to control the air quality and temperature in their classrooms. This greater propensity for the windows to be open in high Daylight Code classrooms resulted in greater transmission of playground and traffic noise within those classrooms.

- *Operable windows were not found to be associated with better student performance in Fresno.*

  In many models that we tested, operable windows were found to be associated with negative student performance. On the other hand, lack of teacher control of the ventilation was found to be positively associated with student performance. This implies that continuous mechanical ventilation is superior to reliance on intermittent mechanical or natural ventilation in Fresno conditions. The city's high incidence of air pollution, dust, and asthma suggest that ventilation may be especially important in Fresno classrooms.

- *The physical conditions of classrooms were found to be highly significant in predicting student performance.*

  Variables describing the physical conditions of classrooms, most notably the window characteristics, were as significant and of equal or greater magnitude as teacher characteristics, number of computers, or attendance rates in predicting student performance. Overall, information about the physical environment of schools and classrooms was found to predict about 2% to 5% of the total variation in student performance observed. While the effects of school and classroom design may be subtle, they are also likely to be highly persistent, influencing the performance of generations of students.

- *The study provides useful tools and guidance for other researchers who may pursue these issues.*

  This study successfully measured variation in school environmental conditions and related these to measured student performance under field conditions. The studies have established a range of likely effect sizes that other researchers can use to refine the data sensitivity needs of future studies. Other follow-on studies are required to refine the parameters describing the key components of indoor environmental exposures such as daylight, view and ventilation and to explore direct or indirect causal mechanisms between these conditions and student performance.

Products

- Windows and Classrooms: A Study of Student Performance and the Indoor Environment (2.4.10)

2.5. Healthy Offices: Daylighting, Lighting and Ventilation (Project 2.6)

2.5.1. Introduction

Background and Overview

This project was designed to carry forward earlier studies on the interaction of daylighting and productivity by extending those inquiries to office buildings.

The basic hypothesis of this project was that daylight has a positive influence on the performance of office workers. To test this hypothesis, the research team collected information about the environmental conditions in each worker's specific office cubicle and surrounding areas. The team also collected data to provide an objective measure of performance.

Project Objectives

The objectives of this project were to:

- Apply the findings of the daylighting in schools and daylighting in retail sales to office building environments;
- Develop a methodology for measuring worker performance in a field study of an office environment, and hopefully correlate individual performance to organizational productivity;

- Collect relevant data to assess the indoor environmental quality for the office workers in the study, including daylight, electric light, ventilation, view, acoustics and thermal comfort; and
- Determine the energy implications of indoor environmental conditions that are found to enhance worker performance.

2.5.2. Approach

The project comprised the following key tasks:

- *Evaluation criteria and site selection (Tasks 2.6.1 and 2.6.2).* Evaluation criteria were created to select a participant that would be most likely to have appropriate work and environmental conditions for the study. The three candidates who were judged to have the greatest potential were visited by the researchers to assess their appropriateness for the study. The participant selected has one building that provides exemplary daylit conditions for its workers, while two other buildings on the same campus provided non-daylit control conditions necessary for the study. The participant's management agreed to assist in the study and exceeded the researchers' expectations in terms of the level of cooperation and commitment to the study.
- *Data collection (Tasks 2.6.3 through 2.6.4).* Existing data was collected from the participant on employee status and facility conditions. The data was evaluated and a research plan developed. Site visits were conducted to verify the existing data and collect supplemental data via measuring, monitoring, interviewing and documentation.

  During the course of the research, it became clear that the office study would benefit from a more in-depth analysis than originally proposed. With the cancellation of Project 2.5 (Manufacturing), Element 2 was able to shift some funds to Project 2.6 and expand the office research to include two parallel observational studies that would inform each other. One study used pre-existing metrics of the *Call Center* to correlate worker performance to indoor environmental conditions. The other study used individual performance data collected via short computerized tests taken by professional and clerical office workers in other parts of the various office buildings for a *Desktop study* comparing daylit and a non-daylit environments. Both approaches involved collection of environmental data for use in the analysis, including air temperature, ventilation, view, daylight and electric light levels.

  Call Center study: This study analyzed performance data from 100 employees in the Call Center, which handles incoming calls. This performance data was collected automatically by the computer system that monitors each Call Center employee's performance, with metrics such as calls completed per day, average call (talk) time, average work (call wrap-up) time, and total handling time per call. An initial one-month study period in September 2002 collected daily performance and environmental metrics. A more detailed three-week study period in November 2002 collected hourly performance and environmental metrics. A waiting period between the two study periods was necessitated by the introduction of a new software component at Call Center operations. In order to artificially increase the amount of variation in the daylight and ventilation conditions, the window blinds settings were changed for a few days during the middle of both study periods and the rate of outdoor ventilation was changed for a few days in the second study period.

Desktop study: This study compared office worker performance across a variety of daylight conditions in different buildings on the campus. Because there were no uniform measurements of employee performance in all these environments, the research team created a series of simple computerized tests to measure a number of different dimensions of employee performance such as memory, alertness span, dexterity and visual acuity.

These mini-tests were administered over an internal network, which allowed the collection of real-time performance data in milliseconds under the workers' normal desk conditions. The tests were administered once a week over the course of five weeks during a limited two-hour time period. To identify the final study population, approximately 700 workers were considered for the study, 515 participated in an initial survey, and 235 were invited to take the mini-tests.

In addition to the mini-tests, the participants also filled out a 15-page questionnaire about their personal assessment of environmental quality at their workstations. The final study population consisted of 201 employees who completed the mini-tests at least once and completed the questionnaire.

Data describing physical comfort conditions were collected via a variety of means. Miniature data loggers set on top of cubicle partitions collected instantaneous information in fifteen minute intervals on horizontal illumination levels, temperature and humidity both inside and outside of the spaces. Surveyors visited the office workers' desks during a series of Saturday study days to assess view quality, glare conditions and ventilation status, and to determine the interactive relationship between daylight and electric light illumination levels. Indoor air quality was measured only once in each space with VOC and CO_2 recorders. Operation of the HVAC and economizer systems was assessed with data from the Facilities Department, data loggers and outdoor weather records. Correlation of the data from these many disparate sources became a major challenge.

For a complete description of the data collection activities, see the "Report on Onsite Data Collection" (deliverable 2.6.5).

- *Analysis.* Multivariate regression statistical analysis was performed, testing alternative models and the strength of different variables.(Task 2.6.6). Three models were created for the Call Center study: a daily performance model for the September period, and both a daily and an hourly performance model for the November study period. Five models were created for the Desktop study, one for the outcome of each of the five mini-tests. Both linear and logged variables were considered. The natural log of illumination levels was used in the final models. For the hourly Call Center model, both simultaneous readings and readings lagged by one hour were considered. The one-hour lag of the daylight illumination levels (logged) was found to provide the best statistical fit.

  Physical environment explanatory variables considered included daylight and electric light illumination levels, quality of view and glare from windows, indoor air temperature, floor register (ventilation) status, and location in the new building.

Demographic control variables were included for education level, age, gender, tenure with the company, department assignment, monitor resolution, and test session number. Pearson's correlations were used to look at relationships between questionnaire health and comfort responses and physical conditions in the workspace.

2.5.3. Technical Outcomes

- *Daylight illumination levels were significant and positive in predicting better performance on a test of mental function and attention.*

  The Backwards Numbers (Digit Span Backwards) test is widely accepted in psychological research as a valid test of mental function and attention span. An increase in daylight illumination levels from 1 to 20 footcandles resulted in a 13% performance improvement in the ability to instantly recall strings of numbers. A logged function was found to have the best fit, implying the greatest increase in performance at the lowest levels of daylight illumination and a diminishing positive effect at increasingly higher daylight illumination levels. Thus, a 20-footcandle increase in daylight at the high end of illumination levels, from 80 to 100 footcandles, was reflected in only a 1% improvement in performance. Daylight illumination was found to have the greatest predictive power of any variable considered for the Backwards Numbers test.

  The daylight illumination explanatory variable was defined as the natural log of the average of horizontal daylight illumination at the participant's chair position for the two-hour time period during which the test could be taken. It was derived from data measured on the horizontal plane at the top of a 5-ft high partition near the participant's cubicle.

- *Daylight illumination levels were not significant for the visual acuity tests or long-term memory test.* Daylight illumination levels had an association with a slight decrease in Call Center performance for one of three models.

  Daylight illumination was not found significant in any of the other models considered, with the exception of the November daily model for the Call Center, where an increase in average horizontal daylight illumination from 1 to 20 footcandles was found to be associated with a 6% decrease in performance, or a 23-second increase in daily average call handling time. An hourly analysis of the same time period did not show a change in Call Center performance related to hourly fluctuations in daylight illumination levels.

- *An ample and pleasant view was consistently found to be associated with better office worker performance.*

  A better view was the most consistent explanatory variable associated with improved office worker performance, in six out of eight outcomes considered. Views from a workstation were rated for both primary view (angular size of window view while looking at the desktop computer monitor) and break view (angular size of view from other seated vantage points in the cubicle). Both types of view were rated on a scale of 0 to 5 first based on size, and secondarily by vegetation content and activity versus only built elements. Workers in the Call Center were found to process calls 7 % to 12% faster when they had the best possible view versus those with no view. Office workers were found to perform 10% to 25% better on tests of mental function and memory recall when they had the best possible view versus those with no view.

Results from the questionnaire administered to participants in the Desktop study supported the performance findings. There was a very high correlation between workers' and surveyors ratings of view. Those workers in the Desktop study with the best views were the least likely to report negative health symptoms. Reports of increased fatigue were most strongly associated with a lack of view.

A large window view could also potentially be an indicator of the exposure of the worker to vertical illumination levels. The visual details of window views were often partially screened by perforated vertical blinds which still provided a large bright vertical plane within the field of view.

- *Glare from windows was associated with worse office worker performance.*

  In the Desktop study, each cubicle was rated for its potential of glare from the primary view windows, defined on a simple 0-4 scale of none to frequent.. The greater the glare potential, the worse the office worker performance was on three mental function tests, decreasing performance by 15% to 21%. For the Backwards Numbers test it was found that primary view had a positive relationship to performance only if there was no glare potential from that view. It is possible that participants with a high glare potential were more likely to close their window blinds, thus diminishing their view. Participants close to windows generally had control of their windows blinds, but blind position was not monitored during the test period.

  Two other indicators of glare potential were also found to be negative. Primary view was found to be associated with slower performance on one visual acuity test (Landolt-C). Being closer to a skylight was found to be associated with negative performance on another visual acuity test (Letter Search). Questionnaire responses from office workers indicated that glare from skylights on computer monitors was the only negative comfort condition reported by workers close to skylights.

- *Increased ventilation was found to be associated with improved worker performance in the Call Center and improved office worker performance on one mental function test.*

  In the hourly analysis of the November study period for the Call Center, it was found that a 1CFM/sf (50%) increase in outside air was associated with a 4% improvement in hourly worker performance. It is possible that this finding could be confounded by other hourly changes in working conditions.

  Workers in both the Call Center and the Customer Services Center had the ability to set their floor register to provide more or less ventilation from the building's air handling system. In the Call Center, those workers in who set their floor registers fully open handled calls 3% to 10% faster in all three models considered, than those that had their floor registers fully closed.

  In the Desktop study, workers who left their floor registers full opened performed 17% better on one test of mental function (Number Search), while their performance was worse for two tests of visual acuity and dexterity (-15% to -20%).

These ventilation findings may also be related to local air temperature in the cubicle. Researchers noticed that the ventilation air supply temperature was 10°F to 15°F lower for employees in the Call Center than for participants in the Desktop Study. Indoor air temperature in the models was measured at 5 ft above floor level, which may not have captured the personal thermal comfort effects of an individualized floor air delivery system. Thus, in the Call Center, workers with a fully open floor register were likely to be surrounded by lower air temperatures than those recorded by the data loggers, while participants in the Desktop Study were more likely to be in a local thermal environment close to the recorded air temperature.

- *Increased indoor air temperature reduced worker performance in two out of eight outcomes and improved it for one outcome.*

  Indoor air temperature, measured 5 ft above the floor near the participant's cubicle, was found to reduce worker performance in the November hourly model. Over the course of the study periods, indoor air temperature varied over only a 6°F to 8°F range. For each 2°F increase in temperature, average hourly call handling speed increased by 2%. In the Desktop study, an increase in 2°F was associated with an 8% decline in performance on a visual acuity test (Landolt-C), while it was also associated with an 8% increase in performance on the long-term memory test.

- *The natural log of illumination and the daylight illumination level of the previous hour had the best fit in predicting performance.*

  In various models tested, the natural log of both daylight and electric light illumination levels was found to have the best fit in the models of both Call Center and office worker performance. In addition, for the Call Center November hourly models, a one-hour time lag of daylight illumination levels was found to provide the best model fit, even though this explanatory variable was not found significant in the final model. This implies that illumination levels can be expected to have diminishing effects as they increase in intensity, and that any effects on human performance are likely to have a physiological component (delayed effect) in addition to a visual component (instantaneous effect).

- *Physical comfort conditions were an important component of models predicting office worker performance.*

  Overall these potential influences on worker performance were found to have high statistical significance, and represent changes in performance ranging from about 1% to 20% better or worse than norm. All together information about the physical conditions of the workers was able to explain about 2% to 5% of the variation observed in a measure of worker productivity (Call Center Study) or in performance on short cognitive assessment tests that were thought to be related to worker productivity (Desktop Study). Other information available about the workers such as demographic characteristics or employment status was able to explain about 6% to 19% of the variation in their performance.

  The combination of physical comfort conditions considered—illumination, view, ventilation and temperature—typically provided one-eighth to one-third of the explanatory power of the models. Demographic information—such as which group manager or department the employee was assigned to, their age, years of experience, and education—provided the remaining two-thirds to seven-eighths of the models' explanatory power. These studies were done comparing worker performance in a very uniform, modern and high-quality office environment where variations in comfort conditions were maintained well within current standards of practice. This implies that facility managers can expect that subtle variations in physical comfort in their buildings could potentially alter worker performance by one-eighth up to one-third of the variation observed due to organizational or hiring practices.

- *The studies provide useful tools and guidance for other researchers who may pursue these issues.*

  Both studies successfully measured variation in office worker environmental conditions and related these to measured office worker performance under actual employment conditions. The Desktop Study pioneered the use of computerized cognitive assessment tools to gauge office worker performance in field conditions. The studies have shown that indoor environmental conditions can have a measurable relationship to changes in office worker performance and have established a range of likely effect sizes that other researchers can use to refine the data sensitivity needs of future studies. Other studies will be required to test if these findings can be replicated in other settings and to explore potential causal mechanisms between the environmental conditions and worker performance.

Products

- Windows and Offices: A Study of Office Worker Performance and the Indoor Environment (2.6.10)

Market Connections

PRESENTATIONS

* = presentation funded by non-PIER sources

- *ACEEE Summer Study.* August 2002. Two presentations: Daylighting reanalysis study and discussion roundtable to energy and building scientists.
- *California utilities.* The Institute made visits or contacts with each of the California IOUs and SMUD during 2001-2002 to brief them on the PIER objectives, anticipated products and schedule. NBI and project team members will visit each of these utilities at the end of 2003 to provide the efficiency program staff with completed PIER products and to discuss the transfer of the results into their programs. The IOU staff has indicated that the Savings by Design statewide program will be the best mechanism for integration of the majority of the PIER results.
- *Center for the Built Environment.* October 2003. Key note presenter at the partners meeting to the Center for the Built Environment at University of California, Berkeley. Presented on the PIER daylighting in schools research, findings on student performance, building environmental impacts and energy savings potential.
- *Coalition for Adequate School Housing.** Sacramento, February, 2002. Daylighting in Schools reanalysis study presented to 70 attendees including government, school & building industry representatives.

- *Coalition for High Performance Schools (CHPS).** 2002–2003. CHPS runs training programs for architects and school administrators. There have been about a dozen in 2002 and 2003. Training includes 15 minutes on the daylighting reanalysis study; also, information from the Fresno onsite data collection (Healthy Schools study) was used to inform the workshops.
- *Emerging Technology Council for California Utilities.** December 2002. School daylighting reanalysis findings and description of Daylighting and Retail Sales presented.
- *FEMP Advanced Lighting Workshop.** April 2003. Presented findings of schools study to federal energy program managers.
- *IESNA***.** Ottawa, August 2001. Daylighting in Schools reanalysis study presented to lighting researchers and industry members.
- *InterTech USA conference.* Tucson, February 2002. Conference on Energy Efficient Lighting Systems. Presentation on PIER results to lighting manufacturers and lighting program managers.
- *LightFair.** San Francisco, June 2002. Presented school lighting design seminar and school daylighting reanalysis results.
- *Lighting and Health workshop.** In May 2003, led "Lighting and Health" workshop in Washington D.C., presenting on current and past work, in particular the Healthy Offices study (presentation funded through non-PIER sources).
- *PG&E's Pacific Energy Center.** San Francisco, March 2003. Training for design professionals, titled "Daylighting Basics for Lighting Designers and Electrical Engineers," included presentation of E2's results.
- *PG&E's Pacific Energy Center.** San Francisco, April 2003. Training for design professionals, titled "Lighting for Schools" communicated results from Daylighting in Schools Reanalysis study and Healthy Schools study.
- *Seattle AIA.** May 2003 presentation in Seattle at local AIA conference on both school studies

PUBLICATIONS

- *ACEEE Summer Study Proceedings.* August 2002. Fifteen-page paper titled "Daylighting in Schools." Audience: Energy efficiency & building sciences professionals.
- *ASHRAE Journal***.** June 2002. "Daylighting and Human Performance," an article in featured series on best studies in indoor environment. Included Daylighting in Schools study. Audience: Mechanical engineering industry.
- *Council of Educational Facilities Planners International Journal***.** Summer 2002. Lead article for special sustainable schools edition for school architects and facility planners.
- *IESNA Journal.* Summer 2002. Article highlighting Daylighting in Schools Reanalysis results. "Daylighting Impacts on Human Performance in Schools." Audience: Lighting industry professionals.
- *LD&A, LightFair Preview Edition***.** May 2002. Article on Daylighting and Schools. Audience: Architecture and lighting engineering firms, design and lighting industry.

CODES, STANDARDS AND GUIDELINES

- *LAUSD/CHPS.* The "Daylighting in Schools: Reanalysis Report" contributed to the Los Angeles Unified School District's decision to adopt the Coalition for High Performance Schools (CHPS) guidelines as a standard for their district which will result in improved daylighting in their new schools.
- *Title 24.* Strength of original retail study findings helped pave acceptance of the Title 24 code proposal to require skylights with integrated controls in some building types (this code proposal is described in Element 5's section of this report).
- *State code development.* Provided comments about schools study results for code development process in Washington State, Massachusetts and Pennsylvania.

NETWORKING AND COLLABORATION

BUSINESS ORGANIZATIONS

- *Corporate Management & Realty Corporation.* CMRC presents national seminars to facility managers and architects. These seminars now include information from Elements 2, 4 and 5.
- *Retail chains & Element 5.* Publicity about the previous retail study and contacts made during this study provided access to high-level decision makers in retailer chains for participation in the associated study in Element 5 on integration of skylights with T-bar ceilings.
- *National retail chains.* More than a dozen large national retail chains are known to be currently building skylit stores or developing prototypes to investigate how skylighting could best be applied to their format. In addition, in 2003 the head of store planning for a national department store corporation and seven other major retailers consulted Lisa Heschong for advice on including skylighting in their stores. The PIER research greatly facilitates her discussions as a national leader and resource on daylighting with market players considering daylight designs.
- *Manufacturer interest.* Initial screening of potential sites for the Daylighting and Manufacturing Productivity study (which was subsequently cancelled) turned up a number of interesting possibilities, and telephone interviews with the owners of the manufacturing plants revealed considerable interest in the study and the positive effects of daylight. The door remains open for such a study, but it became clear from interviews that manufacturers are most interested in performance studies that consider the constraints of their particular industry, not manufacturing as a generic building type.

RESEARCHERS/CONSULTANTS

- *North American researchers.* Methodologies and research tools from Elements 2 and 5 are being exchanged with researchers at the Lighting Research Center, the LightRight Consortium, and National Research Canada. Also, the team provided samples of Healthy Schools teacher surveys and onsite methodology to other researchers in California and other states, and likewise reviewed and commented on their research methodologies. And during the course of the Healthy Offices study, the research team collaborated with researchers working on similar office-based projects at U.C. Berkeley, National Research Canada, and the Lighting Research Center at Rensselaer Polytechnic University.

- *International researchers.* Research team has responded to inquiries about methodologies and findings from researchers from abroad, including New Zealand, Australia, Singapore, Japan, Brazil, India, South Africa and England..
- *Rocky Mountain Institute.* The Schools Reanalysis results were incorporated into RMI databases and conference/seminar presentations.

GOVERNMENT AGENCIES AND SCHOOL DISTRICTS

- *U.S. Department of Energy.* Data from Elements 2 and 5 will contribute to the DOE "Roadmap" on daylighting and skylighting design.
- *State agencies.* Collaborated with California Department of Health Services and other California agencies in a constellation of studies examining school health outcomes.
- *School districts.* Worked closely with both the facilities department and the research department of Fresno Unified School District.

UTILITIES

- *Utility programs.* California utilities have expressed interest in funding demonstration projects helping retailers determine how to economically retrofit skylighting into existing stores. Also, daylighting in retail settings have been added to utility program design assistance and incentive programs in California, the Pacific Northwest, New York, and the New England states.

2.6. Conclusions and Recommendations

2.6.1. Conclusions

Daylighting in Schools: Grade Effect and Teacher Assignment (Project 2.2 "Reanalysis Report")

- Daylighting remained a strong indicator of student performance.
- There was not a teacher bias effect. Even with the addition of further information the findings held and remained significant.
- There was not a grade level effect, nor was there a relationship between more daylighting or the type of classroom and absenteeism.

Daylighting and Retail Sales: Replication Study (Project 2.3)

- There was a positive relationship between more daylight and higher sales. This average relationship was substantially weaker than the 1998 retail study but still positive and significant (0–6%).
- There was a dose-response relationship between more hours of daylight and a larger effect on sales.
- There was a similar although more modest effect on number of transactions.
- There was no seasonal effect, which suggests a long-term customer loyalty effect and not a short-term impetus on sales.

Healthy Schools: Daylighting, Lighting, and Ventilation (Project 2.4)

The Fresno data did not lend itself to simple explanations, and the final model is highly complex. There are no definitive answers or "proof positive" of any hypothesis. There are, however, some consistent suggestions about the importance and value of good classroom design, with an assessment of the magnitude of its influence on student performance.

- Higher levels of daylight illumination or more hours of useful daylight per year, as indicated by the Daylight Code, were not associated with better student performance in Fresno.
- Teachers expressed a strong desire for more daylight and better views.
- Interesting window views enhance rather than detract from student learning.
- Glare, sun penetration and lack of window controls (blinds or curtains) negatively impact learning.
- Portable classrooms are not inherently bad for student learning. There is, however, a much wider range of good-to-bad conditions in portable classrooms than permanent classrooms. Portable classrooms with better views and good sun control performed well.
- Finger-plan classrooms in Fresno with high Daylight Codes performed above average, especially those with better views and better sun control.
- There were consistent problems associated with the high Daylight Code classrooms, most notably acoustic problems caused by higher reverberation levels and open windows allowing sound transmission from the outside.
- Continuous mechanical ventilation should be preferred in Fresno to provide classroom ventilation rather than reliance on operable windows or locally controlled fans.
- Fresno classrooms have a tangled relationship between acoustic conditions, ventilation, thermal comfort and air quality that forces teachers to choose to improve one condition while making others worse. Careful attention should be given to providing good ventilation and air quality while minimizing negative acoustic and thermal comfort impacts.

Healthy Offices: Daylighting, Lighting and Ventilation (Project 2.6)

- A positive association between high daylight illumination levels and better mental function was found in one outcome studied and is considered one of the most reliable metrics predicting mental function and attention span.
- Daylight illumination was <u>not</u> found to be associated with improved performance of incoming Call Center workers or performance on visual acuity tests measured on computer monitors.
- The size and quality of view from the workstation was found to be the most consistent predictor of improved worker performance. This was true for both the Call Center and the Desktop studies.
- The size and quality of view was also found to be strongly associated with better self-reports of health conditions. Those workers with the least view reported the highest incidence of fatigue.

- Increased levels of outside air ventilation in the Call Center were associated with improved hourly performance. Increased local ventilation rates (as indicated by floor register status) were also associated with better performance in the Call Center.
- Workers in the Desktop study who had cubicles with the greatest potential for glare from their primary view windows performed worse on tests of mental function. In one test, primary view was found to have a positive.
- Physical comfort conditions have an important influence on worker performance. Estimates from this study suggest that subtle differences in physical comfort may be responsible for 2% to 5% of the variation in worker performance in a modern office environment.

2.6.2. Commercialization Potential Or Commercialization Initiated

Based on the experience of the published results from the previous schools and retail studies, the correlations between building design and occupant performance can be enormously motivating for building owners and designers. For example, a manager at Project 2.3's retail participant had this to say after reading the project's final report:

> *"I just finished reviewing your fine report. Wow! It's very gratifying to see something materialize after 15+ years of wanting this... I just hope that the company takes to heart some of the key findings and uses them to their advantage. I also suspect that your findings will impact retail design on a large scope in future years."*

In the past few years, there has already been a dramatic change in attitudes toward daylighting in schools and retail environments. It's important to note, however, that the greater complexity and more detailed findings of Element 2's PIER-funded studies may result in a more complex response from building owners and designers.

Studies like those conducted by Element 2 help make the linkage between the built environment, the public benefits of reduced energy use, and the public benefits of improved human health and well-being. By helping a broad spectrum of people understand those connections, the State is likely to accrue much greater energy savings. These studies provide a first estimate of the magnitude of the influence of the physical environment on student or office worker performance, and suggest that about 2% to 5% of the overall variation in individual performance may be attributable to the design and operation of buildings housing those students or workers.

An important lesson of both the schools and office studies is that daylighting is not a magic cure-all, but an architectural technique that must be done correctly to avoid potential negative impacts such as glare or sun penetration. Both of these studies will provide substantive new information to help educate designers and motivate changes in architectural design practices.

Architects and manufacturers of daylighting components, such as skylight and photocontrol manufacturers, have proven to be an important force in presenting the daylighting studies' findings to the public. The demonstrated positive effects of daylight have been widely used as a "marketing hook" to interest both designers and building owners in the potential of other advanced building concepts.

Based on experience, however, the most powerful way to influence the market is to get the findings into the mainstream media. The extraordinary attention paid by the popular press to the previous Heschong Mahone daylighting studies continues to this day, with the studies' findings described in an article about the benefits of daylighting in the June 17, 2003 edition of the *New York Times*. The mainstream media interest originally came about as a result of the Commission informing a local *Sacramento Bee* reporter of the studies' results. The *Bee's* article was immediately picked up by national television, newspapers and other media outlets. Having the Commission provide the results to the media was extremely effective and had powerful consequences.

It will also be important to have speakers present the studies' results at targeted conventions and to publish articles in targeted professional journals, because some building-industry professionals have more confidence in information that reaches them through familiar industry channels.

Outreach to the health community, as represented by the Centers for Disease Control and Health and Human Services, will be another important mechanism for driving change in how buildings are designed and built. These agencies are developing a keen interest in the relationship between the physical environment and human health, and would welcome more substantive discussions of the issues. This connection is primed to happen but needs ongoing support.

2.6.3. Recommendations

Daylighting and Retail Sales: Replication Study (Project 2.3)

- *Encourage increased use of daylight illumination level in retail stores.*

  Providing daylight illumination to retail stores combined with photosensor lighting controls can provide a high-quality visual environment and provide significant energy savings. It has been twice shown to be associated with increased sales in retail stores. It also provides increased continuity, safety and security during daytime power emergencies. This study showed that, with parking levels at or above mean and all other things being equal, the more hours of daylight illumination per year, the higher the sales per store.

  There are very strong reasons to encourage more California retailers to consider using daylight illumination as a primary source of light for their daytime operations, while reducing their use of electricity to light and cool their buildings. The use of skylights to provide daylight from above is a very simple and relatively inexpensive method to achieve widespread distribution of daylight in low-rise retail environments. Other sources have addressed best practices in skylight selection, design and integration with electric lighting systems.

Healthy Schools: Daylighting, Lighting, and Ventilation (Project 2.4)

- *Encourage the incorporation of view windows in K-12 classrooms.*

  In this research, ample and pleasant views were shown to be consistently associated with better student performance. Various educational theories and engineering practices over the years have argued against providing window views for schoolchildren, resulting in a net reduction of view-level windows. The current study clearly argues in favor of mentally stimulating window views as an aid to educational achievement. Good views are assumed to have either significant vegetation or human activity at a far viewing distance.

- *The addition of automatic daylight controls that reduce electric light use when daylight is available could potentially save the district, and the state, a great deal of money and energy.*

  The energy savings, combined with the positive effects of view out of windows observed in Fresno, or the positive effects of increased daylight observed in Capistrano, create a win-win situation for daylighting design in classrooms. Designers and school officials are advised to avoid designs that create glare or allow direct sun into classrooms, while optimizing the opportunities for interesting views and energy savings with their school designs.

- *The acoustic problems associated with the high Daylight Code classrooms in Fresno can be addressed with better classroom design and material selection.*

  Adding more sound-absorbing surfaces in finger-plan classrooms will help reduce background noise levels from inside the classroom, while the addition of dual-pane low-e glass will reduce sound transmission from outside the classroom and improve overall thermal comfort. Any south- or east-facing windows should be shaded from the direct sun, and adding planting strips with trees outside of classrooms will improve both radiant comfort and reduce noise transmitted by students banging on the walls as they pass or play nearby. The research team recommends the provision of quiet, continuous mechanical ventilation in Fresno combined with local teacher control of the thermostat in order to avoid reliance on operable windows for ventilation and temperature control.

- *The tangle of poor ventilation, acoustics, air quality, and thermal comfort in classrooms needs to be solved.*

  Teachers need options that will maintain good ventilation and air quality in their classrooms without compromising thermal comfort or acoustic quality. Noisy ventilation systems, erratic temperatures from the heating and cooling system, poor indoor air quality from damp, unventilated rooms, poor outdoor air quality from pollution, dust and noise from landscape blowers and traffic all combine to make classrooms conditions that are challenging at best, intolerable at worst. Teachers are faced with additional challenges from crowded classrooms, use of other noisy (and heat-generating) equipment such as overhead projectors, and lack of local controls for immediate options to solve these constantly changing comfort problems. We have too long been providing classrooms to teachers that provide the bare minimum of comfort for each of these conditions, such that any additional stress on the system causes failure. We need to provide classrooms that have more latitude for providing a comfortable environment for their occupants, so that teachers can be effectively teaching every day of the year.

Healthy Offices: Daylighting, Lighting and Ventilation (Project 2.6)

- *Encourage the design of office buildings with views provided for all workers.*

Both the school and the office studies found strong and consistent correlations between better views and better performance. There is a clear suggestion from this work that window views are important for sustained human performance. Building codes in Europe have long required that all office workers have access to window views, typically stipulating that no workstation be more than about 20 feet from a window. Initially the importance and value of views for worker performance should be communicated to office building owners, managers and designers. Eventually both government and voluntary programs and standards should encourage the design of office buildings with narrower floor plates that allow more perimeter area for views. Additional research may be able to refine the parameters involved in this interaction between view and performance, to provide more guidance on view content, quality and proximity.

- *Encourage additional research on the relationship between ventilation rates and worker performance.*

  The Call Center study is strongly suggestive that increased ventilation rates are likely to improve worker performance. These findings may be confounded with other simultaneous changes in the environment. As discussed above, ventilation rates are often entangled with other environmental parameters, such as room air temperature, indoor and outdoor air quality, acoustic conditions and occupant control. In order to optimize worker performance while maintaining maximum energy efficiency, building designers need more guidance on how to balance these factors.

- *Support the development of better indoor environmental monitoring and assessment tools.*

  This study was challenged by the limitations of inexpensive data collection tools for monitoring indoor environmental conditions. The miniature data loggers used for long-term data collection were well adapted to record air temperature, or static electric illumination conditions, but were far from ideal for measuring daylight illumination. Inexpensive tools to monitor air flow rates, air quality metrics, or acoustic conditions over time were not available. Appropriate methods to assess exposure to vertical daylight illumination or to assess the quality of a window view have yet to be defined. The ability to study variations in indoor environmental conditions is largely dependent upon being able to accurately measure those variations. Thus, an improved tool kit for indoor environmental assessment will greatly help to advance the field and support the development of knowledge that can provide specific guidance to building designers.

2.6.4. Benefits to California

In addition to energy savings discussed below that can be achieved through the use of photo-sensing lighting controls combined with buildings designed to optimize the use of daylight for illumination, there are many other potential benefits to California for supporting this research into the impacts of the indoor environment on human performance.

Risk Reduction. The use of daylight for illumination in non-residential buildings greatly reduces the risk of business disruption during power outages and greatly increases public health and safety during any emergency which may involve disruptions of the electricity supply. The incorporation of a large stock of buildings throughout the state with adequate daylighting increases the options for voluntary power reductions during peak emergencies.

Reduction in pollution and greenhouse gasses. The use of daylight for illumination is the most efficient and environmentally benign form of daytime illumination. The daylight is already continuously available—no generation is required. There are no transmission losses to account for. There is simply a need for buildings that are designed to distribute the outside daylight appropriately throughout the indoor environment, while maintaining good visual quality and thermal comfort.

Business success. Local retailers who adopt daylighting for their store design are likely to find a competitive advantage reflected in higher sales, greater customer loyalty and perhaps also employee loyalty. Even if all retailers incorporate daylighting into their building designs, they will continue to benefit from the energy savings and a more attractive and safe work environment. Likewise, corporations that inhabit office buildings that provide ample views, daylight and ventilation for their workers are likely to benefit from improved employee performance and retention.

Improved worker and student performance and well-being. These studies have demonstrated that the design and operation of our commercial building stock has a significant and measurable impact on the performance of elementary schoolchildren and office workers. It is possible that continued exposure to adequate daylight levels in schools or the workplace may improve a person's overall circadian health. The people of the State of California will benefit from having buildings designed and built that are more supportive of their needs for indoor environmental comfort.

Long-term return on investment. A building designed to optimize human performance has a very long life span. Thus, while any influences on performance may be subtle, they are highly persistent, likely to continue to accrue for twenty to fifty years, if not more.

Daylighting and Retail Sales: Replication Study (Project 2.3)

RETAIL SAVINGS

- Based on current energy prices, the average whole-building (lighting and HVAC) energy savings for this chain's daylit stores is estimated to be $0.24/ft^2 for their current "standard" design, with a potential for up to $0.66/ft^2 with state-of-the-art design.
- The value of energy savings from daylighting is far overshadowed by the value of the predicted increase in sales due to daylighting. By the most conservative estimate, the profit from increased sales associated with daylight is worth at least 19 times more than the energy savings.
- The lighting energy savings from this chain's current skylights and photocontrol operation tend to run from about 20% to 30% compared to electric lights on at full power, while the whole-building energy dollar savings range from about 15% to 25%.

STATEWIDE SAVINGS

- California builds up to 31 million square feet of new retail per year. The vast majority of this is single-story construction. Nationally, 46% of retail space has dropped ceilings, while 54% has exposed ceilings.[2] If we assume that skylights can be used in 50% of the total area below dropped ceilings and 75% of the total area with exposed ceilings, then we estimate that there is 20 million ft^2 of retail per year in California that could potentially include skylighting.

- If we apply the energy and dollar savings achieved by the average store in this study (with a "standard" daylighting design) across a 10% first year penetration of the market, then the value of this savings would be $0.5 million dollars per year, or 3,500 MWh/yr.[3] Based a 1% increase in penetration per year, after the end of ten years of construction, the value would potentially increase tenfold, to $6 million per year, or 50,700 MWh/yr.[4] Cumulative savings over ten years is 249,986 MWh equal to a cost savings of $34 million dollars.
- At the "best" level, with state-of-the-art components capturing the maximum technical potential, these numbers could increase to $1.3 million per year or 9,600 MWh/yr. Based a 1% increase in penetration per year, after ten years, the value would potentially increase tenfold, to $19 million per year or 139,400 MWh/yr. Cumulative savings over ten years is 687,460 MWh equal to a cost savings of $94 million dollars. If a retrofit market for skylights and automatic photocontrols developed, these values would potentially increase by about 50%.

Healthy Schools: Daylighting, Lighting, and Ventilation (Project 2.4)

SCHOOL DISTRICT RETROFIT SAVINGS POTENTIAL

- The approximate energy savings for the Fresno district to retrofit *all* of its elementary classrooms with daylighting controls and better window glazing and electric lights would be 1,950 MWh per 10-month school year.
- The average energy savings per retrofitted classroom is about 1.15 MWh, or an estimated average power reduction of approximately 1.1 kW per classroom (for combined lighting, heating and cooling effects) over the 10-month traditional school year. Since many of the District's classrooms are operated during the summer months, the energy savings would be considerably higher for those classrooms.

STATEWIDE NEW CONSTRUCTION SAVINGS POTENTIAL

- The estimated energy savings if all new schools construction in California optimized the classroom design to take advantage of sidelighting (daylighting from windows) and daylighting controls would be 330 MWh/yr. Using a first year market penetration of 10%, the approximate first year energy savings from toplighting (using skylights) and daylighting controls would be 478 MWh. With an increase in market penetration of 1%

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[2] Armstrong Industries, 2002, private communication.
[3] These values are based on SkyCalc runs, which account for lighting, heating and cooling savings, and combine the net annual value of electricity and gas impacts into a blended kWh value.
[4] It is not possible to translate megawatt-hours into peak megawatt impacts, since the dynamics of climate and electric peaks greatly complicate the equation. A separate study should be done to understand the potential peak impacts of skylighting systems on state power demand.

per year the cumulative savings after 10 years will be 23,595 MWh with a cumulative cost savings of $3.2 million dollars.

Healthy Offices: Daylighting, Lighting and Ventilation (Project 2.6)

PARTICIPANT SAVINGS

- The incremental energy savings due to the addition of daylighting controls to the Customer Service Center (one of the two study sites) would result in a total of 69,000 kWh/yr of lighting energy savings (0.37 kWh/ft^2) and a total of 112,000 kWh/yr of electric energy savings (0.6 kWh/ft^2) when the additional cooling energy savings are included. Electricity peak demand for lighting would be reduced by 49 kW for the building, due to electric lights turned down during the day.

STATEWIDE SAVINGS

- Out of the total area of new construction/retrofit buildings in California, 30.9 million ft^2 are large offices and 9.9 million ft^2 are small offices. If all offices in California had daylighting potential similar to that of Customer Service Center, then adding daylighting controls would result in electric energy savings of 24,830 MWh/yr.
- Electric energy savings would be approximately 2,483 MWh in year one if daylighting controls were added to 10% of the large and small offices built in California. Increasing the market penetration by 1% per year over ten years, this would result in cumulative electric energy savings of 177,500 MWh and cost savings of over $24 million.

3.0 Integrated Design of Large Commercial HVAC Systems (Element 3)

3.1. Introduction

This research element focused on problems of integrated HVAC system design in large buildings (100,000 ft^2 and larger), and developed building-science solutions to support successful system integration and improved efficiency and performance.

Built-up HVAC systems are complex custom assemblies whose performance depends on a range of players. The designer stands in the midst of this process coordinating the activities of various entities to produce a product that works for the owner within the design constraints of time and budget. Due to the complexity of the process, the lack of easily accessible analysis tools and the limitations in fee and time, many choices are made based on rules-of-thumb and experience rather than analysis. In most cases, these factors lead to less than optimal performance of the resulting system.

The design of high performing built-up variable-air-volume (VAV) systems is fraught with challenges including mechanical budgets, complexity, fee structures, design coordination, design schedules, construction execution, diligence in test and balance procedures, and execution of the controls and performance of the building operators. With care however, a design professional can navigate this landscape to provide systems that are cost effective to construct and robust in their ability to serve the building as it changes through time.

During the course of this three-year program, the research team conducted field studies of HVAC systems in large commercial buildings to quantify problems with component/system selection as well as building controls and operation that cause energy inefficiencies. The primary focus was on the air side of VAV systems with chilled water plants. While covering only a minority of all systems installed in California, this is the most common type of large HVAC system and accounts for a large fraction of the state's cooling capacity, estimated to be 20% to 25%.

The detailed information from the field studies fed the team's efforts to develop new integrated design solutions, and was used to determine savings potentials. The project results provide engineers with an Advanced VAV System Design Guide (Design Guide) to enhance effective system integration. The Design Guide addresses the following areas:

- Early design and integrated design issues
- Zone issues
- VAV box selection
- Ducts design
- Supply air temperature reset
- Fan type, size and control
- Coils and filters
- Outside air/return air/exhaust air control

3.1.1. Element Objectives

The Element's overall objective was to identify energy savings solutions associated with large HVAC systems in California buildings over 100,000 ft^2. A specific technical objective was to increase the energy efficiency and functionality of VAV reheat air distribution systems by 25%. This guideline would be ready to disseminate to designers and manufacturers of large HVAC systems; portions of it ultimately may be appropriate for adoption into Title 24.

3.1.2. Project Team and Technical Advisory Group (TAG)

Element 3 was led by Erik Kolderup of Eley Associates with support from Tianzhen Hong and John Arent. Subcontractors were Taylor Engineering, SBW Consulting and New Horizons Technology.

Eley Associates and New Buildings Institute would like to acknowledge the invaluable guidance and advice provided by members of Element 3's TAG, which included:

- Karl Brown, California Institute for Energy Efficiency
- David Claridge, Ph.D., Department of Mechanical Engineering, Texas A&M University
- Paul DuPont, P.E., Managing Partner, DuPont, Dobbs & Kearns Engineers, LLC
- Ken Gillespie, Technologist, Technical & Ecological Services Department, Pacific Gas & Electric Company
- Tom Hartman, P.E., Principal, The Hartman Company
- Henry Lau, P.E., Senior Engineer, Engineering Analysis & Development Department, Southern California Edison
- David Sellers, Portland Energy Conservation, Inc. (PECI)

3.2. Field Studies (Project 3.2)

3.2.1. Objectives

This project's objective was to monitor performance of large commercial HVAC systems in five California buildings for six-month periods to collect data that would be used in Project 3.3, Building Science Solutions.

3.2.2. Approach

Project 3.2 comprised the following tasks:

- *Preliminary screening (Tasks 3.2.1 and 3.2.2).* After developing a list of buildings over 100,000 ft^2 built in California since 1995, including their occupancy type, the researchers surveyed those sites by telephone to determine which met the field study requirements and were potential candidates for onsite inspections.
- *Onsite inspections (Tasks 3.2.3 and 3.2.4).* Onsite inspections of 21 of those facilities were conducted to collect detailed information on their HVAC equipment and operation. Onsite inspection reports were completed describing each site's qualifications as a candidate for detailed monitoring.
- *Site selection (Task 3.2.5).* From those candidate sites, the researchers selected five buildings that had sufficient EMCS/sensors in place and operational to allow for

necessary data to be collected within budget, and detailed monitoring plans were developed for those sites. Data collection at sites 3, 4 and 5 took advantage of existing monitoring systems and collaboration with other research efforts at those sites.

- *Monitoring and data collection (Tasks 3.2.6 and 3.2.7).* The original research plan called for monitoring of each of the five buildings for a six-month baseline period. The actual monitoring periods differed from the original plan: Sites 1 and 2 were monitored for about one year; Site 3 for about five months; Site 4 for about three months; and Site 5 for about a year and a half (collecting partial data) and for two more months (obtaining additional data). The original intention was for the research team to then develop a baseline period report, implement proposed solutions in the buildings, conduct experimental field tests identified in Project 3.3, and monitor building performance again. However, due to monitoring and participant authorization delays, the experimental solutions could not be implemented within the contract period. Based on feedback from the PAC and TAG, the research team reevaluated the monitoring approach and devoted more time to analysis of building science solutions (Project 3.3) and development of the Advanced VAV System Design Guide (Project 3.6).

3.2.3. Technical Outcomes

- *Most plants sized below 400 ft²/ton.* Telephone interviews reached more than 500 sites identified from F.W. Dodge construction data. Eight percent of the total sample met all selection criteria. Onsite surveys conducted at 21 qualified buildings revealed that the majority of chilled water plants are conservatively sized at less than 400 ft²/ton, with most falling in the range of 200 to 400 ft²/ton. The following three figures show cooling capacity in ft²/ton (Figure 2), building floor area (Figure 3), and chilled water plant capacity (Figure 4). The complete results of these surveys are available in the Onsite Data Inspection Report (deliverable 3.2.4).
- *Average annual construction using chilled water plants is 2.6 million ft² per year and 8,200 tons per year.* The site survey information can be used to roughly estimate new construction population size and HVAC energy and demand. The 21 sites total 6.5 million square feet of floor area and 20,500 tons of cooling capacity. Each of these buildings was completed during (roughly) a 2.5–year period. Therefore, annual average construction volume for this sample is 2.6 million ft² per year and 8,200 tons per year.
- *Five sites were selected for detailed monitoring.*

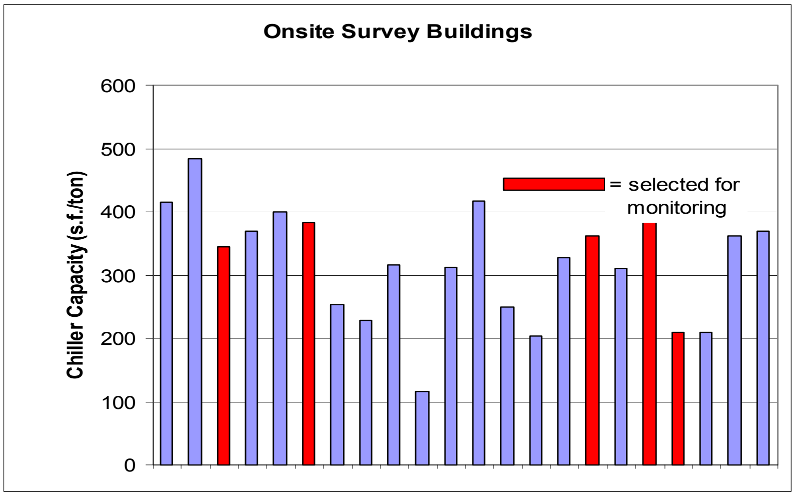

Figure 2. Onsite Survey Results by Chiller Capacity (ft²/ton)

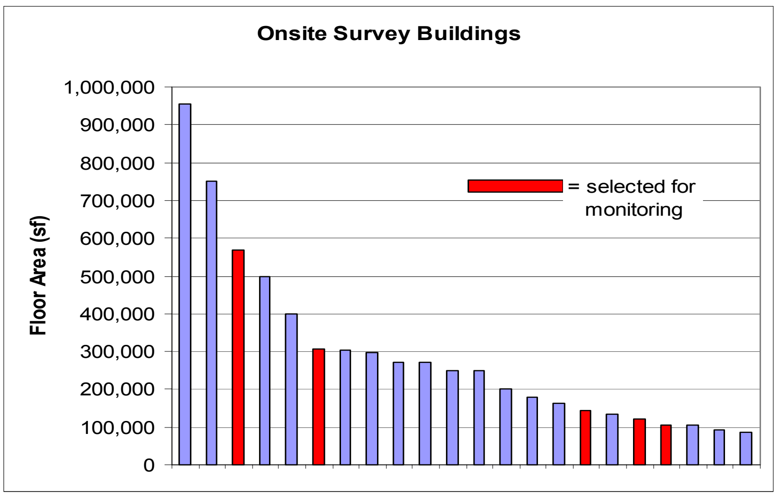

Figure 3. Onsite Survey Results by Floor Area (ft²)

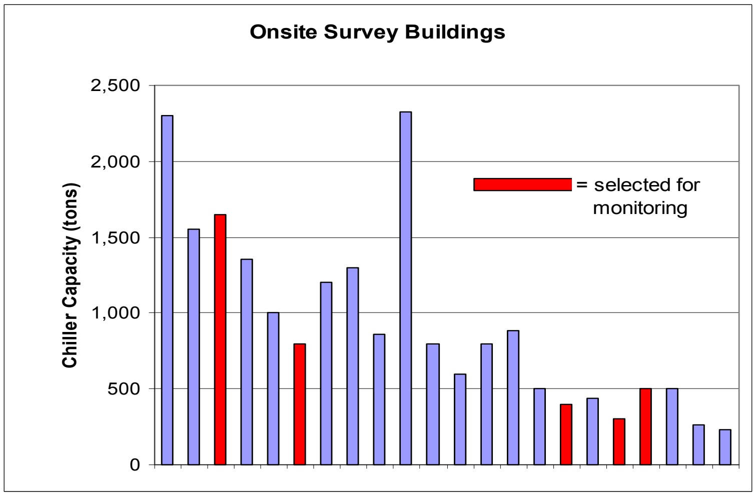

Figure 4. Onsite Survey Results by Chiller Capacity (tons)

Products

- A database listing buildings over 100,000 ft² completed in California since 1995, including occupancy type (3.2.1)
- Summary report: screening interviews with candidate sites (3.2.2)
- Field data collection protocols (3.2.3)
- Onsite inspection report for 21 sites (3.2.4)

3.3. Building Science Solutions (Project 3.3)

3.3.1. Objectives

This project's objective was to use the data collected in Project 3.2 to:

- Characterize design and operational problems in large commercial HVAC systems;
- Develop solutions;
- Estimate the energy benefit of improved design; and
- Provide calibration data for simulation models used to evaluate alternative solutions.

3.3.2. Approach

- *Sensitivity analysis and preliminary solutions (Tasks 3.3.1 and 3.3.2).* The researchers quantified problems with controls and operation that cause energy inefficiencies. This included studying the load profiles, controls and system performance to identify improvements, and testing different design approaches using simulations and engineering calculations. The researchers then developed a preliminary list of solutions and an analysis of their potential energy impact.

  As part of the sensitivity analysis, simulations of a 105,000 ft² office building were performed to estimate the range of impacts for measures planned to be covered in the Design Guide. The simulated building represents monitoring Site 1; in some cases preliminary monitored data from that site was used in the analysis. The analysis results were used to help streamline the monitoring effort in the other buildings being studied.

- *Baseline solutions report (Task 3.3.3).* This report documents the analysis of fan selection and control issues, including the impacts of fan type selection, fan sizing and supply pressure reset. The report documents the research that provided a basis for the Design Guide, but *actual conclusions and recommendations are in the final Design Guide.* Topics covered in the Baseline Phase Solutions Report are: fan systems, coils, terminal units, demand-control ventilation, internal heat gain, system effects, reheat source and control, supply air temperature control, and night purge.
- *Field test plan and report (Tasks 3.3.4 and 3.3.5).* The original research plan called for performing field tests of energy efficiency measures to support development of the Advanced VAV System Design Guide. The type of experiment was expected to be limited to control system modifications, such as implementing supply air pressure reset controls. However, during the course of the research the project team found that experiments were not practical within the project budget and schedule. The team instead focused more effort on simulation analysis and analysis of monitored data to provide more directly useful information for the Design Guide. Although experiments did not take place, facility managers from three of the five sites have stated that they plan to implement measures uncovered and evaluated in the course of Element 3's research. Task 3.3.4, the solution field test plan, was completed; it contains descriptions of the building managers' plans to implement system modifications, but this is not a public report since it contains details considered confidential by the building managers. Task 3.3.5 was eliminated.
- *System performance comparison and revised solutions (Tasks 3.3.6 and 3.3.7).* As described above, the tasks related to field testing were not performed as originally planned. Instead, the revised solutions report and information to support the Design Guide recommendations was developed using analysis and simulations. Task 3.3.6, a comparison of system performance to expected savings, was eliminated. Task 3.3.7, a revised design solution list, was merged with Task 3.3.3 as part of an ongoing analysis task in support of the Design Guide development.

3.3.3. Technical Outcomes

- *Identification of 14 preliminary solutions.* The sensitivity analysis resulted in observations and conclusions related to 14 measures that would have the greatest impact on energy efficiency (see Figure 5). These are *preliminary* observations whose purpose was to inform the Design Guide development. Final conclusions and recommendations appear in the actual Design Guide.
- *Sensitivity to energy cost analyzed.* Figure 5 illustrates the energy cost sensitivity results for each measure. The longer the bar on the graph, the more potential energy impact for the measure. These results are useful for a rough comparison of the importance of individual measures but are not conclusive results. A number of alternatives were evaluated for each measure. Some measures were evaluated over a relatively conservative range of options while others cover extremes beyond likely design range. Several results are reported for two different operating schedules (24/7 vs. 5 days per

week) because the hours of operation are significant for the impact of some measures, especially supply air temperature reset and VAV box sizing.

- *Solutions ranked for relative energy impact.* The analysis shows that supply air temperature control (i.e., reset) has the largest potential individual impact. The high energy case assumes a constant-supply air temperature setpoint throughout the year. The lowest energy case assumes that the supply air temperature is reset upwards as high as possible while still satisfying cooling loads in the warmest zone. Duct sizing, VAV box sizing and fan selection follow supply air temperature control in order of their impact on the building energy use.

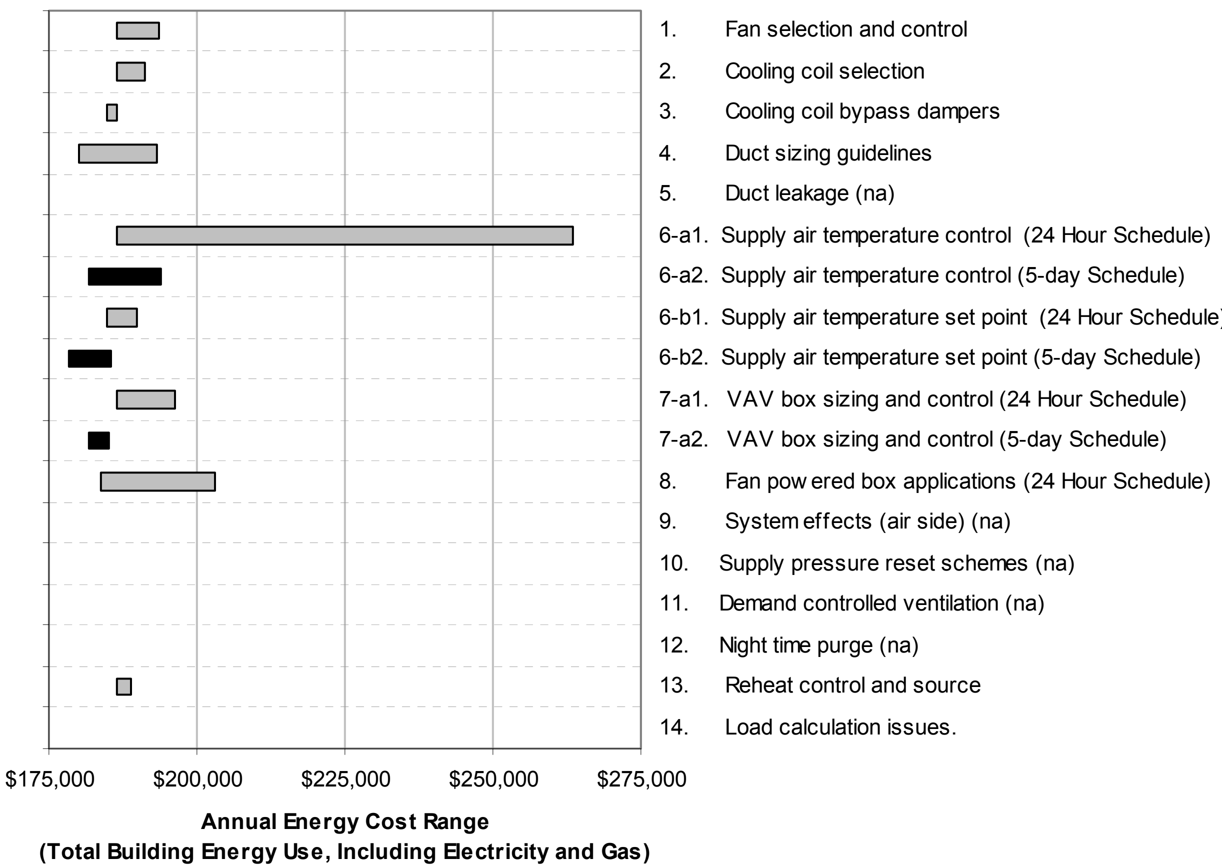

Figure 5. Estimated Range of Energy Cost Impact for Each Measure (100,000 ft² office building)

(Those indicated with "na" were not evaluated during the initial sensitivity analysis)

- *Analysis underlying the Design Guide.* The "Baseline Phase Solutions Report" documents the research that provided a basis for the Design Guide, but *actual conclusions and recommendations are in the final Design Guide.* Key observations per component from this baseline phase report are listed here:
  - *Fan Systems. The team developed a model that more accurately represents fan system performance than the models in current simulation programs.* In addition to fan efficiency, the model also represents motor, belt and variable-speed drive efficiency. This model is a good match to manufacturer's data and was used along with the monitored fan data to inform many of the Design Guide recommendations. This fan model is

described in an article written by team members Mark Hydeman and Jeff Stein of Taylor Engineering, published in the May 2003 issue of *HPAC Engineering* (available at www.newbuildings.org/pier).

- *Terminal Units.* A simulation analysis compared the energy performance of alternative VAV box sizing criteria, considering impacts on fan energy, cooling energy and reheat energy. The results indicate that *selecting boxes for a 0.5 in. total pressure drop provides optimal performance in most cases.*
- *Demand-Control Ventilation (DCV). DCV can help reduce energy in areas that have varying occupancy patterns.* A method was developed for calculating potential savings for reducing outside air flow based on CO_2 control. The "Baseline Phase Solutions Report" provides the calculation details.
- *Internal Heat Gain. The monitored loads show low lighting power of under 0.4 W/ft^2 and plug loads peaking at about 0.6 W/ft^2.*
- *System Effects.* Actual airflow patterns of fans are almost always different from the laboratory test. These "system effects" cause the fan to develop a different characteristic curve, as well as introduce additional pressure drop. It is better to plan for system effect in the design. *To reduce fan system effect and air pressure loss through duct, it is recommended to layout the air duct first and then the AHU*, so that sudden turns and changes in air flow can be minimized.
- *Reheat Source and Control.* The results show ***significant variation in reheat loads between buildings located nearby each other, indicating that there are potential savings due to design and/or operation in many buildings***. Definitive conclusions are not possible regarding the comparison of electric vs. hot water reheat, though the one building in the monitored group with electric reheat consumes less reheat energy than a nearby building.
- *Supply Air Temperature Control.* Simulation analysis of different supply air temperature reset schemes is provided in this section of the "Baseline Phase Solutions Report." Results indicate that *lowest energy consumption occurs when supply air temperature is reset to the highest point possible whenever the system runs in economizer mode.* Results comparing standard design to best practice design are also presented.
- *Night Purge.* A review of other research indicates that successful *applications of nighttime purge* (operating fans at night to precool building mass and reduce cooling energy) *demonstrate significant reduction of peak cooling load* during daytime and energy cost savings if time-of-use rate applies.

- *Improvements planned at the monitored buildings.* The team briefed the facility managers on the energy impacts and proposed recommendations that are a part of the new Design Guide. Facilities managers at three sites have said they intend to make changes that will improve the performance of their VAV systems and reduce building energy use. Some of the proposed measures are described below:
  - *Supply pressure reset by demand.* At one site, the researchers recommended the use of supply pressure reset by demand to mitigate problems related to fan operation in the surge region. The research team's preliminary analysis indicates that reset will

reduce annual fan energy use by about 50%. The facility may need to upgrade its somewhat outdated EMCS software before they can implement this change.

- *Supply pressure reset controls.* Another site is also a candidate for supply pressure reset controls. The site has electric resistance heat, so may also benefit from resetting the VAV box minimums and employing aggressive supply temperature reset.
- *Supply pressure reset by zone demand and other measures.* Another site is a likely candidate for several measures: supply pressure reset by zone demand, control of return fan to maintain pressure in the exhaust plenum and exhaust damper to maintain space pressure, and active demand-control ventilation (DCV).

Products

- Sensitivity analysis (3.3.1)
- Baseline phase solutions report (3.3.3)

3.4. Statewide Energy Estimate (Project 3.4)

3.4.1. Objectives

This project's objective was to apply the individual building-savings findings and analysis to the statewide building population.

3.4.2. Approach

The researchers used baseline energy consumption data from PG&E's 1999 Commercial Building Survey for the office building category to estimate the electricity savings per square foot of floor area for a building design employing the best practices recommended in the Design Guide. Savings fractions for fan energy, cooling energy, and heating energy were based on simulations comparing standard practice to best practice for a 50,000 ft^2 office building. In addition, the monitored data from the five study sites were used as a baseline comparison of the modeled outcomes.

3.4.3. Technical Outcomes

- *12% total building electrical savings.* For buildings adopting the Design Guide, HVAC electricity savings are estimated to be 25%, corresponding to 12% of total building electricity consumption. Total building natural gas heating savings are estimated to be 41%.

  The California Energy Commission predicts large office building construction volume of about 30 million square feet per year over the next ten years, equal to 20% of new commercial construction in California. A reasonable estimate is that about one-half of those buildings will be served by VAV reheat systems. Therefore, the Design Guide will apply to roughly 150 million square feet of new buildings built in the ten-year period between 2003 and 2012.

  The researchers applied annual energy savings estimates of 12% combined with a market penetration of 10% of the large commercial office space with VAV reheat systems over each of the next 10 years. This is equal to 5% penetration of all large commercial office space.

- *2,220 MWh/yr statewide electricity savings.* If the best practices recommended in this study were implemented, statewide electricity savings are estimated to be 2,220 MWh/yr for new construction. Savings would reach 22,200 MWh/yr at the end of 10 years, and the cumulative electricity savings over that time would be 122,100 MWh.Products
- Statewide energy impact report (3.4.1)

3.5. Design Guidelines for Integrated Design Solutions (Project 3.6)

3.5.1. Objectives

This Element's product—in addition to a large set of valuable data available through the web sites listed in the preface—is a guideline for integrated HVAC system design that compiles research results and summarizes the most important data and design recommendations.

The intent of the guideline is to promote efficient, practical designs that advance standard practice and can be implemented successfully today. The goal is HVAC systems that minimize life-cycle cost and can be assembled with currently available technology by reasonably skilled mechanical contractors. In some cases, even greater savings might be captured through more advanced controls or with additional construction cost investment.

3.5.2. Approach

Building on the research and analysis conducted in Projects 3.2 (Field Studies) and 3.3 (Building Science Solutions), the project team developed an "Advanced VAV System Design Guide" (Design Guide) for designers of large HVAC systems in new commercial buildings. This Design Guide was written to help HVAC designers create systems that capture the energy savings opportunities, and at the same time feel comfortable that system performance will meet client expectations. This is a best practices manual developed through experience with design and commissioning of mechanical and control systems in commercial buildings and informed by research on five case study projects.

3.5.3. Technical Outcomes

- *Targeted application and audience of the Design Guide.* The Advanced VAV System Design Guide focuses on built-up variable air volume (VAV) systems in multi-story commercial office buildings and targets those located in California or similar climates. But much of the information is useful for a wider range of systems types, building types, and locations. Topics such as selection guidelines for VAV terminal units apply equally well to systems using packaged VAV air handlers. And recommendations on zone cooling load calculations are relevant regardless of system type.

  The Design Guide is written for mechanical designers and addresses their issues and interests in a manner that is respectful of their role and responsibility in the construction process. It is organized around common design decisions and components to help the reader easily access useful information, and it provides extensive technical depth and references.

- *Comprehensive Guideline Content.* The Design Guide addresses air-side system design, covering fans, air handlers, ducts, terminal units, diffusers, and their controls, with emphasis on getting the air distribution system components to work together in an integrated fashion. Figure 6 illustrates the interrelationship of the Design Guide topics (the numbered labels correspond to specific sections of the Design Guide).

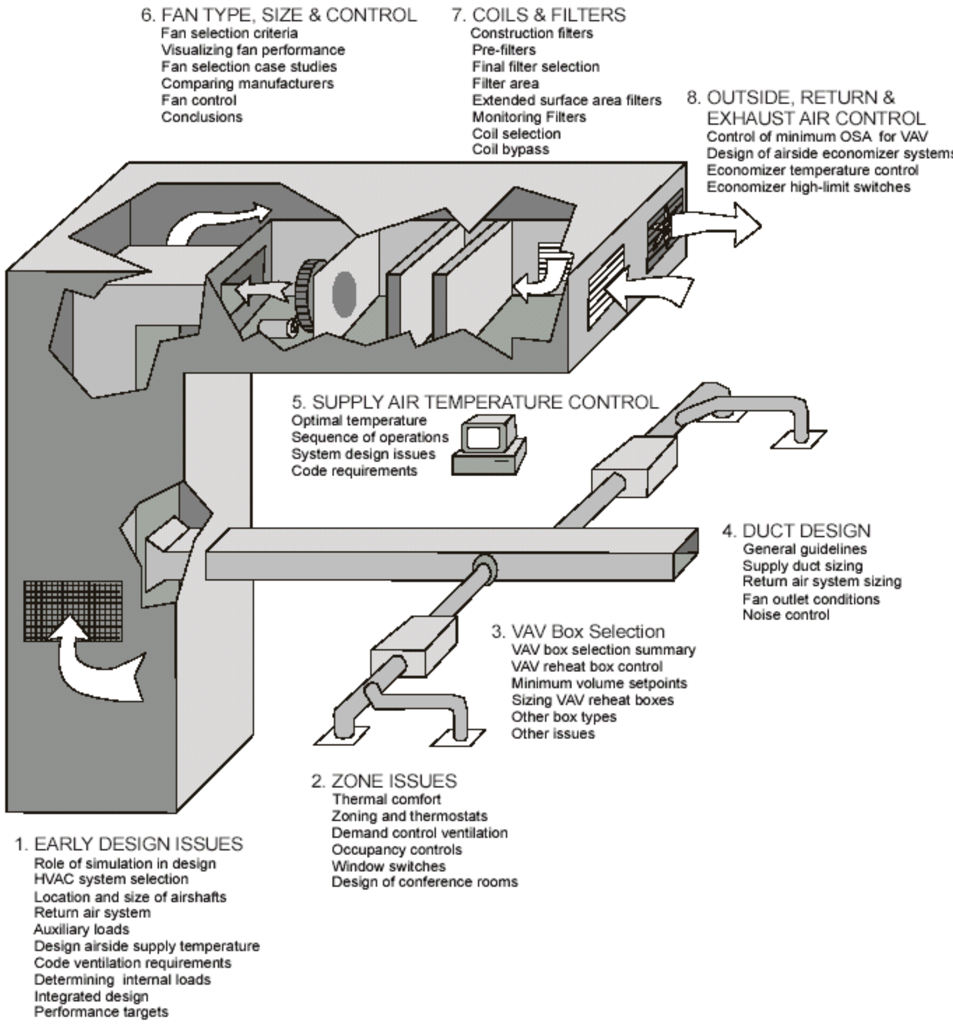

Figure 6. Overview of Design Guide Contents

- *12% total building electricity and 25% HVAC electricity savings.* For buildings adopting the Design Guide, HVAC electricity savings are estimated to be 25%, corresponding to 12% of total building electricity consumption. Natural gas heating savings are estimated to be 41%. In a commercial building, fans represent a significant part of the total building energy and demand. In the five monitored sites, fan energy represents between 20% to 50% of the total HVAC electrical energy use, or 10% to 30% of the total building electrical energy usage, which can be more than the chiller. The design techniques described in the Design Guide can reduce this fan energy by 50% or more, contributing the lion's share to the total building energy savings of 12%.
- *Key principles for achieving these savings include:*

1. Reduce design system static pressure by carefully selecting the terminal unit, and by avoiding system effects, sound traps, and high loss fittings.

2. Employ demand-based static pressure reset.
3. Use low-pressure plenum returns with relief fans where possible.
4. Employ demand-based, supply temperature reset to reduce reheat energy and extend economizer effectiveness.
5. Design fan systems to turn down and stage efficiently because actual system demand is normally significantly lower than design.
6. Optimally size terminal units to balance the energy impacts of pressure drop and minimum airflow control.
7. Set terminal unit minimums as low as required for ventilation and use intelligent VAV box control schemes to prevent stratification during heating.
8. Employ demand-based ventilation controls for high-density occupancies.
9. Design conference rooms and other high-density occupancies to provide ventilation without excessive fan energy or reheat.
10. Design 24/7 loads to allow efficient system turndown and use of economizer cooling.

- *Summary of Recommendations.* Table 1 summarizes the Advanced VAV System Design Guide's key recommendations.

Table 1. Summary of Design Guide Recommendations

Issue	Recommendation
Early Design Issues	1. Use simulation tools to understand the part-load performance and operating costs of system alternatives. 2. Develop a system selection matrix to compare alternative designs. 3. Consider multiple shafts for large floor plates 4. Place the shafts close to, but not directly under, the air-handling equipment. 5. Use return air plenums when possible because they reduce both energy costs and first costs. 6. Design the HVAC system to efficiently handle auxiliary loads that do not operate on the normal HVAC schedule. 7. Select a design supply air temperature in the range of 52°F to 57°F. 8. Size interior zones for 60°F or higher supply air temperature. 9. Avoid overly conservative estimates of lighting and plug loads.
Zone Issues	10. Consider demand control ventilation in any space with expected occupancy load more dense than 40 ft2/person. 11. For conference rooms, use either a VAV box with a CO2 sensor to reset the zone minimum or a series fan power box with zero minimum volume setpoint.
VAV Box Selection	12. Use a "dual maximum" control logic, which allows for a very low minimum airflow rate during no- and low-load periods. 13. Set the minimum volume setpoint to the larger of the lowest controllable airflow setpoint allowed by the box and the minimum ventilation requirement (often as low as 0.15 cfm/ft2). 14. For all except very noise sensitive applications, select VAV boxes for a total (static plus velocity) pressure drop of 0.5" H2O. For most applications, this provides the optimum energy balance.
Duct Design	15. Go straight. 16. Use standard length straight ducts and minimize both the number of transitions and of joints. 17. Use round spiral duct wherever it can fit within space constraints. 18. Use radius elbows rather than square elbows with turning vanes whenever space allows. 19. Use either conical or 45° taps at VAV box connections to medium pressure duct mains.

Issue	Recommendation
	20. Specify sheet metal inlets to VAV boxes; do not use flex duct. 21. Avoid consecutive fittings because they can dramatically increase pressure drop. 22. For supply air ducts, use a starting friction rate for VAV systems of 0.25″ to 0.30″ per 100 feet. 23. At the end of the duct system, choose a minimum friction rate of 0.10″ to 0.15″ per 100 feet. 24. For return air shaft sizing maximum velocities should be in the 800 fpm to 1200 fpm range through the free area at the top of the shaft (highest airflow rate). 25. To avoid system effect, fans should discharge into duct sections that remain straight for as long as possible, up to 10 duct diameters from the fan discharge to allow flow to fully develop. 26. Use duct liner only as much as required for adequate sound attenuation.
Supply Air Temperature Reset	27. Use supply air temperature reset controls to avoid turning on the chiller whenever possible. 28. Continue to use supply air reset during moderate conditions when outdoor air temperature is lower than about 70°F.
Fan Type, Size and Control	29. Use demand-based static pressure setpoint reset to reduce fan energy up to 50%, reduce fan operation in surge, and to improve control stability. 30. Use housed air-foil fans whenever possible, even if space is constrained.
Coils and Filters	31. Avoid using pre-filters. 32. Specify final filters with 80% to 85% dust spot efficiency. 33. Utilize the maximum available area in the air handler for filters rather than installing blank-off panels. 34. Use extended surface filters. 35. Consider lower face velocity coil selections ranging from 400 fpm to 550 fpm and selecting the largest coil that can reasonably fit in the allocated space. 36. Consider placing a bypass damper between coil sections where the intermediate coil headers are located.
Outside Air/Return Air/Exhaust Air Control	37. For outside air control use a dedicated minimum ventilation damper with pressure control. 38. Use barometric relief if possible, otherwise relief fans (rather than return fans) are recommended in most cases. 39. For economizer control, stage the outdoor and return air dampers in

Issue	Recommendation
	series rather than in tandem. 40. Specify differential drybulb control for economizers in California climates.

- *Designing integrated systems.* The Advanced VAV System Design Guide focuses on air-side design and selecting components to work efficiently as an integrated system. Achieving optimal air-side efficiency and maximum savings also demands attention to the integration of HVAC and architectural design decisions.

  HVAC and architectural design affect each other in many ways. Space is the primary issue: larger ducts, shafts, and coils result in lower air pressure loss and lower fan energy. Central plant design is another integrated design issue, because performance of the air distribution system and the chilled water system are integrally linked. Air-side temperature controls affect both fan energy and chiller efficiency. Table 2 identifies a number of integration issues that should be considered early in the design process; see the referenced Design Guide chapter for details.

Table 2. HVAC and Architectural Coordination Issues

Issue	Integrated Design Considerations	See Design Guide Chapter on:
Shaft size and location	Larger shafts reduce pressure loss and lead to lower fan energy.	Duct Design
Air handler size	Larger face area for coils and filters reduces pressure loss. Adequate space at the fan outlet improves efficiency and may allow the use of housed fans, which are usually more efficient than plenum fans.	Coils and Filters Duct Design (section on Fan Outlet Conditions)
Floor-to-floor height	More space above the ceiling allows for larger ducts and VAV boxes, potentially reducing pressure losses.	VAV Box Selection Duct Design
Return air path	Plenum returns are more efficient than ducted returns, but they require fire-rated construction.	Early Design Issues (section on Return Air System)
Barometric relief	Barometric relief is more efficient than return fans or relief fans but requires large damper area and has a bigger impact on architectural design.	Outside Air/Return Air/Exhaust Air Control
Outside air intake	Sizing and location of outside air dampers are especially important in California due to the savings available from air-side economizer operation.	Outside Air/Return Air/Exhaust Air Control
Noise	The architect and HVAC designer should work together to identify noise control measures that do not compromise system performance.	Duct Design (section on Noise Control)
Window shading	Reduction or elimination of direct sun on the windows offers several benefits in addition to the direct cooling load reduction. Ducts and VAV boxes serving perimeter zones can be smaller and less expensive due to lower peak air flow requirements. Perhaps more importantly, the glass will stay cooler, improving the comfort of occupants near the windows.	Zone Issues (section on Thermal Comfort)
Window orientation	Favorable orientation can be the most cost effective solar control measure. Avoid east or west-facing windows in favor of north facing windows and south facing windows with overhangs.	Not discussed further in Design Guide
Glass type	Where exterior shades and/or good orientation are not feasible, use spectrally selective glazing with low solar heat gain coefficient (SHGC).	Not discussed further in Design Guide

Zoning	Grouping spaces with similar ventilation requirements, cooling loads and occupancy schedules can provide first cost savings (due to fewer zones) and energy savings (due to opportunities to shut off portions of the system).	Zone Issues (sections on Zoning and Thermostats)

Products

- Advanced VAV System Design Guide (3.6.2)

Market Connections

PRESENTATIONS

- *ACEEE.* See "Publications" below.
- *ASHRAE Winter 2004 conference***.** There has been considerable excitement about the new fan model within the ASHRAE community. A seminar and a symposium are scheduled for the January 2004 Anaheim national conference
- *ASHRAE local chapters.* Taylor Engineering presented some of the research results at a Salt Lake City chapter meeting on March 7, 2003. The presentation was funded separately by the Institute. Golden Gate chapter meetings in San Francisco are being pursued.
- *California utilities.* The Institute made visits or contacts with each of the California IOUs and SMUD during 2001-2002 to brief them on the PIER objectives, anticipated products and schedule. NBI and project team members will visit each of these utilities at the end of 2003 to provide the efficiency program staff with completed PIER products and to discuss the transfer of the results into their programs. The IOU staff has indicated that the Savings by Design statewide program will be the best mechanism for integration of the majority of the PIER results.
- *PG&E's PEC training.* Element 3 results and Design Guide will be presented at a Pacific Energy Center (PEC) training session in October 2003.

PUBLICATIONS

- HPAC Engineering. An article describing the new fan model developed by Element 3 was published in the May 2003 issue of *HPAC Engineering* (see Project 3.3 Technical and Market Outcomes for details). *HPAC Engineering's* California subscribers include more than 4,000 HVAC and building industry professionals, including engineering management; system designers, installers and maintenance personnel; and facility managers. Industry responses to the article include this comment from a reader: "Last month's article on fans was excellent. I used it yesterday to help explain a control static set point problem on a VAV system while at the job site. The owner, consulting engineer, controls engineer and others were all present." The magazine publisher said that it's rare to get such positive feedback from readers.
- *ACEEE.* A paper, "Measured Performance and Design Guidelines for Large Commercial HVAC Systems," was presented and published as part of the ACEEE Summer Study in August 2002.

- *ASHRAE.* A Journal article has been accepted for December 2003 or January 2004. The symposium paper will also be published from the National Conference in January 2004. (See "Presentations" above.

CODES, STANDARDS AND GUIDELINES

- *Title 24.* PIER findings on static pressure reset, sensor location and fan power sizing modified the prescriptive requirements for space conditioning systems in the 2005 Standards.
- *Advanced Building Guidelines.* Team members Mark Hydeman and Erik Kolderup provided a brief review of mechanical system design criteria proposed for the Institute's *Advanced Building Guidelines* (ABG). The Institute is entering into an agreement with ASHRAE and AIA to use the ABG "E-Benchmark" criteria in an ASHRAE-sanctioned national guide for their members within a year. The guide will be under the ASHRAE banner and the Institute will be listed as a contributor. Since the ABG contains Element 3 PIER findings, this new agreement will help move the PIER work directly into the most widely used reference for mechanical designers.

NETWORKING AND COLLABORATION

- *Collaboration with PECI.* Element 3, the Institute and PECI discussed the overlap of E3's Design Guide and the PECI/LBNL PIER project, "Control System Design Guidelines and Air System Test Guidelines." The general conclusion was that while the two projects have different focuses, they are very complementary. The PECI project focuses on successful field implementation and testing (commissioning) of HVAC systems while E3's project focuses on "front-end" system selection and design. One outcome of the discussions was that David Sellers of PECI joined the E3 TAG.
- *Lawrence Berkeley National Laboratory and U.C. Berkeley.* E3 provided technical data that enhanced LBNL's Duct Research and Fan Diagnostics projects. E3 and LBNL/UCB project team's coordination on data collection for Site 3. This data-sharing resulted in costs savings for E3 and the LBNL/UCB teams.
- *Other PIER programs.* E3 collaborated with researchers in another PIER program (AEC program, project headed by Tom Webster) who were studying fan system diagnostics measurements. They installed extra monitoring points needed for E3's analysis, in turn, they used data collected by the E3 team from sites 1 and 2. Also, a researcher working on another PIER project studying low-energy cooling systems is using data from E3's fan research and simulations to improve the fan models they are using from Energy Plus.
- *U.S. General Services Administration (GSA).* At Site 5, a courthouse in Sacramento, E3 collaborated with GSA's controls engineer, who is responsible for troubleshooting throughout the region. As a result, E3's research and findings have influenced operations at federal facilities throughout the region.
- *Energy simulation software.* An EQuest/DOE2.2 developer has expressed interest in using the fan model in their simulation engine. The fan model results are likely to become incorporated into software during the natural upgrade periods.

3.6. Conclusions and Recommendations

3.6.1. Conclusions

- *The Design Guide recommendations can save approximately 12% of total building electrical energy use.*
  - For buildings adopting the Design Guide, HVAC electricity savings are estimated to be 25%, corresponding to 12% of total building electricity consumption. Natural gas heating savings are estimated to be 41%.
  - Fan energy represents between 20% to 50% of total HVAC electrical energy use, or 10% to 30% of the total building electrical energy usage, which can be more than the chiller energy use. The Design Guide recommendations can reduce the fan energy by 50% or more.
  - Fan-only peak day electric demand reaches between 0.5 and 1.0 W/ ft^2. Following the Design Guide recommendations could provide a modest reduction in demand due to better duct design and lower overall pressure drop, but most of the measures affect part-load efficiency.
  - Electricity savings of approximately 1.5 kWh/ft^2-year and 8.5 kBtu/ft^2-year are predicted for the measures in the Design Guide compared to current standard practice.
  - If the best practices recommended in this study were implemented, statewide electricity savings are estimated to be 2,220 MWh/yr for new construction. Savings would reach 22,200 MWh/yr at the end of 10 years, and the cumulative electricity savings over that time would be 122,100 MWh.
- *Key principles to achieving these savings include:*
  1. Reducing design system static pressure by carefully selecting the terminal unit, and by avoiding system effects, sound traps, and high loss fittings.
  2. Employing demand-based static pressure reset.
  3. Using low-pressure plenum returns with relief fans where possible.
  4. Employing demand-based, supply temperature reset to reduce reheat energy and extend economizer effectiveness.
  5. Designing fan systems to turn down and stage efficiently because actual system demand is normally significantly lower than design.
  6. Optimally sizing terminal units to balance the energy impacts of pressure drop and minimum airflow control.
  7. Setting terminal unit minimums as low as required for ventilation and use intelligent VAV box control schemes to prevent stratification during heating.
  8. Employing demand-based ventilation controls for high-density occupancies.
  9. Designing conference rooms and other high-density occupancies to provide ventilation without excessive fan energy or reheat.

10. Designing 24/7 loads to allow efficient system turndown and use of economizer cooling.

- *Most systems operate at part-load the majority of the time.* Systems and controls must be designed to be efficient across the full range of operation. The most important measures are careful sizing of VAV boxes, minimizing VAV box minimum supply airflow setpoints, controlling VAV boxes using a "dual maximum" logic that allows lower airflows in the deadband mode, and supply air pressure reset control. Together these provide substantial fan and reheat savings because typical systems operate many hours at minimum (yet higher than necessary) airflow.
- *Early design issues are most critical.* Optimal performance of the HVAC system depends on the integration of the design with the other building components during the early phases of building design. The Design Guide focuses on the following early design issues to be addressed: integrated design, simulation, system selection, location and size of air shafts, establishment of the return air path, provisions of auxiliary and 24/7 loads, selection of design air-side supply temperature, determination of code ventilation requirements, determination of actual internal loads, and establishment of performance targets.
- *HVAC designers need reasonable and credible recommendations.* The HVAC design community is wary of radical departures from standard practice and is risk adverse. The Design Guides are written to help them create systems that capture the energy savings and performance opportunities, and at the same time feel comfortable that system results will meet the client expectations. It provides "best practices" that can help meet efficiency objectives through tools and strategies familiar to, but not often applied by, the designers.

3.6.2. Commercialization Potential Or Commercialization Initiated

The California Energy Commission predicts large office building construction volume of about 30 million square feet per year over the next ten years, equal to 20% of new construction in California. A reasonable estimate is that about one-half of those buildings will be served by VAV reheat systems; therefore, this Design Guide will apply to roughly 150 million square feet of new buildings built in the ten-year period between 2003 and 2012.

For the Design Guide "commercialization' really means the distribution and application of the contents resulting in improved energy performance of buildings. There are many conduits for the results and the project team initiated several as described under "market connections". For example, distribution of the Design Guide was started through the California utilities and exposure to the research findings and Design Guide content through industry publications and trainings. The Design Guide content is also being adopted into the criteria phase (E-Benchmark) and the Design and Owners Guide of the Advanced Building Guidelines (ABG). The ABG is serving as a platform for a new advanced guide within ASHRAE, thus the PIER HVAC work will become integrated into two national best practices guides that are widely accepted and used by the design community.

The continued promotion of the Design Guide document and its specific objectives and recommendations by the Commission, and its partners, will be important to commercialize its active use.

3.6.3. Recommendations

The project team's recommendations for further research, product development and market penetration fall into three categories: the integration of PIER results into HVAC design and modeling tools; distribution and promotion of the Design Guide; and the development of an owner's "roadmap" to integrated high-efficiency HVAC system design.

Integrate PIER Results into HVAC Design and Modeling Tools

- *Fan model improvement.* The Element 3 team developed fan models to support the Large HVAC PIER work. The team recommends building on those models to create a series of modules that would improve the simulation of VAV systems. These modules would take several different forms, depending on the application and the target market, and could include:
    - *Automated calibration assistant.* Develop an automated database tool that would provide a quick fix to improve the accuracy of current simulation engines.
    - *Default system curve generator***.** Develop a tool for default/generic VAV system airflow and pressure to assist in early evaluation of fan design alternatives such as size, type, staging and pressure reset.
    - *Migration of fan system models into marketplace***.** Work directly with simulation model developers to gain market penetration of the simulation models and evaluation techniques developed by Element 3. The developers for eQuest and EnergyPlus have already expressed interest.
    - *Manufacturer selection programs***.** Work directly with fan model developers to incorporate characteristic system curves and evaluation techniques into the ranking of life-cycle costs of fan selections and to allow users to compare fans across classes of fan types (i.e., plenum and housed fans).
    - *Simulation tool user interface.* Develop an MS Access-based simulation tool that together with the default system curve generator would allow accurate modeling of fan systems in the near term.
- *VAV box minimums.* Practical VAV box minimums have a large impact on the energy used for airflow (fans) and reheat. Although the Design Guide describes the process by which these can be determined, it is more practical to work directly with the VAV box manufacturers to build these practical control minimums into their box ratings. The project team recommends developing a standard box rating methodology with ASHRAE or ARI.
- *Field evaluation of supply pressure reset.* At three of the five sites studied by Element 3, the building owners expressed an interest in retrofitting supply pressure reset controls for both energy savings and to reduce the instability of the supply fans. The project team recommends measuring these post-retrofit systems and comparing their performance against the extensive baseline data already collected by the project. Based on the findings, the Design Guide would be updated and related papers and articles published.

Distribution and Promotion of the VAV Design Guide

The Advanced VAV System Design Guide was the culmination of the extensive work under this research element. Introduction of the Design Guide to the California utilities was completed during the contract term and as well as several methods for highlighting key content and the complete guide to the design community (see Market Connections).

This momentum should be continued over the next year to gain exposure and adoption of the Design Guide recommendations via the following type of specific activities: promotion of the Design Guide findings through professional journals via ads and articles; continued contact with utility program managers regarding use of the Design Guide in their programs; distribution of the Design Guide to known large office mechanical firms in California; durative publications on specific items of high impact (eg. Fan model); targeted web links to the Guide from industry and professional association sites; distribution of the Design Guide to California mechanical engineering schools; and availability of the Design Guide through common publication channels.

Owner's "Roadmap" to Integrated High-Efficiency HVAC System Design

The project team recommends the development of an Owner's Planning Guide and Design Standards, two companion documents that would give owners a tool to help make sure they are getting effective, efficient HVAC design. The planning guide would provide the benefits of advanced HVAC design and direction for HVAC design and bid management. It would leverage the work under the *Advanced Building Guidelines* planning document but be customized for California large commercial developers. A companion document, the Owner's Design Standards, would include instructions to the design team describing the owner's requirements. The information would be based on the Design Guide but would be expanded and packaged so that they could be readily used by building owners.

3.6.4. Benefits to California

The California Energy Commission predicts large office building construction volume of about 30 million square feet per year over the next ten years, equal to 20% of new construction in California. A reasonable estimate is that about one-half of those buildings will be served by VAV reheat systems. Therefore, the Design Guide will apply to roughly 150 million square feet of new buildings built in the ten-year period between 2003 and 2012.

The researchers applied annual energy savings estimates of 12% combined with a market penetration of 10% of the large commercial office space with VAV reheat systems over each of the next 10 years. This is equal to 5% penetration of all large commercial office space. If the best practices recommended in the Design Guide were implemented, first-year statewide electricity savings are estimated to be 2,220 MWh/yr for new construction. Electricity savings would reach 22,200 MWh/yr at the end of 10 years, and the cumulative electricity savings over that time would be 122,100 MWh. First year natural gas savings would be 127,000 therms resulting in a cumulative gas savings over ten years of 6,980,000 therms.

Fan-only peak day electric demand reaches between 0.5 and 1.0 W/ ft2. Following the Design Guide recommendations could provide a modest reduction in demand due to better duct design and lower overall pressure drop, but most of the measures affect part-load efficiency and do not benefit demand.

Electricity savings of approximately 1.5 kWh/ft^2-yr and 8.5 kBtu/ft^2-yr are predicted for the measures in the Design Guide compared to current standard practice. The corresponding annual utility cost savings are about $0.20/ft^2 for electricity and $0.07/ft^2 for gas, based on 2003 PG&E rates. Based on the statewide energy savings this would result in $16.7 million electricity savings for building owners in California and $5.8 million gas savings during a ten year period at current rates for a total of $22.5 million in cost savings.

4.0 Integrated Design of Small Commercial HVAC Systems (Element 4)

4.1. Introduction

This Element looked at 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 small commercial HVAC 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 Element researched these problems and developed solutions to prevent or overcome them.

Through short-term monitoring and onsite surveys of current practice, the researchers identified problems with equipment, controls, distribution systems, and operation and maintenance practices that lead to poor system performance. Based on the technical and operational fixes identified, the research team developed guidelines and market/technical papers for specifying, installing and operating high-performance systems, documented statewide savings potentials, and identified future code upgrade options.

4.1.1. Element Objectives

The objective of this Element's research was to identify the key problems in the efficiency and performance of small package HVAC units and create solutions to address those problems.

The overall technical goals were to:

- Improve the energy efficiency and cost effectiveness of small packaged rooftop commercial HVAC systems through development of guidelines for integrated design and recommendations for future energy code upgrades.
- Increase the energy efficiency and functionality of small packaged rooftop commercial HVAC systems by 10%. The overall economic goals were to:
- Establish several baselines where none exist, representing the number and type of small commercial HVAC systems installed in new buildings within California by building type and Standard Industrial Classification (SIC) code.
- Determine, on a statewide basis, the potential for performance improvements attributable to small package HVAC systems integration.
- Develop an estimate of annual energy cost savings for reducing small commercial HVAC system energy consumption.

4.1.2. Project Team and Technical Advisory Group (TAG)

Element 4 was led by Pete Jacobs of Architectural Energy Corp, with staff support from Dave Roberts, Tracy Phillips, Erik Jeanette, John Wood, Matt Potts, Kosol Kiatreungwattana and

Pablo Calderon-Rodriguez. RLW Analytics, a subcontractor, provided field testing, engineering support and statistical analysis, with contributions from Roger Wright, Matt Brost, Jeff Staller, Eric Swan and Stacia Okura. Eskinder Berhanu, principal of Eskinder Berhanu Associates, also provided field testing and engineering support.

Architectural Energy Corp. and New Buildings Institute would like to acknowledge the invaluable guidance and advice provided by members of Element 4's TAG, which included:

- Tudi Hassl, Portland Energy Conservation, Inc. (PECI)
- Jan Johnson, Southern California Edison
- Richard Lord, Carrier Corporation
- Dr. Mark Modera, Carrier Aeroseal
- John Proctor, Proctor Engineering Group

4.2. Background Research (Project 4.3)

4.2.1. Project Objectives

This project's objective was to inform the development of research questions that address systems integration problems with small commercial HVAC systems.

4.2.2. Approach

To inform this Element's subsequent projects that comprise, the project team conducted background research in areas relevant to improving the installed efficiency of small HVAC systems through improved systems integration. The research activities fell into two general categories:

- *Market characterization***.** This involved gathering information to better understand the demographics of buildings with small HVAC systems and the market penetration of various types of small HVAC systems. Tasks included:
  - Analyzing the California Statewide Non-Residential New Construction (NRNC) database and other data resources to characterize the demographics and market penetration of small HVAC systems.
  - Reviewing existing literature to understand the processes by which buildings and their HVAC systems are designed and delivered to their owners.
  - Developing simulations of each building in the NRNC database and of the end-use energy consumption of each building, leading to the development of estimates of HVAC energy consumption for small systems.
  - Identifying market connection opportunities with current and planned projects that are doing research related to Element 4's work.
- *Systems integration.* This involved reviewing existing literature to identify the types of problems expected in small HVAC systems in new commercial buildings, and the potential energy impacts of avoiding these problems.

4.2.3. Technical Outcomes

For the complete findings of this project, see Element 4's report, "Background Research Summary, Final August 15, 2002," deliverable 4.3.1. What follows are some of the more significant findings from the research.

MARKET CHARACTERIZATION

The primary data resource used to develop the market characterization data relevant to this project was the California Statewide Non-Residential New Construction (NRNC) database. The NRNC data was compared to estimates of new construction activity in 2001 supplied by the Commission. The data was analyzed to determine common types of HVAC systems, number and size of buildings with small HVAC systems, design practices, and energy consumption.

COMMON TYPES OF HVAC SYSTEMS (FIGURE 7

- Single package DX air conditioners are the most popular HVAC system type in new construction in the State, cooling about 44% of the total floor space.
- Built-up systems are the second-most popular, conditioning about 17% of the total floor space.
- The combined total of single package and split DX air conditioners and heat pumps represents slightly more than half of the total floor space in the state.
- A significant portion (about 19%) of the total NRNC floor space is not cooled.

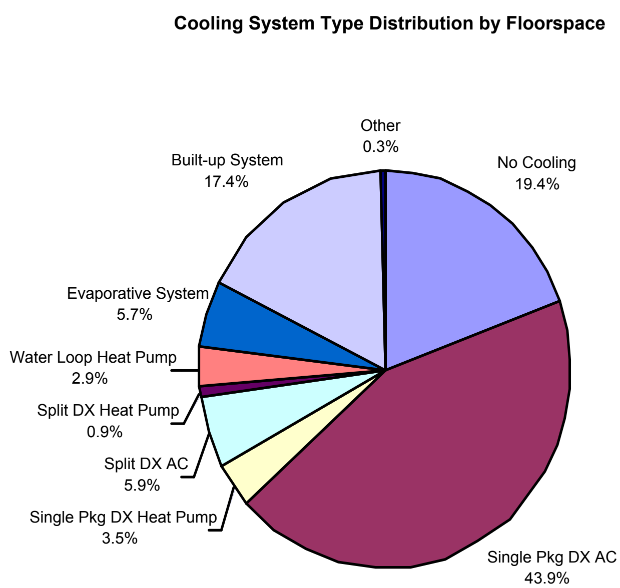

Figure 7. Cooling System Type Distribution by Floor Space

Figure 8 and Figure 9 show the market penetration of single-zone constant volume packaged DX air conditioners and heat pumps.

- Single package equipment is the most popular packaged DX system type in new commercial buildings.
- Split systems and heat pumps, although present, do not represent a large fraction of the number of systems or installed cooling capacity.

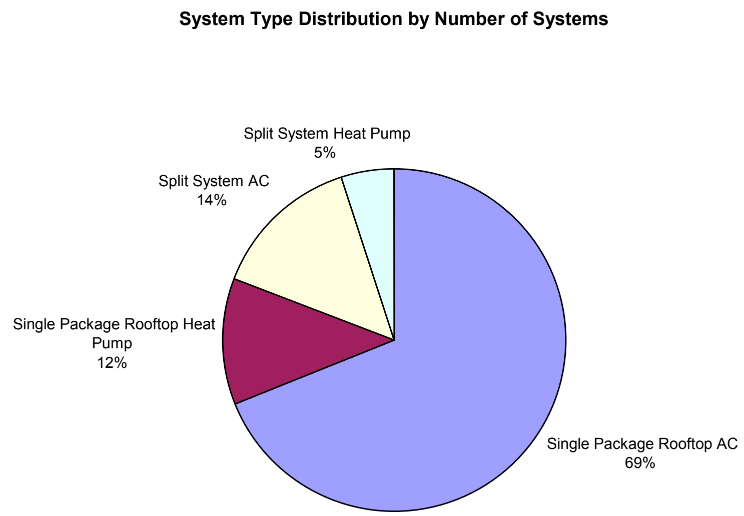

Figure 8. Distribution of DX System Types by Number of Systems

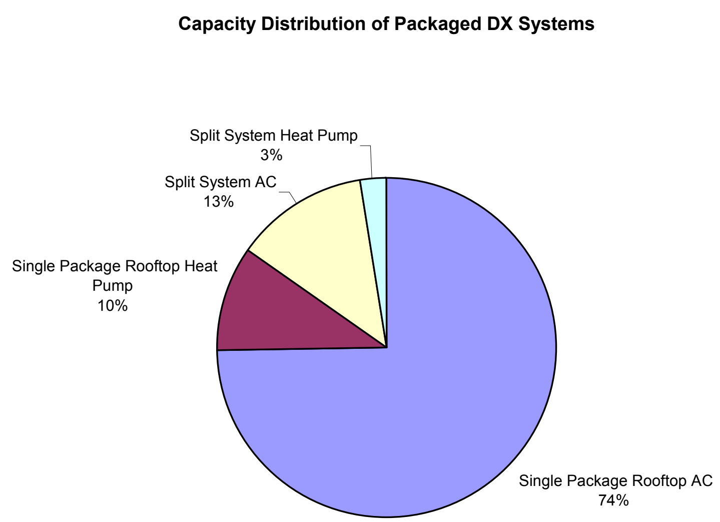

Figure 9. Distribution of DX System Types by Installed Capacity

The size distribution of packaged DX systems is shown in Figure 10 through Figure 12.

- In terms of number of systems installed, the most popular packaged DX system size is 5 tons (Figure 10).

- Units between 1 and 10 tons represent close to 90% of the total unit sales in new buildings in California.
- In terms of installed cooling capacity, the 10-ton unit is the most popular, followed by the 5 ton unit (Figure 11).
- Figure 12 shows the cumulative distribution of packaged DX system capacity. Units 10 tons and smaller represent about 58% of the total packaged DX cooling capacity in the State.

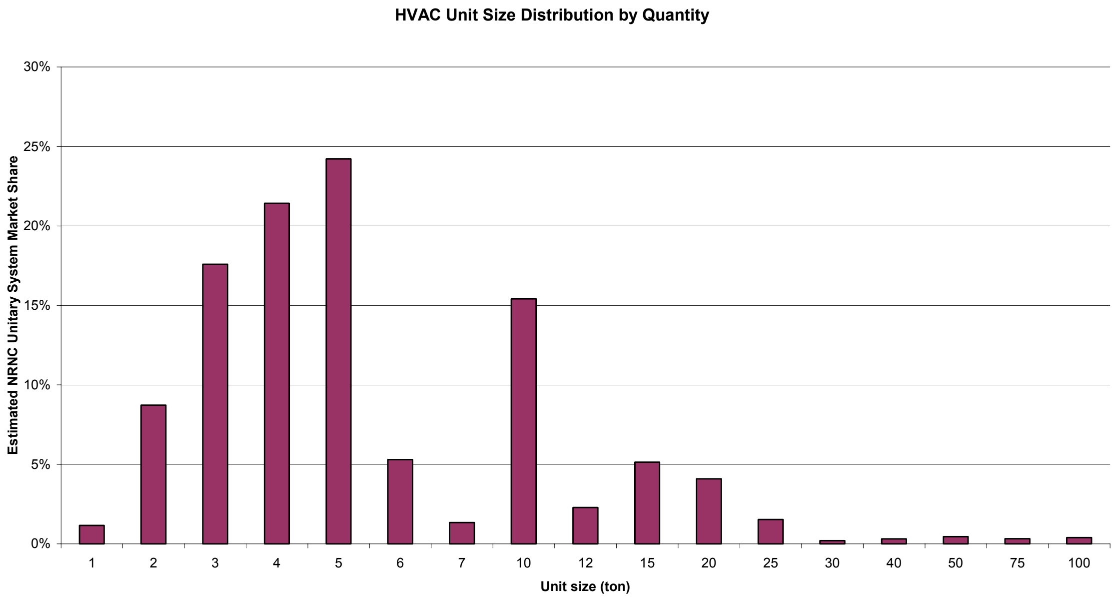

Figure 10. Distribution of Packaged DX System Size by Number of Systems

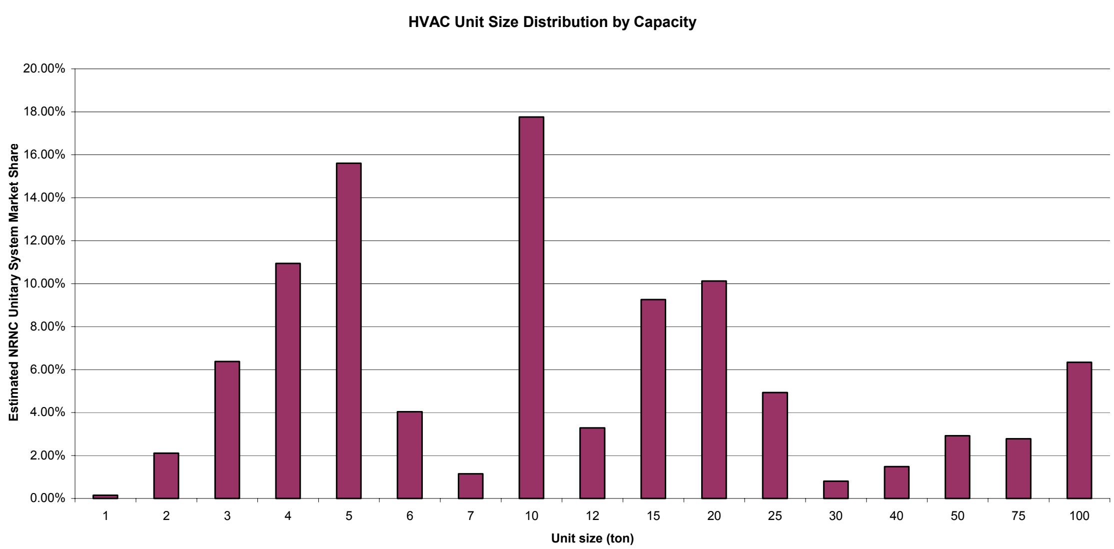

Figure 11. Distribution of Packaged DX System Size by Installed Capacity

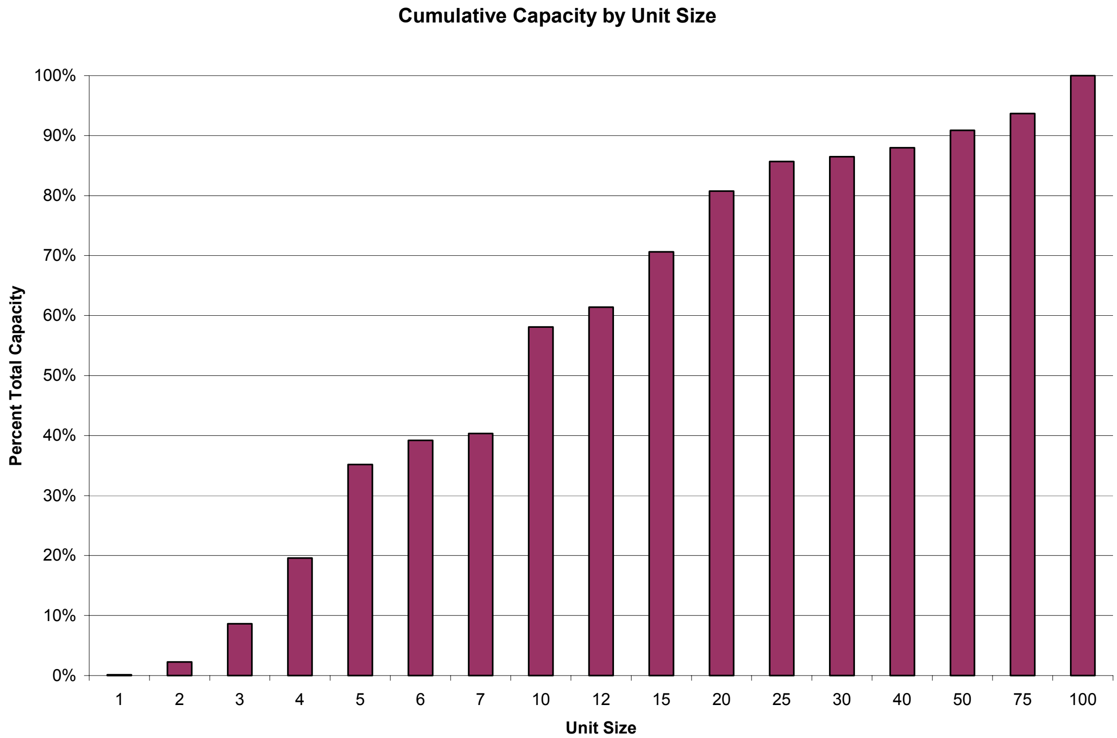

Figure 12. Cumulative Distribution of Packaged DX System Size by Installed Capacity

TYPES AND SIZES OF BUILDINGS WITH SMALL HVAC SYSTEMS

The NRNC database was queried to develop an understanding of the types and sizes of buildings using small HVAC systems, defined here as units 10 tons and smaller, and the number of units installed per building. The prevalence of small HVAC systems is fairly high in most building types, reflecting their high overall market penetration (Table 3).

Small HVAC systems appear in buildings of all sizes. Many large buildings are cooled by multiple small systems. The size of the unit is often dictated by the size of the HVAC zone within the building, not the overall size of the building. See the complete report (deliverable 4.3.1) for details.

Table 3. Buildings with Small HVAC Systems

Commission Building Type	% with at least one small unit	Average units/ building[1]
Large Retail	92.5%	7.0
Small Retail	91.8%	5.3
Restaurant	83.8%	3.2
Small Office	78.4%	6.2
Food Store	74.0%	2.6
Miscellaneous	74.0%	4.0
Elem/Secondary School	72.7%	11.9
Non-Refrig. Warehouse	71.4%	2.8
Hotel/Motel	56.2%	2.3
Large Office	53.9%	2.5
Hospital	51.9%	2.4
Medical Clinic	49.6%	2.0
College, University	34.0%	1.6
[1]Buildings with at least one small system.		

Design Practices

The background research included a review of the existing literature about how buildings are designed and delivered to the owners. Here are some of the more significant findings:

- Design-bid-build is the most common method of building delivery, but design/build is projected to become more popular in the future.
- In the design of small buildings (< 20,000 ft^2), manual methods (rules of thumb, simple nomographs, printed literature and forms) are the most popular design methods for all design decisions except HVAC-equipment sizing.
- Design time per project is usually very limited compared to built-up systems.
- The most commonly used tool for HVAC-equipment sizing is software supplied by HVAC equipment manufacturers.
- The wide use of computerized design tools for HVAC system sizing raises the possibility for improved building systems integration using computerized sizing tools as the platform.

ENERGY CONSUMPTION

Element 4 created simulation models for each building in the NRNC database using automated modeling software tied to the building characteristics data. The modeling software created a DOE-2.1E simulation model of each building, and the end-use energy consumption of each building was simulated. The energy consumption predicted for the population of buildings in the database was adjusted to reflect the Commission's estimate of NRNC activity for the year 2001. Table 4 summarizes the results.

Table 4. Summary of NRNC floor space and Commission New Construction Projections

Parameter	Value	Comments
Total floor space in NRNC database	233.2 million ft^2	Sum of weighted floor area in database
Estimated 2001 new construction activity	155.1 million ft^2	Excludes refrigerated warehouses
Adjustment factor	0.665	

Table 5 shows the estimated end-use energy consumption for the statewide NRNC population, based on 2001 construction activity.

Table 5. Estimates of Statewide End-Use Consumption in New Commercial Construction

End-Use	Value	End-Use Share	Comments
Lighting	734 GWh	28.0%	Interior lighting only
Miscellaneous	840 GWh	32.1%	Includes plug, process, and exterior lighting loads
Cooling	356 GWh	13.6%	
Heating	16 GWh	0.6%	Primarily heat pumps and electric reheat
Fans	400 GWh	15.3%	
Refrigeration	274 GWh	10.4%	Primarily grocery store refrigeration systems with external condensers. Refrigerators reported as plug loads
Total	2619 GWh		

Estimates of HVAC energy consumption for small systems were developed by calculating the fraction of the floor space in each building served by a packaged HVAC system, and multiplying this fraction by the estimated fraction of the total packaged system capacity that is represented by packaged DX units from 1 to 10 tons. The results are shown in Table 6. Small package systems, for example, are estimated to use 31% of the total cooling energy in the NRNC database.

Table 6. Estimates of Energy Consumption by Small HVAC Systems

End-Use	Small System Consumption	Fraction of NRNC Total End-Use Consumption
Cooling	111GWh	31%
Heating	7 GWh	47%
Fans	125 GWh	31%

SYSTEMS INTEGRATION PROBLEMS

- Small HVAC Problem Areas

Review of the literature on small HVAC systems applied to residential and commercial buildings provided insight into the types of problems expected in small systems in new commercial buildings. Problems were identified in the areas listed below; for a description of the specific problems in each area, see the Background Research Summary (deliverable 4.3.1).

  - Thermostats
  - Fan controls
  - Economizers
  - System sizing
  - Distribution systems
  - Condenser and outdoor air entering conditions
  - Supply fan power
  - Unit air flow
  - Refrigerant charge
  - Maintenance access

- Products
  - Background Research Summary (4.3.1)

4.3. Field Surveys (Project 4.4)

4.3.1. Project Objectives

This project's objectives were to:

- Conduct field surveys to compile a database of information from which analysis activities could be subsequently conducted. The database will include characteristic information about each building, the failure modes or suboptimum performance observed in each building, and responses to occupant interviews.
- Develop short-term measured data from each building that is monitored.
- Quantify the incidence with which each of the systems integration problems is encountered in the building population with small commercial HVAC.

- Monitor a statistically useful number of building sites having systems installed within the past five years.

4.3.2. Approach

This project made use of one of the outcomes of Project 4.3, a database of buildings built in California within the past four years, to define a sample, recruit participants, and conduct field surveys. These activities are described below.

- *Recruitment and survey development.* The research team developed criteria to stratify that population into logical groupings. Researchers then attempted to recruit buildings according to that stratified random sample design. Participants were recruited through the use of introductory letters and follow-up phone calls. Simultaneous with the sampling and recruiting activities, the project team developed the survey methodology, survey instruments, and questionnaire to implement the survey.
- *Onsite survey.* The onsite survey gathered information on building shell, lighting, internal loads, operating schedules and other similar data sufficient to develop a DOE-2 model of each space served by the units. Besides basic building characteristics data, thermostat make and model data were collected to see if the thermostats were appropriate for commercial building applications. The thermostat control settings were observed, and the calibration of the thermostat sensor was checked. Thermostat location was noted and compared to the spaces served by the system. The researchers also conducted occupant comfort surveys to assess the overall satisfaction of the occupants with their thermal environment.
- *One-time tests.* The second level of data collection involved a series of one-time tests conducted on the units selected for study. These tests are described below.
    - *Fan flow and power.* The unit was cycled through each mode of operation (standby, fan-only, cooling stage one, and cooling stage two if applicable), and the unit's true electric power and current was measured during each mode using a portable wattmeter. Air flow rate was measured using a flow grid, which is an averaging flow meter designed to be installed in place of the filters. A digital micromanometer measures the pressure drop across the plate, and reads out directly in cfm. The manometer was also used to measure supply static pressure, return static pressure, and total unit external static pressure.
    - *Economizer.* If the unit had an air-side economizer, the minimum outdoor air position potentiometer was adjusted to test the operation of damper motors and linkages. The economizer outdoor air temperature sensor was cooled down using a "cool" spray, simulating cool outdoor air conditions and the response of the economizer was observed.
    - *Refrigerant charge.* Service gauges and temperature sensors were used to verify the state of charge of the rooftop unit, using the CheckMe! procedure.[5] The high side and low side pressures were measured, along with the suction line temperature, the condensed liquid temperature, outdoor drybulb temperature entering the condenser,

[5] CheckMe! is a product of the Proctor Engineering Group, San Rafael, CA.

and drybulb and wet bulb temperature entering the evaporator coil. Refrigerant was added or removed from the system until the suction line superheat on units with fixed metering devices, or the condenser line subcooling on units with thermostatic expansion valves (TXV) was within the target specified by the CheckMe! software.

- *Short-term monitoring*. Selected units were monitored over a two- to three-week period using portable, battery-powered data loggers to observe unit operation over a variety of operating conditions. An AEC MicroDataLogger (MDL) was installed in each unit selected for the study. The MDL measured unit current, supply air temperature, return air temperature, and mixed air temperature. The data were stored on a five-minute basis. The MDL uses thermistor sensors with a 0.5°F accuracy over the full range. The current sensors were equipped with signal conditioning equipment to provide true RMS current readings. True RMS current measurements were coupled with the spot kW and current measurements to estimate time series kW data for the unit. In addition to the MDL installed at each unit, the local rooftop temperature and humidity was monitored at each site. AEC Enforma diagnostic software was used to analyze the short-term monitored data. Problems were identified based on the results of each test.
- *Analysis.* At the conclusion of the monitoring period, the data were analyzed to identify faults and sub-optimum performance. The data allowed the research team to create a computer model of each building in Round One of the field work, identify failures or problems, and compile statistics on modes of failure and suboptimal performance.

  Development of the DOE-2 model was facilitated by the SurveyIT/ModelIT software package developed by AEC. Building characteristics data were entered into a Microsoft Access database by the surveyor. The building characteristics data were read by the software, and a DOE-2 model was automatically developed from these data. This process greatly reduced the time required to develop a simulation model, allowing the AEC/RLW team to create models for each space served by each unit studied within the time and budget constraints of the project. The models are created from a series of rules imbedded in the software, providing a consistent modeling approach across all sites and surveyors.

4.3.3. Technical Outcomes

This section summarizes two areas where the research type achieved significant outcomes: 1) field findings, and 2) Title 24 code changes proposals.

FIELD FINDINGS

- *215 HVAC units were tested at 75 sites.* The research team conducted site inspections, interviewed occupants and conducted short-term monitoring. Permission to monitor buildings became more difficult following the September 11, 2001 terrorist attacks, and the original goal of 82 sites was not attained. However a total of 215 HVAC units were tested at 75 sites, which met the project's statistical objectives.

  Figure 13 shows the number of sites surveyed by building type.

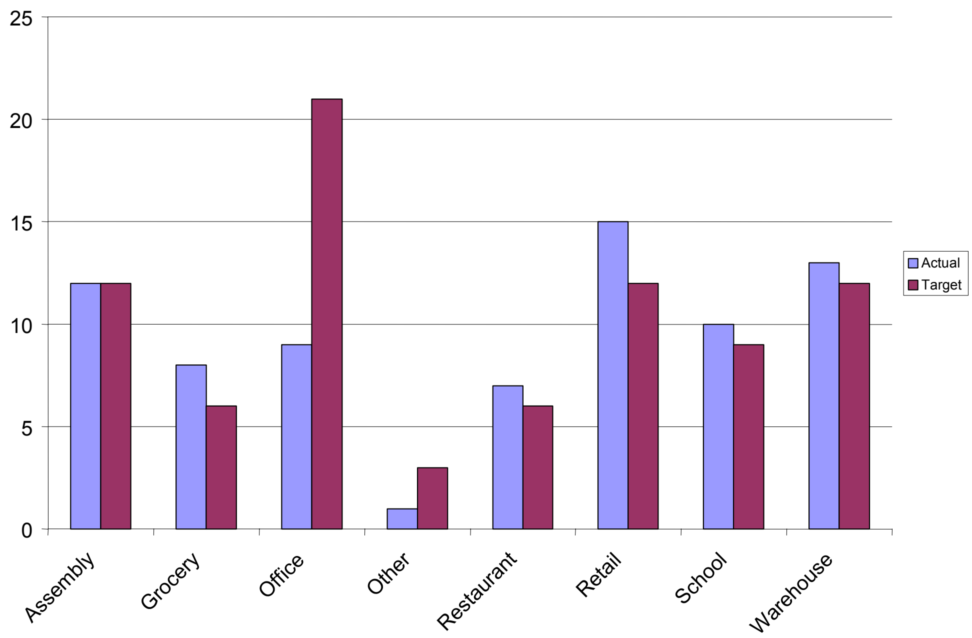

Figure 13. Number of Sites Surveyed, By Building Type

- *The researchers 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 air flow, inadequate ventilation air, and simultaneous heating and cooling. A summary of the findings is shown in Figure 14 and the primary problems are discussed in the next sections.

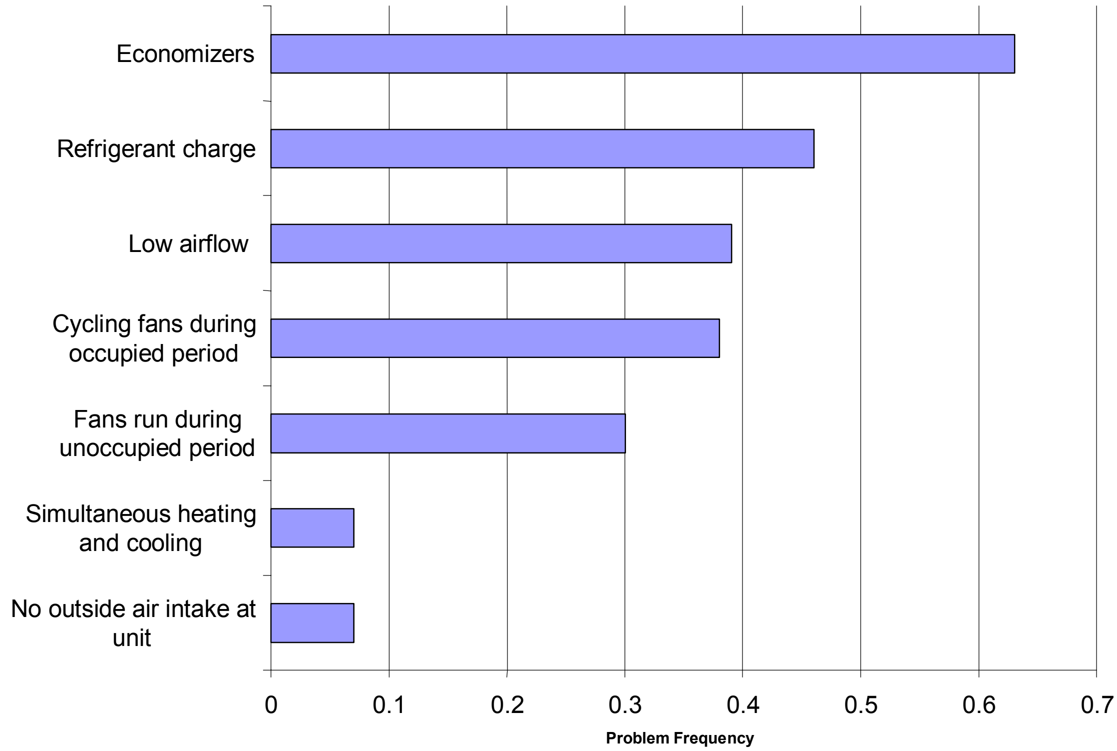

Figure 14. Frequency Of Problems Encountered On Small Commercial HVAC Systems

- *Economizers show a high rate of failure.* Of the 215 units tested, 123 units were equipped with economizers and 75% of these economizers were field installed. Economizers are required by code on units over 6.25 tons but were found on 40% of the units smaller than 6.25 tons. Of the units with economizers, 30 units (24%) would not move at all, 36 units (29%) did not respond to the cold spray test, and an additional 13 (10%) displayed poor operation during the short-term monitoring period.

  Differential enthalpy economizers were the most popular style (40%), which do not require setting a changeover point. For those with the single-point enthalpy economizers however, according to the Title 24 Energy Standards, these should use the "A" changeover setpoint, but this was the case in less than 30% of the units; most units used the "D" setpoint, which provides the fewest economizer operating hours.

  The majority of the problems were found on the field installed economizers, not on the factory installed units. This finding helped support the absence of performance verification requirements under the new Title 24 2005 Standards for factory installed economizers.

- *46% of the units tested had improper refrigerant charge,* 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. ; Figure 15 shows the frequency distribution of the observed charge levels. The average energy impact (not including units that were fully discharged and obviously leaking) was about 5% of the annual cooling energy.

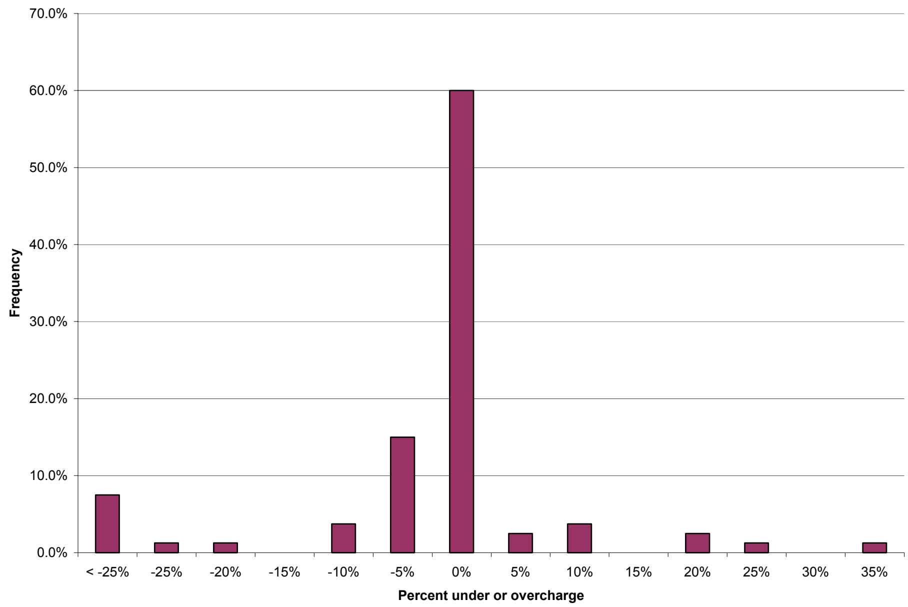

Figure 15. Frequency Distribution Of Refrigerant Charge.

- *39% of the units tested had very low airflow rates (< 300 cfm/ton)*. The average flowrate of all units tested was 325 cfm/ton, which is about 20% less than the 400 cfm/ton flowrate generally used to rate unit efficiency. Reduced air flow results in reduced unit efficiency and cooling capacity. Low airflow increases annual cooling energy about 9%. Figure 16 shows the distribution of the measured air flow.
- *The average measured fan power was about 20% higher than the assumptions used in the Title 24 Energy Standards* (365 W/cfm or about 0.15 kW/ton), causing a commensurate increase in the annual fan energy. If the fan flow is increased to 400 cfm/ton to meet design flowrate targets, the fan power will increase to 0.34 kW/ton increasing fan energy consumption by almost 90% over current operating practice (measured in-situ rate of 0.18 kW/ton). This increase would effectively drop the efficiency of a 10.3 EER unit to 9.1.

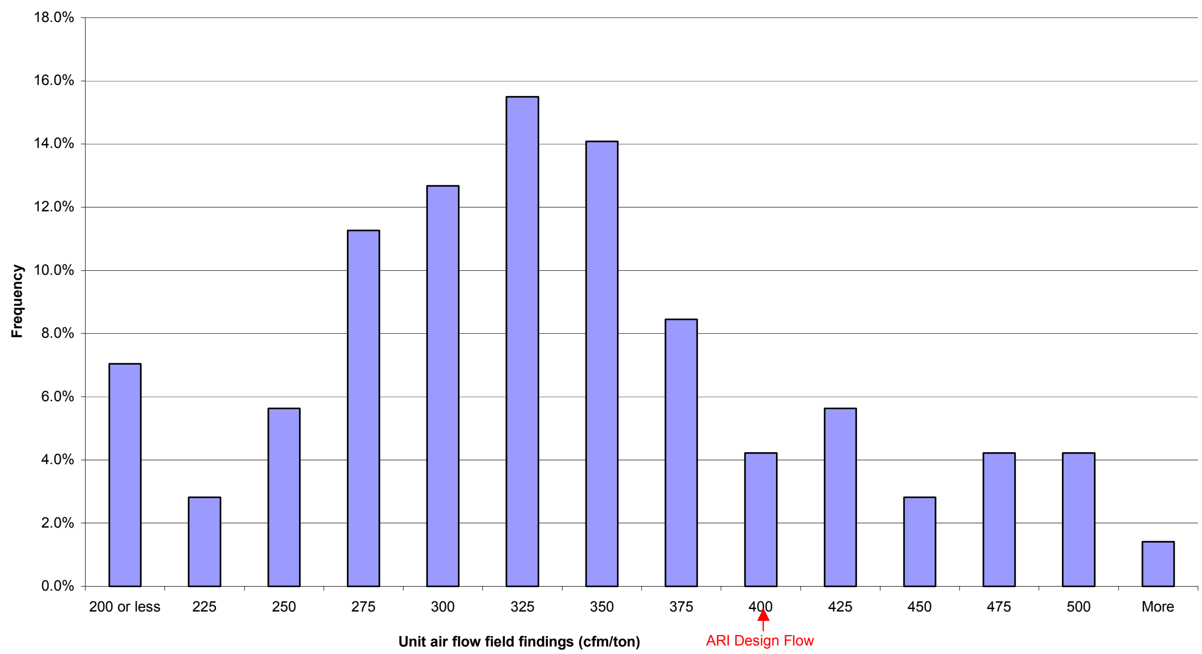

Figure 16. Frequency Distribution Of Unit Air Flow Rate

- *The combination of high fan power and low flow rate is due largely to excessive pressure drop in the duct systems.* Figure 17 shows the frequency distribution of unit external static pressure at the measured flow rate. 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, or almost three times the ARI assumption. The ARI assumptions are not applicable to commercial buildings and undervalue fan energy in the efficiency calculations. We recommend a design static pressure not to exceed 0.5 in. w.c. at design flowrate (400 cfm per ton).
- *The field data indicate that duct systems are undersized, causing the low air flow rates and increased fan energy.* A well designed system should provide design flow rates and efficiency without a fan energy penalty.

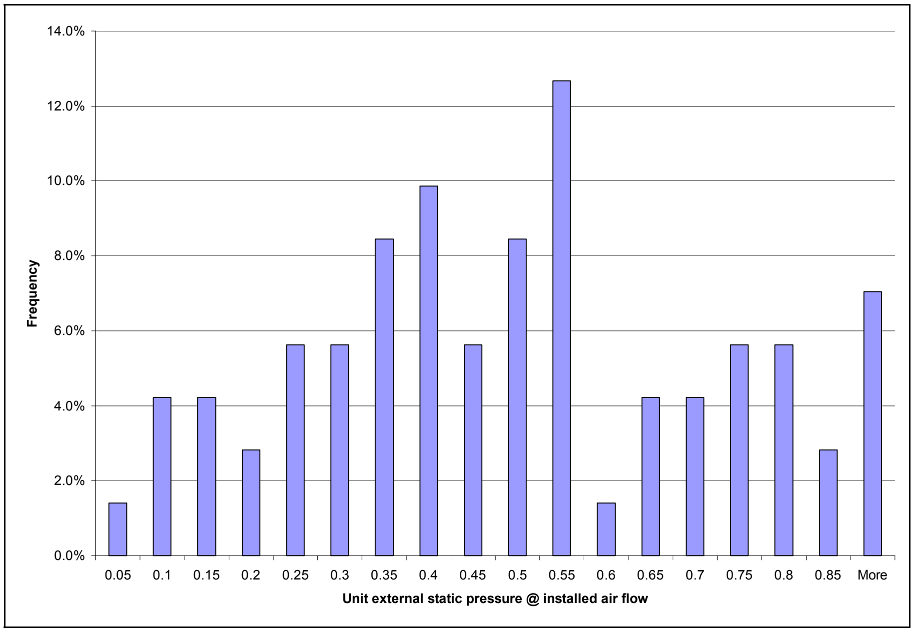

Figure 17. Frequency Distribution Of Unit External Static Pressure

- *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. Most of the thermostats surveyed (86%) were observed to be "commercial" type thermostats capable of controlling the systems according to the Title 24 and ASHRAE standards. These units can be set to operate the fan independently of the thermostats call for heating or cooling. Failure to operate the building with a continuously operating fan reduced the effective ventilation rate significantly, as shown in Figure 18.

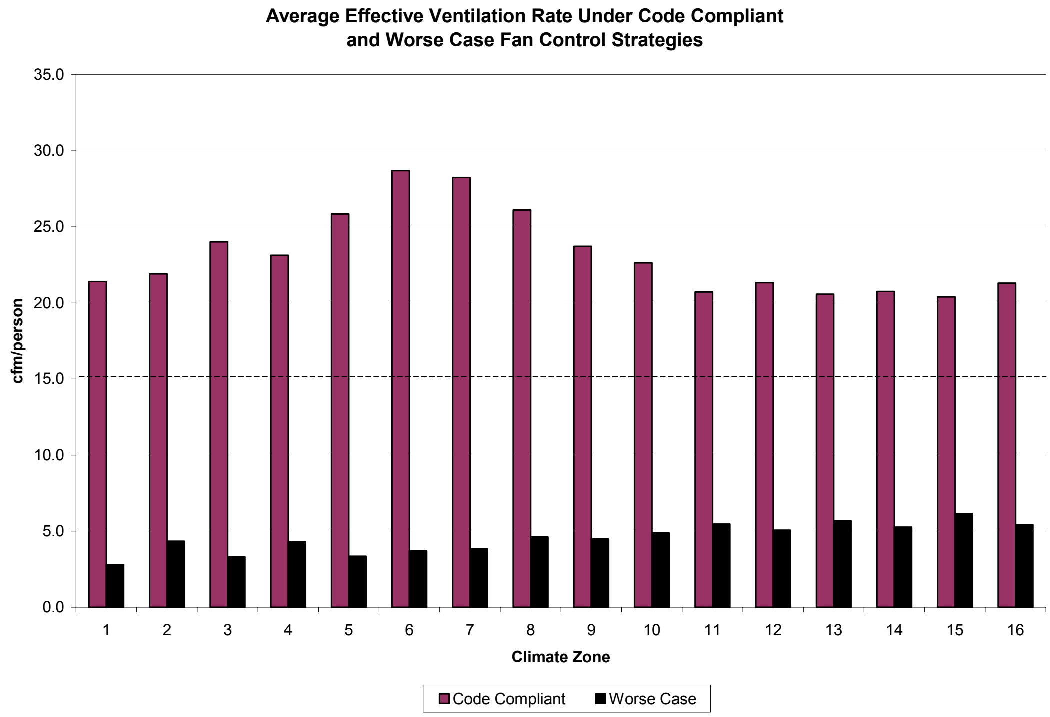

Figure 18. Effective Ventilation Rate For HVAC Units With Continuous And Cycling Fans

In both cases shown in Figure 18, the minimum outdoor air damper is set to provide 15 cfm/person of outside air, the typical ASHRAE recommended level. 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. Thirty-eight percent of the units were in this mode (no economizer and cycling fans).

- *Fans ran 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.
- *Adjacent units controlled by independent thermostats were observed to provide simultaneous heating and cooling to a space in 8% of the units monitored.* This was largely due to occupant errors in the set up and use of the thermostats, and poor thermostat placement during construction.
- *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.
- *Other installation and maintenance problems.* Other installation problems revealed by the field surveys include units ducted to the wrong zone, missing controller boards, and supply/return bypass at duct connections. Maintenance problems include frozen coils, dirty filters, missing access covers, shoddy work and bird infestation. Figure 19, for example, is a photo 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.

Figure 19. Example Of Maintenance Problems Revealed During Field Surveys

CODES AND STANDARDS OUTCOMES

Element 4's research played a significant role in the two code change proposals to the California 2005 Title 24 standards: the proposal for Acceptance Requirements for Nonresidential Buildings, and the Nonresidential Duct Sealing and Insulation proposal. These are described in the Market Connections section of this report.

Products

- Description of the field methods (4.4.1)
- Survey method and questionnaires (4.4.2)
- Database of compiled information from the field surveys (4.4.3)

4.4. Analysis and Statewide Estimates (Project 4.5)

4.4.1. Project Objectives

This project's objectives were to:

- Understand the underlying causes for the failures and suboptimum performance identified in Project 4.4;
- Determine the extent to which better systems integration can prevent them; and
- Develop an estimate of the savings statewide that can be produced through better integration of small commercial HVAC systems.

4.4.2. Approach

The research team analyzed the failures and suboptimum performance found in Project 4.4 to determine the underlying causes. Activities included:

- Creating DOE-2 computer models and file of information about the first 45 buildings surveyed;
- Modeling the problems uncovered in Project 4.4 in each of the 990 buildings in the Nonresidential New Construction (NRNC) database;
- Expanding the modeling results to the statewide building population;
- Developing statewide savings estimates for each failure mode and for the entire population of buildings; and
- Identifying the 10 failure modes that waste the greatest amount of energy for further investigation in Project 4.6.

The original workplan called for modeling all 75 sites surveyed and expanding those results to the statewide level. The researchers, however, decided to pursue a more rigorous approach that would provide greater value: rather than expanding the energy impacts from a fairly small population of buildings (75), they expanded it from a much larger population (990) up to the statewide level.

4.4.3. Technical Outcomes

- *Average building electricity savings are 8.4% and natural gas savings are 30.2% resulting in a combined average energy cost saving of $0.26 /square foot.*
- *Reduction in system size on the order of 40% and reduction in annual energy costs on the order of 25% to 30% are possible with simple integrated design strategies.* To show the interactions between HVAC system size and costs and the load-avoidance strategies recommended in the Design Guide, a series of computer simulations were done on a simple "box" model of a small commercial building in coastal (Oakland/climate zone 3), Central Valley (Sacramento/climate zone 12), and desert (Palm Springs/climate zone 15) locations. Figure 20 and Figure 21 show the impacts of insulation location, reduced lighting power density, high-performance glass, cool roofs, duct leakage sealing, HVAC system "right sizing," and the application of high-efficiency HVAC units on the building first cost, HVAC equipment size and cost, and energy costs.

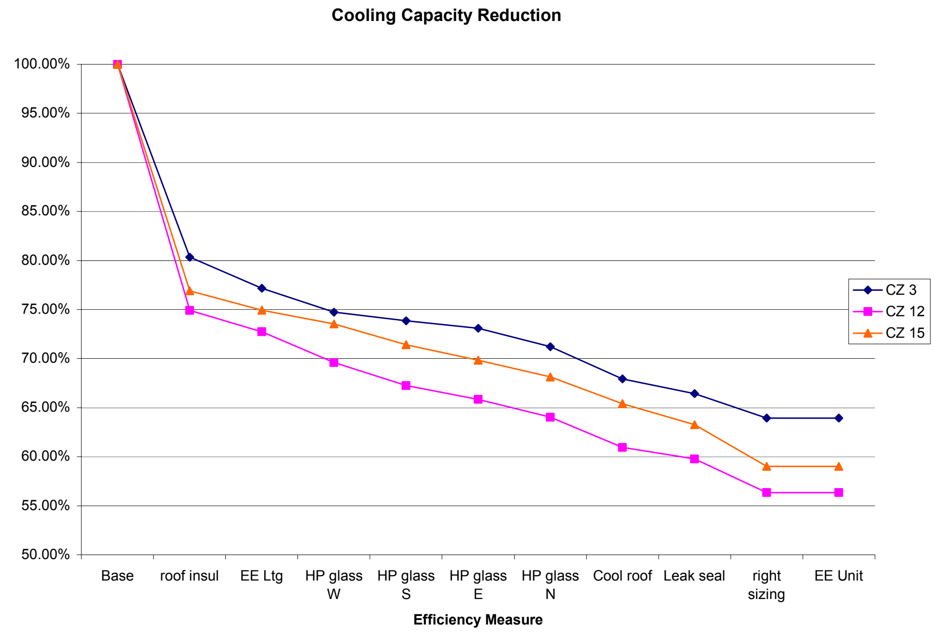

Figure 20. Impacts of Integrated Design on HVAC System Size

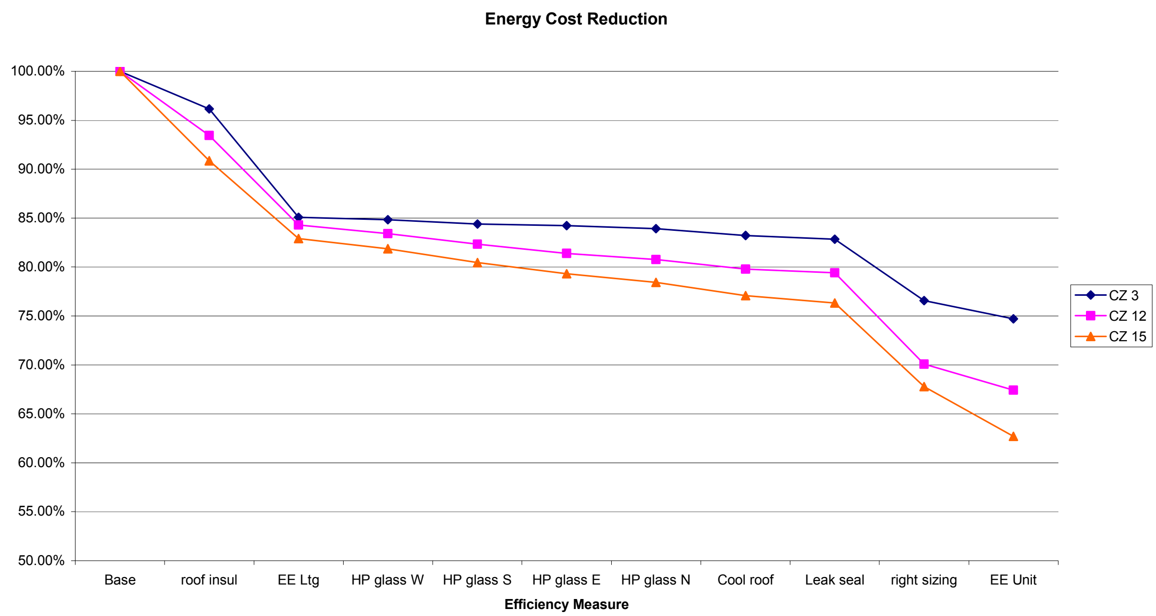

Figure 21. Impacts of Integrated Design on Energy Cost

Products

- Report on underlying causes of faults or suboptimum performance in each building (4.5.1)

- Results from expanding the faults to statewide population of buildings (4.5.3)

4.5. Building Science Solutions (Project 4.6)

4.5.1. Project Objectives

This project's objective was to develop building-science solutions to reduce or eliminate the 10 worst faults and suboptimum performance problems discovered in the previous projects.

4.5.2. Approach

The research team developed building-science solutions and recommendations to the common installation and operation problems identified during the Field Surveys (Project 4.4). These solutions are based on the research and analysis results, as well as on contributions from leading experts and on other current research on small package systems.

4.5.3. Technical Outcomes

Below is a summary of the main solutions; for detailed information, refer to the Small Commercial HVAC System Design Guide (Design Guide).

- *Integrated design solutions.* Include load-avoidance strategies in a building's design to reduce the size and energy consumption of the HVAC system. Recommended strategies include:
  - *Reduce lighting power density***.** The *Advanced Building Guidelines* E-Benchmark recommends lighting power densities by space type that are about 30% lower than the proposed 2005 Title 24 allowances.
  - *Use high-performance glazing and skylight systems* to improve thermal comfort, reduce glare, and reduce solar heat gain and conduction losses.
  - *Use cool roofing materials* such as white single-ply or white liquid-applied products. The most effective products have both a high reflectance and a high emittance.
  - *Avoid lay-in insulation.* Lay-in insulation installed on top of a dropped ceiling generally performs poorly: items installed in the ceiling grid interfere with insulation coverage, and the insulation inevitably is displaced when ceiling tiles are moved. Instead of lay-in insulation, install insulation directly on the roof deck so that the plenum is located within the building envelope. This substantially reduces the impacts of duct conductive loss and duct leakage on HVAC system efficiency.
- *Unit sizing.* Many small HVAC systems are significantly oversized, resulting in inefficient operation, reduced reliability, and poor humidity control, as well as wasted capital investment. Solutions for proper sizing include:
  - *Use sizing calculations that take into account any load-avoidance strategies that the building designers incorporated.*
  - *Use reasonable assumptions for plug loads.* Engineers often base HVAC sizing on the full nameplate or "connected" load of office equipment and assume it operates simultaneously. In fact, most equipment operates at a fraction of the nameplate value, and rarely operates simultaneously. An ASHRAE study of plug loads

indicated that 1 W/ft^2 is a reasonable upper boundary; the Title 24 default value of 1.5 W/ft^2 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. ASHRAE Standard 62–1999 allows the design to be based on the actual anticipated occupant density, so long as justification is provided.
  - *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.
- *Unit selection.*
  - *Specify units that meet the Consortium for Energy Efficiency (CEE) Tier 2 efficiency standards.*
  - *Select capacity of the unit based on actual design conditions, not nominal values.*
  - *Select airflow rate to meet sensible loads.* The cooling capacity of most packaged air conditioners is based on nominal flow rates selected to provide adequate dehumidification in climates that are more humid than California. Increasing the flow rate can extract extra sensible cooling capacity out of the unit, allowing the selection of a smaller "nominal" unit.
  - *Select high-efficiency or premium efficiency motors on supply fans.* This is cost effective in all California climates.
  - *Specify thermostatic expansion valves.* This makes the units more tolerant of refrigerant-charge variations by maintaining unit efficiency over a wide range of under-or over-charged conditions.
  - *Improve economizer reliability by consider the following specifications***:** factory-installed and run-tested economizers; direct-drive actuators; and differential (dual) changeover logic.
- *Distribution systems.* The quality of the duct system can have a profound effect on the efficiency and comfort delivered by the HVAC system.
  - *Reduce duct system pressure drop.* Maintaining design airflow rates without excessive fan power requires close attention to the duct system design and construction practices.
  - *Increase duct insulation levels to R-8.* Increased insulation is cost-effective in duct systems run outside the conditioned space. Duct wrap rather than lined duct is recommended.
  - *Reduce duct system noise.* Strategies that reduce duct system pressure drop also help reduce noise.
- *Ventilation.* 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, and then meet these requirements in the most energy efficient manner possible. Strategies include:

- *Operate unit fans continuously***.**
- *Use demand-control ventilation.*
- *Consider alternative ventilation strategies,* such as two-speed or variable-speed fan systems interlocked with the OA damper and/or a CO_2 sensor 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. Natural ventilation using operable windows can also be used to supply ventilation in lieu of mechanical ventilation.

- *Thermostats and controls***.** 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. Recommendations include:
  - *Use two stage, commercial grade thermostats.*
  - *Consider controller options and interfaces* including standard electromechanical controls, microprocessor controls, and controllers with EMS interface capability.
- *Commissioning.* Commissioning increases the likelihood that a new building will meet the intent of the design team and the client's expectations. Commissioning of small HVAC units should include:
  - *Documentation of the design intent*
  - *Pre-functional inspections*
  - *Functional performance tests*
  - *Correction of deficiencies*
  - *Operation and maintenance training for building occupants*
- *Operations and maintenance.* Preventive maintenance can help optimize operation, energy use, and comfort. Recommended steps include:
  - *Provide reasonable access to rooftop*
  - *Conduct routine maintenance, including checking filters, fan belts and economizer damper linkage; test economizer operation; check supply air temperature and refrigerant charge after unit has been running for 15 minutes; lubricate moving parts; check access panel for tight fit; inspect electrical wiring and connections; and check and clean coils as necessary.*

Products

- Results led to development of the Design Guide described below

4.6. Design and Integration Solutions (Project 4.7)

4.6.1. Project Objectives

This project's objective was to identify the most useful way that the building science solutions can be provided to the members of the design, construction, and maintenance professions to achieve systems integration.

4.6.2. Approach

To address the 10 worst system performance problems identified during the research, Element 4 pursued five distinct but complementary market transformation paths:

1. *Small Commercial HVAC System Design Guide***.** Building on the background research, field surveys, and analysis efforts of the previous projects, the project team developed comprehensive guidelines for the integrated design of small commercial HVAC systems. As a first step toward developing the Design Guide, the project team wrote a design brief on the topic for Energy Design Resources. They expanded that design brief to create the Small Commercial HVAC System Design Guide, which was then reviewed by E4's TAG and finalized.
2. *Manufacturer "White" Paper/ARI Discussions.* E4 wrote a white paper targeted at manufacturers of small packaged HVAC systems. The results and recommendations in this paper were derived from the Design Guide. This was distributed in conjunction with the Consortium for Energy Efficiency's (CEE) national, next-generation performance specification for small commercial, integrated rooftop HVAC systems. Based on discussions with the PIER team in September 2003, the ARI has committed to addressing improved performance opportunities through their technical committee and national meetings in late 2003. Members have also offered to participate in the assessment of an advanced unit in the next phase of PIER work.
3. *CEE's HECAC Initiative.* The team pursued an initiative with CEE that has exciting potential to greatly improve the performance of small commercial rooftop HVAC in California and across the country. The initiative process at CEE is currently in the outreach stage with manufacturers.
4. *Title 24 – Proposal for Acceptance Requirements for Nonresidential Buildings.* See the Market Connections section of this report for details.
5. *Title 24 – Nonresidential Duct Leakage and Insulation Proposal.* See the Market Connections section of this report for details.

Table 7 shows which performance problems are addressed by each of these products.

Table 7. Chief Products Developed to Address 10 Worst System Performance Problems

Issue	Design Guide	White Paper/ARI	CEE's HECAC Initiative	Title 24 – Ducts	Title 24 – Acceptance Requirements
Economizers	✓	✓	✓		✓
Refrigerant charge	✓	✓	✓		
Low air flow	✓	✓	✓		
Fan power	✓	✓	✓		
Cycling fans during occupied period	✓	✓	✓		✓
Fans run during unoccupied period	✓				✓
Ducts outside conditioned space	✓			✓	
No outside air intake at unit	✓				✓
Simultaneous heating and cooling	✓				✓
Maintenance	✓				

4.6.3. Technical Outcomes

DESIGN GUIDE

The Small Commercial HVAC System Design Guide focuses on actions architects, engineers, and design/build contractors can take to improve the energy efficiency of small HVAC systems, reduce operating costs, and improve indoor comfort and environmental quality. In conjunction with the creation of the Design Guide, the project team developed a design brief for Energy Design Resources (EDR), funded by California utility ratepayers and administered by the State's investor-owned utilities. This design brief, which was funded by EDR, is a less detailed version of the PIER Design Guide. The EDR design brief can be found at www.energydesignresources.com (follow the "Design Briefs" link on EDR's home page).

The Design Guide topics include:

- Integrated building design
- Unit sizing
- Unit selection (efficiency, capacity, features)
- Distribution systems (fan power, duct leakage and insulation, ductwork location, building pressurization)
- Ventilation (continuous, demand controlled, dedicated ventilation systems)

- Thermostats and controls (functionality, default settings, programming, user interface, small EMS)
- Commissioning issues (from a designer's perspective)
- Operations and maintenance issues (from a designer's perspective)

The following summarizes some of the key actions designers can take to improve the performance of small HVAC systems. These are described in detail in the Design Guide.

- 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 air flow based on calculated sensible loads without oversizing. Consider increasing unit flow rate to improve sensible capacity in dry climates.
- Specify units that meet Tier 2 efficiency standards, incorporate premium efficiency fan motors, thermostatic expansion valves and factory-installed and run-tested economizers.
- 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 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, air flow rate and fan power.
- Develop clear expectations on the services provided by HVAC maintenance personnel

CEC HECAC INITIATIVE

Element 4 and New Buildings Institute collaborated with the Consortium for Energy Efficiency (CEE) and their High Efficiency Commercial Air Conditioning Committee (HECAC) to develop a national, next-generation performance specification for small commercial, integrated rooftop HVAC systems. A primary goal of the initiative is to improve the actual performance of small rooftop HVAC systems in the field rather than solely focusing on increasing EER and SEER values. CEE surveyed member commercial program managers to identify interest in supporting a new national specification to improve in-field performance by using factory-installed components and on-board diagnostics.

The committee identified two tiers for the specification, as well as a third tier for the future development of a performance-based specification. The first tier includes technological options that are fundamental to unit efficiency and currently available on rooftop units that can be delivered to the customer today. The second tier identifies features of an advanced rooftop unit that are not readily available, but are believed by the efficiency community to be achievable in the future. The third tier is a proposed performance-based measurement for future specification development.

In June 2003, after four months of discussions about and revisions to the draft specification—a process that was facilitated by Rachel Shwom of CEE, Pete Jacobs of AEC, and Cathy Higgins of New Buildings Institute—CEE's HECAC committee agreed to support the proposed specification.

During this process, CEE worked with its members to engage other manufacturers and organizations in the discussions. CEE also initiated discussions in the summer of 2003 with the Air-Conditioning and Refrigeration Institute (ARI) about the HECAC initiative. The process of gathering manufacturer feedback will take place through conference calls, in-person meetings, and written comment into the fall of 2003. The committee will evaluate issues raised by manufacturer and facilitate necessary changes to the draft specification.

Based on meetings with the project team in September 2003, the ARI has committed to addressing improved performance opportunities through their technical committee and national meetings in late 2003. Members have also offered to participate in the assessment of an advanced unit in the next phase of PIER work.

Continued connection with these market players is planned in the next phase of PIER and will increase the likelihood of success toward consensus on the features, and development, of an advanced rooftop unit.

Below is an overview of the draft specifications, which integrates findings from Element 4's research:

Tier 1: This consists of a set of specs that are all currently available on the market, can be requested today, and are fundamental to improving field efficiency and performance. It is intended as the foundation requirements of an advanced rooftop unit, and provides an immediate basis for utilities to upgrade requirements within their programs. Tier 1 addresses issues including:

1. Economizer efficiency control and reliability specification
2. Minimum unit efficiency (i.e., CEE Tier 2 requirement)
3. Refrigerant control capabilities (i.e., thermostatic expansion valves)
4. Improving fan efficiency and reliability, and fan control capabilities
5. Smart thermostat capability to improve unit control and efficiency of ventilation systems, and meet indoor air quality codes (ASHRAE 62.1-2001 or Title 24)

Tier 2: This incorporates the Tier 1 specs plus additional design features to create a new Advanced Rooftop Unit (ARTU) that delivers greater field efficiency and performance. These features are not readily available on the market, but are a part of a development and testing project underway in the next two years through California Public Interest Energy Research and manufacturer partners.

1. Advanced self-diagnostics capabilities (i.e., failure sensors)

2. Capability to independently test and verify the operation of compressors, economizers, air flow, rates and heating systems in the field
3. Cabinet leakage maximums
4. Additional Fan efficiency and control capabilities
5. Thermostat occupancy-sensor interface capabilities

Tier 3 is a proposed performance-based measurement for future specification development. There is currently a lack of performance-based measures and test protocols to address in-field performance problems that affect efficiency. As a result, the HECAC committee has identified a number of measures that would be useful in shifting the specification towards a performance-based measure. These include:

1. Economizers to have a mean time before failure (MTBF) of 15 years
2. Sensors designed to have a MTBF of 15 years
3. Provision for continuous ventilation air during occupied periods in fan only mode and specifications for maximum fan power
4. Specifications for modulating cooling output while maintaining specific efficiencies
5. Requirement for a TXV or other metering device
6. Development of a standard test protocol for economizers

MANUFACTURERS' WHITE PAPER

This is a brief report for manufacturers, who are major partners in developing solutions to many of the system performance problems. The report's objective is to encourage manufacturers to address as many of these problems as possible in the design stage rather than relying on the problems to be identified during commissioning or fixed during O&M activities.

The white paper was distributed in conjunction with the draft specifications identified above for small commercial, integrated rooftop HVAC systems. This project has already dramatically increased national program administrators' awareness of small-commercial-rooftop, in-field energy-efficiency performance issues, and identified technologies that could address these issues across a host of operating conditions.

Products

- Small Commercial HVAC System Design Guide (4.7.5)

Market Connections

PRESENTATIONS

- *ACEEE Summer Study.* August 2002. New Buildings Institute and AEC session on small package HVAC problems and a possible national spec jump starts the CEE collaboration
- *ASHRAE Winter Meeting.* Chicago, January 2003. Presentation on results of E4 research.
- *California utilities.* Fall 2003. New Buildings Institute plans to visit all utilities to provide them with completed products and to provide briefings to account representatives.

- *E Source Annual Forum.* November 2002. Presentation on E4 results.
- *IFMA World Workplace Convention.* Toronto, December 2002. AEC presentation on providing value to building occupants; included E4 results and recommendations.
- *National Conference on Building Commissioning.* Palm Springs, CA, May 2003. New Buildings Institute hosted discussion on E4 Results and Design Guide, with focus on economizers. Also hosted a breakfast meeting on the role of on-board diagnostics in improving small HVAC serviceability and reliability.
- *National Market Transformation Symposium.* April 2003. Presentation on package HVAC problems, solutions and the development of a national specification with CEE.
- *PG&E's Pacific Energy Center.* San Francisco, May 2003. Conducted training session to communicate E4 results to design professionals.

PUBLICATIONS

- *AirCare Plus brochure.* Spring 2003. PIER project results referenced in brochure. AirCare Plus is a new pilot premium service program for small RTUs currently being pilot tested by PECI for the Northwest Energy Efficiency Alliance.
- *CEE's "The Market Transformer" Newsletter.* Spring 2003. Full-page article reporting on E4's research and results presented by E4 at the Market Transformation Symposium, along with news of CEE's current efforts to develop an advanced rooftop unit specification. Distributed to CEE members, manufacturers and other interested stakeholders. Also posted on CEE's website.
- *CEE's "Tech Talk" Newsletter to the HECAC.* Fall 2003. The PIER team contributed to an article on refrigeration charge for the CEE High Efficiency Commercial Air Conditioning Committee.
- *Energy Design Resources (EDR).* EDR funded the project team's development of a design brief, which is an abbreviated version of the Design Guide. It is published on the EDR website: www.energydesignresources.com (follow the "Design Briefs" link on EDR's home page).
- *E Source Report.* September/October 2003. E4's findings and recommendations to be published in an upcoming report entitled, "2003 Update on Packaged Rooftop Air Conditioners: Are Efficiency Levels Topping Out?" The report will includes discussion of the PIER/CEE efforts to create a prototype high-performance package rooftop unit. Audience: Energy-efficiency design professionals.
- *HPAC Engineering Magazine.* Four articles on RTU's: Selecting right unit (8/02); Economizer failure rates (9/02); O&M guide (10/02); and Commissioning (11/02). California subscribers of this national magazine include more than 4,000 HVAC and building industry professionals, including engineering management; system designers, installers and maintenance personnel; and facility managers.

CODES AND STANDARDS

- *Title 24 – Acceptance Requirements.* Element 4's field findings informed the Institute's Nonresidential Acceptance Requirements proposal to the California 2005 Title 24 Standards. The proposal recommends establishing Acceptance Requirements for Nonresidential Buildings, which would include inspection checks and functional and performance testing to determine if specific building components, equipment, systems, and interfaces between systems conform to the criteria set forth in the Standards and to related construction documents (plans or specifications).
- *Title 24 – Duct Leakage and Insulation.* Element 4's analysis work supported the Nonresidential Duct Sealing and Insulation proposal through PG&E's Codes and Standards Enhancement (CASE) initiative. While PG&E funded the preparation of this report, much of the research and analysis that informed the proposal was supported by the E4 PIER effort. This code change proposal updates the treatment of duct systems in light commercial buildings. For any single-zone unitary air conditioning system or heat pump serving 5000 ft^2 or less, with duct systems located outside of the thermal envelope of the building in an unconditioned space or outdoors, duct leakage sealing will be prescriptively required during installation. Duct insulation R-values are increased from R-4.2 to R-8 for ducts located outside of the thermal envelope in an unconditioned space or outdoors. Benefits of the proposal, which would make duct tightening a prescriptive requirement, include:
    - Energy savings of about 20% of the annual cooling consumption in buildings where duct systems are located outside the thermal envelope of the building in an unconditioned space.
    - Peak demand savings
    - Improved comfort in buildings with tight ducts

NETWORKING AND COLLABORATION

- *Advanced Building Guidelines (the Guidelines).* Many of the guidelines and research results developed by Element 4 will be incorporated in the *Advanced Building Guidelines,* an influential new set of voluntary commercial building performance targets being developed by New Buildings Institute. The Institute is entering into an agreement with ASHRAE and AIA to use the Guidelines criteria (called the "E-Benchmark") in an ASHRAE-sanctioned national guide for their members within a year. The guide will be under the ASHRAE banner and the Institute will be listed as a contributor. Since the ABG contains PIER findings, including the E4 Design Guide content, this new agreement will help move the PIER work directly into the mechanical designers marketplace.
- *Air-Conditioning and Refrigeration Institute (ARI).* The project team, in conjunction with CEE, has engaged the ARI in discussions of the draft specification based on the PIER work. The ARI has committed to addressing improved performance opportunities through their technical committee and national meetings in late 2003. Members have also offered to participate in the assessment of an advanced unit in the next phase of PIER work. The role of ARI in development of approved manufacturer testing protocols is highly valuable in order to advance the next generation of small package HVAC

equipment. Dick Lord from Carrier, a TAG member and also an ARI committee chair, has helped to introduce the issues and objectives of the PIER work to the ARI. In May 2003 CEE met with ARI to inform them of CEE's HECAC initiative (described in Outcomes of Project 4.6 above). In September the project team, ARI, and the CEE discussed manufacturer support and barriers to specific items in the specification and next phase work. Additional meetings are scheduled.

- *Building Operator Certification (BOC) Training.* The Institute has arranged for the E4 results to be integrated into the BOC training. The BOC training was developed in the Northwest but is now in use in California and nationally. The E4 results are the most transferable because many of the findings and recommendations can be adopted by operators rather than solely at design.
- *Carrier Corp.* Manufacturer is evaluating equipment design and modifications (details currently proprietary) based on E4 results.
- *Corporate Management & Realty Corporation.* CMRC presents national seminars to facility managers and architects. These seminars now include information from E4's research.
- *Commissioning Collaboratives.* Design Guide content from E4 will inform the work of the California Commissioning Collaborative and the Northwest Energy Efficiency Council/Building Operators Certification Program.
- *Energy Design Resources.* There is interest in E4's results to be included in future EDR seminars (not currently scheduled).
- *Portland Energy Conservation Inc.* Results from E4 will inform the HVAC Commissioning Guideline revision process and be made available directly to commissioning agents.

4.7. Conclusions and Recommendations

4.7.1. Conclusions

- *Average building electricity savings are 8.4% and natural gas savings are 30.2% resulting in a combined average energy cost saving of $0.26 /square foot.*
    - The average energy increase from refrigerant charge problems was about 5% of the annual cooling energy.
    - The annual energy increase from low airflow is about 9% of the annual cooling energy.
    - The average measured fan power was about 20% higher than the assumptions used in the Title 24 Energy Standards, causing a commensurate increase in the annual fan energy.
- *Reduction in system size on the order of 40% and reduction in annual energy costs on the order of 25% to 30% are possible with simple integrated design strategies.*
- *The research identified numerous opportunities for improving the as-installed efficiency of small commercial rooftop units.* Opportunities include improved economizer designs for better reliability and control, design features such as thermostatic expansion devices that maintain unit efficiency over a range of refrigerant charge and air flow rates, improved air-side efficiency, on-board fault detection and diagnostic systems, and the use of thermostats appropriate for commercial applications.

- *Failure to operate the building with a continuously operating fan reduces the effective ventilation rate significantly.*
- *The efficiency of a 10.3 EER unit would effectively drop to 9.1 if the fan flow is increased to meet design flowrate targets (400 cfm/ton) due to the increased fan power of almost 90% over current operating practice.*
- *We recommend a design static pressure not to exceed 0.5 in. w.c. at design flowrate (400 cfm per ton).* The average duct system pressure drop corrected to 400 cfm/ton would equal 0.625 in. w.c, or almost three times the ARI assumption. The ARI assumptions are not applicable to commercial buildings and undervalue fan energy in the efficiency calculations.
- *The field data indicate that duct systems are undersized, causing the low air flow rates and increased fan energy.*
- *The problem of cycling fans on ventilation rates was not previously documented per our research reviews.* Although many of these problems had been previously documented (Felts, PECI, Proctor) the extent of our survey and data is more extensive and provides specific energy and performance correlation as well as new findings.
- *Equipment manufacturers are in a unique position to address these issues through product design changes and reliability improvements.* Although many installation problems can be corrected during commissioning, and reliability problems can be corrected during normal operations and maintenance, it may be more effective to also address these problems at the product design level. Equipment incorporating these design improvements offered by manufacturers and actively promoted through energy-efficiency and market transformation programs represents an opportunity for reduced energy costs for end-users and an enhanced sales opportunity for manufacturers of small rooftop systems.

4.7.2. Commercialization Potential Or Commercialization Initiated

Element 4 and New Buildings Institute collaborated with the Consortium for Energy Efficiency (CEE) and their High Efficiency Commercial Air Conditioning Committee (HECAC) to develop a national, next-generation performance specification for small commercial, integrated rooftop HVAC systems. This initiative consists of two phases:

- *Phase 1:* A proposed specification that is ready now to include in utility and public-benefit programs as a new requirement or recommendation. It includes technological options that are fundamental to unit efficiency and reliability currently available on rooftop units that can be delivered to the customer today.
- *Phase 2:* The development of a performance-based specification for an advanced rooftop unit (ARTU), an enhanced product based on advanced performance features that further improve efficiency and reliability. A prototype of this unit will be developed under the Commission's Phase Last program.

CEE and NBI are in the process of gathering manufacturer input on the proposed specification. The ARI has committed to addressing improved performance opportunities through their technical committee and national meetings in late 2003. Members have also offered to participate in the assessment of an advanced unit in the next phase of PIER work. The ARI noted that this was the first time that the organization as a whole had been asked to help address efficiency issues regarding their industry equipment and they welcomed the opportunity.

4.7.3. Recommendations

PURSUE MARKET TRANSFORMATION OPPORTUNITIES THROUGH O&M PROGRAMS.

Manufacturer initiatives are currently being pursued with some success, but important market transformation opportunities also exist in the O&M arena. At a recent conference on market transformation jointly sponsored by ACEEE and CEE, a study was presented that ranked different types of market connection activities in terms of maturity, market saturation, effectiveness and related issues. One of the program types that ranked highest in terms of savings potential but also highest in terms of complexity was O&M-type programs. Based on its research and analysis efforts and networking activities, the Element 4 team agrees with ACEEE's assessment that O&M programs are the next frontier in market transformation.

A key first step will be raising the consciousness of the building owners, operators and facilities staff who make service-contract purchasing decisions; they need to be educated about equipment performance problems, solutions to those problems, and benefits to fixing them. A related next step would be the development of an infrastructure to provide solutions to the building owners and operators, and changing the scope and rigor of standard small HVAC maintenance contracts.

DEVELOP AN ADVANCED PACKAGE ROOFTOP UNIT.

The Design Guide produced by Element 4 provides designers and operators with performance guidance for improving the efficiency and operation of small package HVAC units. Effecting lasting change, however, involves integrating many of these improvements into a new "advanced" unit and developing a specification for manufacturers to produce these advanced units. A performance-based specification will likely be more effective than a prescriptive specification because it would encourage innovation among manufacturers and their engineers. A performance-based specification would need to include a certification procedure involving a standard test protocol (see details in the Technical Outcomes section of Project 4.6 above).

As a step toward developing a performance-based specification and test protocol, the Element 4 team recommends developing of a prototype advanced rooftop unit of 5-ton cooling capacity that would address many of the energy and ventilation problems found through E4's research. This prototype unit would serve as a demonstration system that could be studied and tested—both in a lab and in the field—by researchers and manufacturers. The research team would work with manufacturers and ARI to develop an acceptable standard test protocol as part of the process of testing the prototype unit to verify the performance of the additional features. The end result would be a set of performance protocols that manufacturers feel comfortable with and the demonstration of a unit that operates according to prevailing ventilation standards, reduces energy use and requires less maintenance.

A related recommended activity would be the development of a rating methodology that accounts for O&M improvements. Currently, salespeople sell systems based on SEER and EER, which is what the equipment is rated on. If there were a way to incorporate operational and reliability issues in the ratings, there would be a built-in marketing incentive to address many of the problems that the E4 researchers found in the field.

4.7.4. Benefits to California

The annual new commercial construction in California is 157 million square per year. Of this, it is estimated that 39.7 million square feet (~25%) will be served by packaged units between 1 and 10 tons in size. With a first year market penetration of 10%, annual energy savings are estimated to be 6,942 MWh. With an increase in market penetration of 1% per year, the ten year cumulative electric energy savings is 496,360 MWh equal to energy cost savings over this period of $68 million.

The natural gas savings are estimated to be 97,107 therms first year savings resulting in a cumulative 10 year savings of 6,943,000 therms and a resulting cost savings of $5.8 million.

The total net energy benefits over ten years to citizens of California would be $73.8 million.

Statewide demand savings are estimated at 1,486 kW per year (1.5 MW) based on a first year market penetration of 10%. With an increase in market penetration of 1% per year, the demand savings in year ten is 21.5 MW.

5.0 Integrated Design of Commercial Building Ceiling Systems (Element 5)

5.1. Introduction

At least 60% of nonresidential ceiling area in California is directly below a roof that can potentially provide access to daylighting, and 90% of new floor space is single-story construction. Skylighting, or toplighting with daylight, has dramatic potential for saving lighting energy. Skylighting is not widely used by building designers or owners because each skylighting design requires the careful integration of the ceiling system, skylight, light well, electric lighting, photocontrols, and air distribution systems. This problem has been discussed for over fifteen years within the building science community, yet before this project the resources had not materialized for integrated solutions to be developed.

This Element was designed to fill research information gaps and develop design protocols to facilitate ceiling-system integration and minimize energy use while meeting all building requirements such as fire protection, seismic safety and acoustics. The Element's primary product is a Design Guidelines document that aims to provide designers and project managers with guidelines for incorporating skylights with light wells in commercial buildings.

5.1.1. Element Objectives

The Integrated Ceiling project's objectives were to:

- Estimate the probability of insulation coverage on T-bar ceilings to help determine if insulated ceilings are a desirable thermal feature.
- Better understand the performance of skylights and light wells when used in conjunction with T-bar ceilings.
- Characterize the thermal performance of skylights. This includes heat transfer across the skylights and through the sides of the light well in addition to the heat that directly enters the conditioned space.
- Provide a method of testing and communicating the photometric distributions of skylights so designers can better predict the illumination characteristics of their skylight designs.
- Compare methods of testing visible transmittance of skylights and of modeling skylighting system transmittance to better predict the performance of skylighting system in commercial buildings.
- Develop an integrated ceiling-system design guideline that will support the effective use of skylighting in buildings with T-bar ceilings.
- Disseminate the above information to the appropriate people and organizations so that the benefits of skylighting can be effectively employed in new and remodeled buildings in California.

This research program consists of three related projects:

1. Comparative energy performance of lay-in insulation (Project 5.2)
2. Comprehensive testing of representative skylighting systems (skylights and light wells), including U-values, SHGC, visible light transmission and photometrics (Project 5.3)

3. An integrated ceiling-system design guideline for quality lighting (including daylight) and energy savings (Project 5.4)

5.1.2. Project Team and Technical Advisory Group (TAG)

Element 5 was led by Jon McHugh of Heschong Mahone Group with support from Lisa Heschong, Puja Manglani, Mudit Saxena, and Rocelyn Dee. Key subcontractors were ETC Labs, Tait Solar, and Lighting Sciences. Additional subcontractors included Architectural Energy Corporation, Benya Lighting Design, Hemphill Industrial Technologies, and Williams + Paddon Architects and Planners.

Heschong Mahone Group and New Buildings Institute would like to acknowledge the invaluable guidance and advice provided by members of Element 5's TAG, which included:

Accralight Skylights—Ivan Johnson

Armstrong World Industries—Bill Beakes, Bill Franz

Australian Window Association—Peter Lyons

California Daylight—Brad Prouty

CPI—Dan Cherney

CrystaLite Inc.—Steve Richter

D&R International—Bipan Shah

DayLite Company—Gus Bernal, John Mors

Florida Solar Energy Center—Jim Cummings, Ross McCluney

Heschong Mahone Group—Charles Erhlich, Lisa Heschong

Independent Testing Laboratories—Bob Berger

Lawrence Berkeley National Laboratory—Dariush Arasteh, Joe Klems, Eleanor Lee, Francis Rubinstein, Stephen Selkowitz

Lithonia Lighting—Richard Heinisch

Micron Vinyl—Doug Cole

National Research Council Canada—Morad Atif, Hakim Elmahdy, Aziz Laoudi

Naturalite Skylight Systems—Randy Heather

NIST—Stephen Treado

Owens Corning—David Ware

Pella Windows—Joe Hayden

Sears—Dave Alexander

Sunoptics Prismatic Skylights— Jerry Blomberg, Jim Blomberg

Velux—Roland Temple

Wasco Products—Sean Flanigan

The following companies provided generous in-kind support to this project:

- CrystaLite Inc.
- DayLite Natural Lighting Technologies LLC
- Naturalite Skylight Systems
- Sunoptics Prismatic Skylights
- Velux Skylights
- Pacific Gas and Electric Company/Pacific Energy Center Tool Lending Library

5.2. Effectiveness of Lay-In Insulation (Project 5.2)

5.2.1. Introduction

Background and Overview

When this research project began, current energy codes allowed the use of lay-in insulation over the top of dropped (T-bar) ceilings. This insulation method is fairly common due to its low installation cost. There have been anecdotal reports that insulation integrity is not maintained over time because it is moved during repairs in the ceiling cavity and not put back after repairs are completed. This creates a thermal short circuit in the envelope insulation system.

Prior to this project, the magnitude of the problem had never been quantified over a population of buildings. Therefore, the cost-effectiveness of allowing lay-in insulation was unknown.

5.2.2. Project Objectives

This project's objectives were to:

- Survey the top floor of 70 commercial building sites in California with dropped ceilings to identify what fraction of the original insulation is in place for both lay-in insulation and under-roof applied insulation.
- Calculate the energy and energy cost impacts of these approaches to roof/ceiling insulation and apply the results to a model of California commercial buildings.
- Evaluate the effectiveness of insulation laid directly on top of acoustic ceiling tiles in T-bar dropped ceilings.

5.2.3. Approach

- Telephone surveys were developed to screen potential candidates for participation in the field surveys, and a site-visit protocol and site sheet were developed (Task 5.2.2).
- Phone surveys of 200 building occupants were completed (Task 5.2.3).
- Site visits to 13 buildings were conducted, with field staff checking the lay-in insulation coverage in several different locations within each building, resulting in 39 observations (Task 5.2.4).

Figure 22. Surveyor Accessing Plenum Space Above The Dropped Ceiling

- Application issues and costs of lay-in insulation versus alternative insulation methods (insulated drywall ceilings and insulated roof decks) were researched (Task 5.2.5). The researchers interviewed architects to understand their preferences in specifying insulation, addressing issues such as longevity, first cost, and ease of installation for different types of insulation. The researchers obtained cost data from two sources: contractors and the RS Means Data, which provides a 20-city average cost for many typical construction methods. The average costs for various insulation and ceiling types were then used to calculate total costs for eight construction options in various California climate zones for a prototypical 2,000 ft² single-story office building with a 9-ft ceiling and a flat roof. This information was used to develop cost-effectiveness options for various locations of insulation in the ceiling system. The results of this task are detailed in deliverable 5.2.5, "Insulation Cost and Application Study."
- The energy and energy-cost impacts of these approaches to roof/ceiling insulation were calculated. The results were applied to a model of California commercial buildings (Task 5.2.6). The energy analysis indicates that infiltration losses across the ceiling effectively bypass much of the insulating value of lay-in insulation. Thus the energy analysis is sensitive to the effective leakage area of the ceiling and the pressure gradient across the ceiling plane. To place high and low bounds on the results, the energy analysis was conducted with a low estimate of effective leakage area from the Association of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) Handbook of Fundamentals and a higher estimate based upon recent research by the Florida Solar Energy Center (FSEC).

5.2.4. Technical Outcomes

- *Phone survey responses indicated a lower than expected number of buildings with lay-in insulation (5%) and a higher than expected number of buildings with skylights (26%).*
- *Measured summer plenum temperatures were relatively cool in most commercial buildings with insulated roof decks – only a few degrees Fahrenheit above the conditioned space temperature.* This is true for both plenum return and ducted return HVAC systems. Heat that enters

the plenum space is inside the thermal boundary of most commercial buildings and is ultimately a load on the HVAC system. Performance of skylights with light wells and tubular skylights is expected to be significantly different for residences and commercial buildings due to different temperatures around the light well and due to the isolation of the ceiling air from the HVAC load.

- Of the 39 observations of lay-in insulation coverage in 13 buildings, *from 10% to 90% of the ceiling area was uninsulated,* with most observations falling between 10% to 40% of the ceiling area without insulation.
- As shown in Figure 23, except for the few outliers, the range of coverage is relatively constant regardless of building age. However, *over time, fewer buildings maintain good insulation coverage.* See Figure 24 and Figure 25 for examples of observed problems with lay-in insulation.

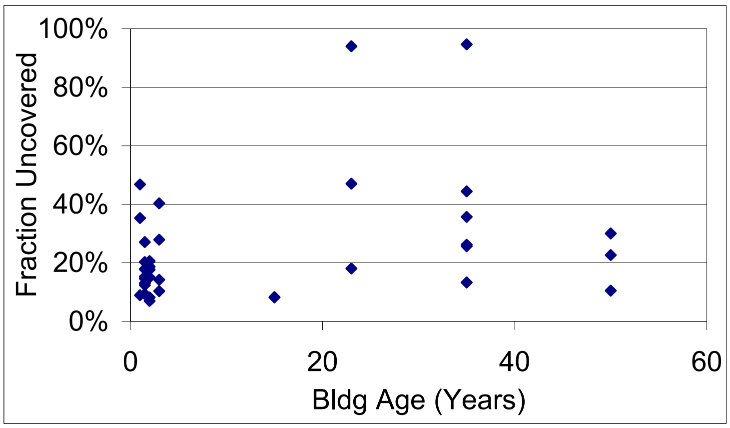

Figure 23. Fraction Of Ceiling Uninsulated Compared To Building Age

Figure 24. Problems With Lay-In Insulation Coverage

Plenum with lay-in insulation on ceiling tiles (left). Missing insulation on recessed light can (right).

 

Figure 25. Two Examples Of Displaced Lay-In Insulation In The Plenum

- The construction costs of *lay-in insulation on acoustic tiles is the least expensive across all climate zones, followed closely by non-rigid insulation under a metal deck with uninsulated plenum walls.* The most expensive option is rigid insulation above a metal deck with insulated plenum walls. Typically, across most climate zones, the second most expensive option is lay-in insulation on a drywall ceiling. Figure 26 shows insulation under a roof deck and insulated plenum walls.

 

Figure 26. Insulation Under Roof Deck With Insulated Plenum Walls

- The energy analysis found that *buildings with lay-in insulation over suspended ceilings in general had higher energy costs than other configurations.* Savings for alternatives to lay-in insulated suspended ceilings were least in the mild California coastal climates and greatest in the warmer inland California climates.
- *The incremental cost of insulating the roof deck instead of using lay-in insulation was very small.* There is a higher initial cost if the plenum walls also need insulation (high mass walls do not necessarily require insulation). For plenum heights under 12 ft, insulating the roof and walls saved more life-cycle energy costs than the incremental cost of the insulation.

- This analysis resulted in *a recommendation that the California building efficiency standards (Title 24) prohibit use of lay-in insulation over suspended ceilings for thermal insulation except for small spaces under plenums that are taller than 12 ft.* This recommendation, if adopted, would be contained in the standard's Section 118: "Mandatory Requirements for Insulation and Cool Roofs."

Products

- Site visit protocol (5.2.2b)
- Report on phone surveys (5.2.3)
- Insulation cost and application study (5.2.5)
- Summary report: onsite data collection and analysis results (5.2.4 and 5.2.6)

5.3. Comprehensive Skylight Testing (Project 5.3)

5.3.1. Introduction

Background and Overview

Over the last 15 years the knowledge about the thermal performance of windows has increased tremendously. Databases now exist that provide the U-factor, solar heat gain coefficient (SHGC), and visible transmittance of virtually every combination of glazing assembly and frame type. The National Fenestration Rating Council rates and labels virtually all pre-manufactured windows.

In contrast, skylights for commercial buildings are rarely tested, and little data exists about their performance. This makes it difficult to specify or recommend skylights based on an objective standard and to model their performance in real buildings.

5.3.2. Project Objectives

This project's objectives were to:

- Analyze existing data on the performance of skylights for commercial buildings; and
- Where existing data is inadequate, conduct controlled tests to characterize the thermal conductance, solar heat gain, and visible light transmittance of skylights that represent typical commercial installations.

5.3.3. Approach

The project consisted of four major activities. For a detailed description of the research methodologies and results, see the reports listed in the Products section below.

U-FACTOR TESTING (TASK 5.3.2)

The researchers analyzed the effects on actual thermal transmittance of various light-well geometries, skylight geometries, and skylight compositions that are common in commercial construction. This was done by testing the U-factors (see Figure 27)of eight skylights in combination with light wells, and analyzing available existing data and the data collected in this task. The test chamber was designed for this project and the tests were conducted by ETC Laboratories in Rochester, New York.

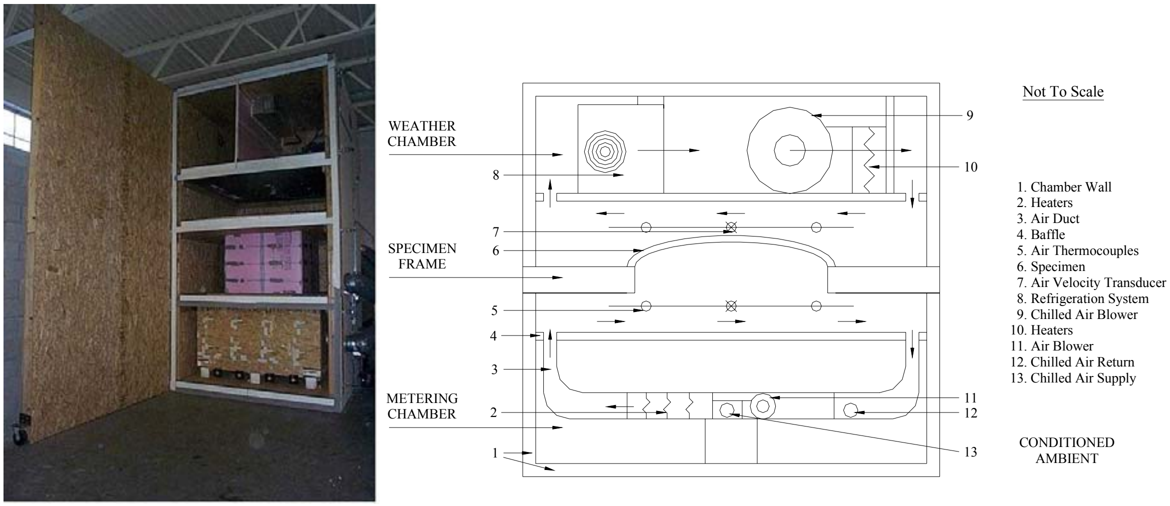

Figure 27. Photo And Diagram Of U-Factor Test Chamber

SHGC TESTING (TASK 5.3.3)

The researchers determined the angular dependence of SHGC for typical commercial skylight types such as curved skylights, and prismatic and other plastic glazing materials. The team also characterized the effect of light wells, and the resultant thermal stratification, on SHGC. This was done by testing eight skylights at the Tait Solar test facilities in Tempe, Arizona, and analyzing available existing data and the data collected in this task.

VISIBLE TRANSMITTANCE TESTING (TASK 5.3.4)

The researchers studied the effects on light properties of various light-well geometries, skylight geometries, and skylight compositions common in commercial construction (see Figure 28.)This was done by testing the same skylights that were tested for SHGC at the Tait Solar test facilities in Tempe, Arizona, and by analyzing the data collected in this task. This data was also compared with the skylight "luminaire efficiency" calculated from the photometric data (Task 5.3.5).

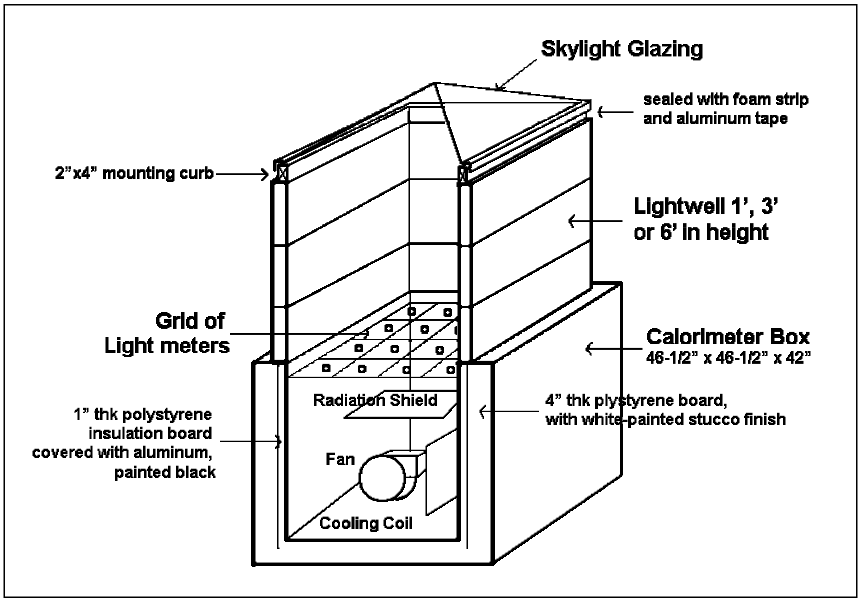

Figure 28. Cut-Away Isometric Of The Skylight Solar Calorimeter Test System (SSCTS)

PHOTOMETRIC TESTING (TASK 5.3.5)

The project team developed accurate photometric data for nine skylights with different light-well geometries. This was done by constructing a skylight testing laboratory in Arizona; performing photometric tests over the course of several days for each skylight/light-well configuration; and creating photometric files for each skylight for different sun positions under available sky conditions. This work was completed for clear-sky conditions and overcast-sky conditions.

5.3.4. Technical Outcomes

U-FACTOR TEST RESULTS (TASK 5.3.2)

- *NFRC test methods need to be updated for projecting skylights.*

  The current method of using a flat CTS (calibration transfer standard) results in erroneous results. Projecting skylights can be tested using the prior area weighted method for measuring the air film resistances.

- *Building simulation algorithms should include the capability to account for the ratio of surface area to projected area.*

  Currently simulation models assume this ratio is always 1.0. Making this change would allow better modeling of the air film heat transfer coefficients on projecting skylights.

SHGC TEST RESULTS (TASK 5.3.3)

Previous studies of skylights with insulated light wells by Joe Klems of LBNL found that SHGC was dramatically reduced by the addition of a light well. Element 5's research team performed similar tests on skylights over an uninsulated light well since light wells are not required to be insulated. The reduction in SHGC was less pronounced with uninsulated light wells because a significant amount of heat flows sideways through the wall of the skylight well into the plenum space. Nonetheless, as shown in Figure 29, the reduction in solar heat gain due to an uninsulated light well is still significant.

The two main findings are:

- *The presence of a light well decreases the effective SHGC of the skylighting system.*
- *Insulating a light well reduces the effective SHGC of the skylighting system.*

  The preliminary analysis indicates that it might be effective to insulate light wells. It may be important to better understand the heat transfer through the side of light wells. A future requirement that light wells be insulated should be researched and considered further.

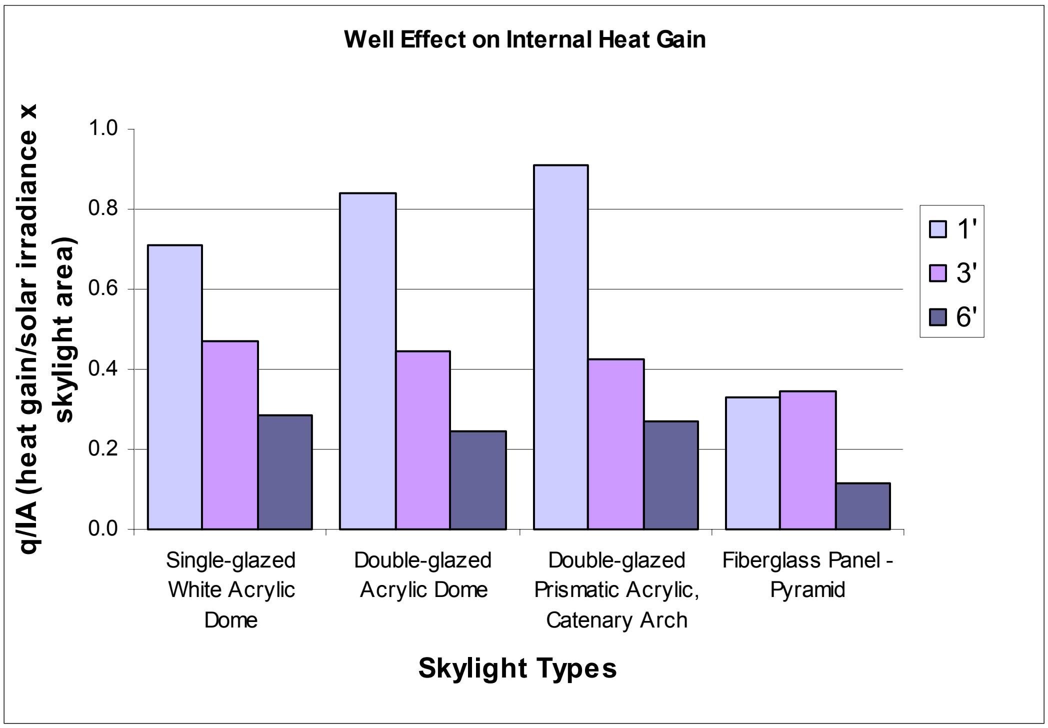

Figure 29. Effect Of Well Height On Internal Heat Gain

VISIBLE TRANSMITTANCE TEST RESULTS (TASK 5.3.4)

The primary observation from this study, illustrated in Figure 30, is that *the effective visible transmittance (EVT) of projecting (dome) skylights behaves markedly better at low sun angles than that of flat horizontal glazing*. The EVT of projecting skylights stays nearly constant over a range of solar angles, whereas the EVT of flat-glass skylights rapidly drops off as solar elevation decreases. This is significant because daylight is most needed at times when the sun angle is low.

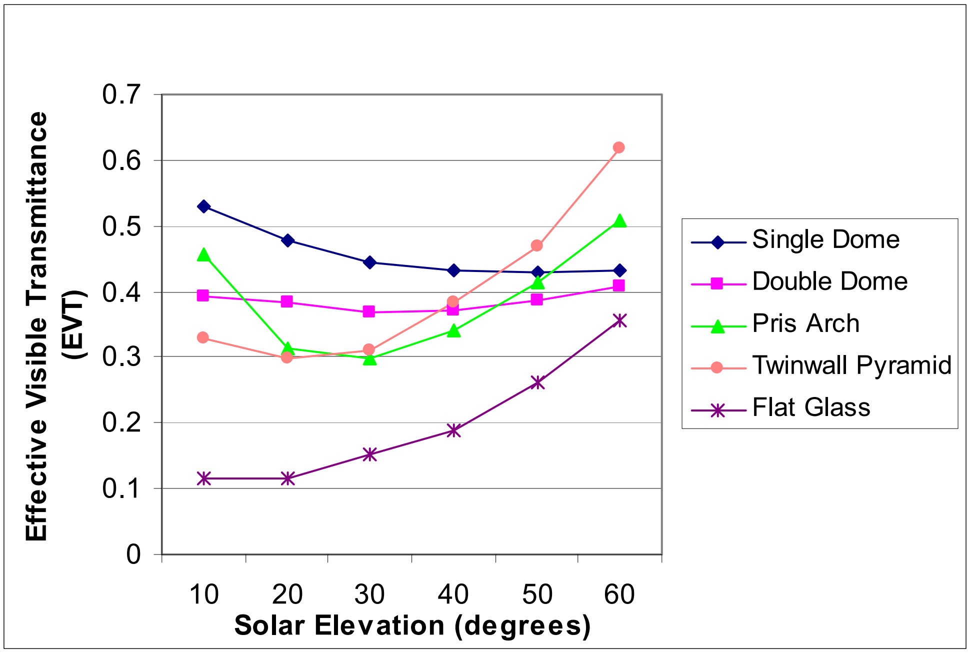

Figure 30. Effective Visible Transmittance Of Various Skylights Over Varying Sun Angles

5.3.5. Conclusions

Conclusions from this study were:

- EVTs diminish as light-well depths increase.
- Specular light wells are more effective at transmitting light through the light well.
- EVTs are proportional in most cases to the visible transmittance of the glazing used. One exception is the fiberglass insulating panels, which have marked attenuation of off-axis light.
- The EVT data more accurately reflects the performance of skylight systems representative of those found in commercial buildings.
- The EVT of projecting skylights can be measured by the test procedure developed for this project, but cannot be measured by the standard visible transmittance test procedure currently used by the National Fenestration Rating Council (NFRC).
- The data collected as part of this study can be used to generate curve fits of EVT with respect to sun angle.
- At the very least, an estimate of a constant EVT with respect to incident angle for projecting skylights is better than angle-dependent EVTs developed for flat glazing.
- In DOE-2 and other simulation programs, it would be more accurate to model projecting skylights with a constant transmittance instead of modeling them as if they were flat-glass skylights.
- The proposed NFRC method of rating the transmittance of tubular skylights (also called tubular daylighting devices, or TDDs) overestimates the transmittance of these devices

for most of the year and creates an uneven playing field between TDDs and projecting unit skylights.

- The current NFRC method of rating transmittance of skylights can only rate flat skylights; this places projecting skylights at a disadvantage as they cannot quality for an Energy Star rating. This is unfortunate because in many cases the projecting skylights have better visible light transmission characteristics than flat skylights for low sun angles.

PHOTOMETRIC DATA (TASK 5.3.5)

Photometric data describe the directionality and magnitude of light from a given light source. Almost all electric light fixtures sold in the United States have a photometric report, which allows one to calculate how the light fixtures distribute light in a room.

In the past, measured photometric information was not readily available for skylights. *As a result of this project, lighting designers now have the same predictive tools for designing with skylights as they do for electric lighting.* These photometric test reports for 22 skylight/light-well combinations under overcast and clear sky conditions have been published in IESNA LM63-1995 formatted files. The files, which are public domain information, can be downloaded from at the PIER section of www.newbuildings.org.

This new skylight photometric data will help designers use skylights not only as general lighting source but also as method of highlighting objects in a space. Figure 31 provides one example of how skylight photometrics can be used in electric lighting software to help decide where to place skylights for optimum lighting quality. For a retail setting, the design on the right is much superior to the design on the left.

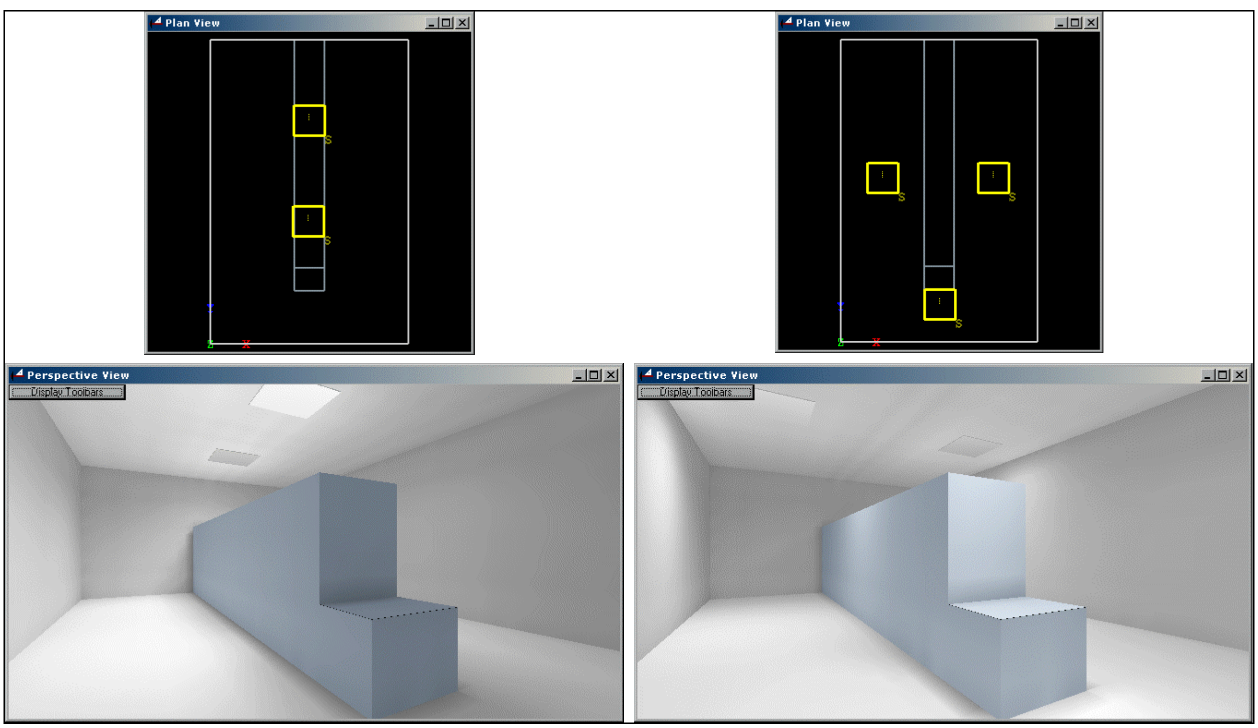

Figure 31. Skylight Photometrics Used To Evaluate Skylight Placement Over Retail Displays

Products

- Thermal transmittance test report (5.3.2)
- SHGC test report (5.3.3)
- VLT test report (5.3.4)
- Summary report describing skylight photometry lab and calibration results (5.3.5-a)
- Summary report of clear sky photometric tests (5.3.5-b)
- Summary report of overcast sky photometric tests (5.3.5-c) (Part of photometric files)

5.4. Integrated Ceiling System for Lighting Quality and Energy Savings (Project 5.4)

5.4.1. Introduction

Background and Overview

Currently, well-integrated skylighting designs that seamlessly meld the building structure, ceiling system, electric lighting, photocontrols, HVAC ductwork, and skylights are custom designs. Such designs require a substantial amount of effort by the designer and builder. The installed costs of such systems to the owner are often uncertain because the contractor may have to make on-the-fly revisions to integrate the components. The result is that skylights are often only included in a building if the owner, designer and contractor are all highly motivated to do so.

Project 5.4 builds upon the two projects discussed above: Project 5.2, which evaluated the effectiveness of lay-in insulation with T-bar ceilings, and Project 5.3, which characterized skylight performance.

5.4.2. Project Objectives

The primary focus of this research project was to develop a specification for a modular light well that integrates into T-bar ceilings. This specification would:

- Provide excellent lighting and daylighting quality, thermal comfort, lower construction costs, acoustic performance, and energy efficiency;
- Allow modularity and interchangeability of components so that multiple sourcing can be assured for competitive pricing, fast-track availability, and eventual replacement of components and reconfiguration;
- Address multi-dimensional requirements of flammability, seismic safety, acoustics, thermal and solar heat gain transmittance, and glare and data communication;
- Assure that the ceiling system meets overlapping safety, energy and environmental quality requirements; and
- Allow design freedom while addressing building codes and component integration issues.

5.4.3. Approach

The project team conducted research, including visiting manufacturers, analyzing the issues that drive ceiling system specification, researching applicable codes, and investigating likely combinations of building components for existing interconnection protocols and standards.

The team then drafted an integrated ceiling-system design guideline for how ceiling components can effectively interconnect and work in an optimal fashion. Example specifications of modular skylight designs were developed using the photometric files created in Project 5.3. Two electric lighting system designs—a direct system and a direct/indirect system—were developed that could be used in conjunction with the modular skylight. These example designs comprise an essential part of the final guideline, titled "Design Guidelines for Skylights with Suspended Ceilings" (Design Guidelines).

5.4.4. Technical Outcomes

The primary outcome of Project 5.4 was the development of the "Design Guidelines for Skylights with Suspended Ceilings," which addresses two audiences: designers/project managers and manufacturers.

The Design Guidelines aim to provide designers and project managers with guidelines for incorporating skylights with light wells in commercial buildings. It discusses the design process, implications of different design solutions, and code- and performance-related issues. Designers can use the information in the Design Guidelines to create a custom skylight/light-well system for their projects. In addition, the Design Guidelines' valuable coordination and integration information will help facilitate the designers work with other construction professionals. The main building types that will benefit from the Design Guidelines are new and retrofit constructions of low-rise offices, retail stores and schools with suspended ceiling systems.

For the manufacturer, the Design Guidelines communicates system design, component requirements, code and performance metrics, and market information about modular skylight systems and the market benefits of providing such a product.

The solutions presented in the Design Guidelines are based on research results, as well as input from industry members. They are also based on the experiences of project managers and designers who have installed or designed light wells with suspended ceilings. Following the recommendations of the Design Guidelines will result in the effective installation of skylight systems that provide optimal energy performance and superior lighting quality.

The guideline has six chapters:

- *Chapter 1 – A Case for Skylights and Suspended Ceilings*. Addresses issues such as the benefits of skylights, reasons for using suspended ceilings, market potential, energy savings, descriptions of current building practices of projects that have integrated skylight installations with a suspended ceiling system, and projections for future skylighting trends in California.
- *Chapter 2 – Nomenclatures and Functions.* Establishes common terms and definitions for light-well components to help the relevant industries communicate effectively. Functions associated with each component are included to define the functional basic requirements.
- *Chapter 3 – System Design.* Lays out the process of designing a skylight well, including issues of sizing, spacing, design coordination, and component requirements. Preliminary design is done using rules-of-thumb and by accommodating other building services. More in-depth analysis can be accomplished by using photometrics and isolux graphs.

Also discusses the coordination of skylights with other systems from the design to the construction stages of a project.

- *Chapter 4 – Component Requirements***.** Discusses the geometry and physical properties required of each component to satisfy their performance goals.
- *Chapter 5 – Product Evaluation and Approval.* Explains the approvals and evaluation process that will allow modular skylight well systems to be installed in buildings. Addresses the building permit plan check, third-party product evaluation and applicable codes and tests.
- *Chapter 6 – Conceptual Systems.* Presents four conceptual systems that were developed through consultation and design sessions with industry professionals. A detailed step-by-step design process is explained through a sample project. The four systems are: a fixed-splay system with a flexible throat (Figure 32); an adjustable-splay system with a fixed metal throat (Figure 33); a fixed-splay system with a tubular adjustable throat (Figure 34); and a fixed-splay system with a fixed throat and flexible connector (Figure 35).

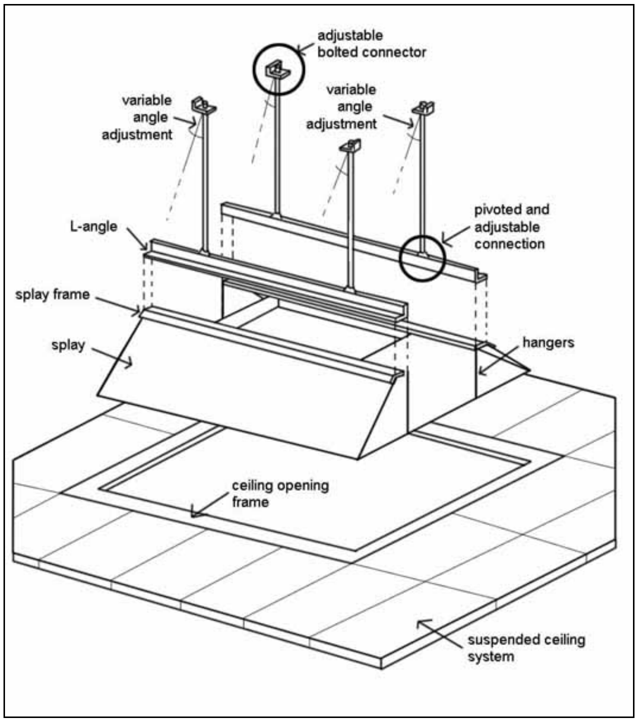

Figure 32. Fixed-Splay; Flexible Throat

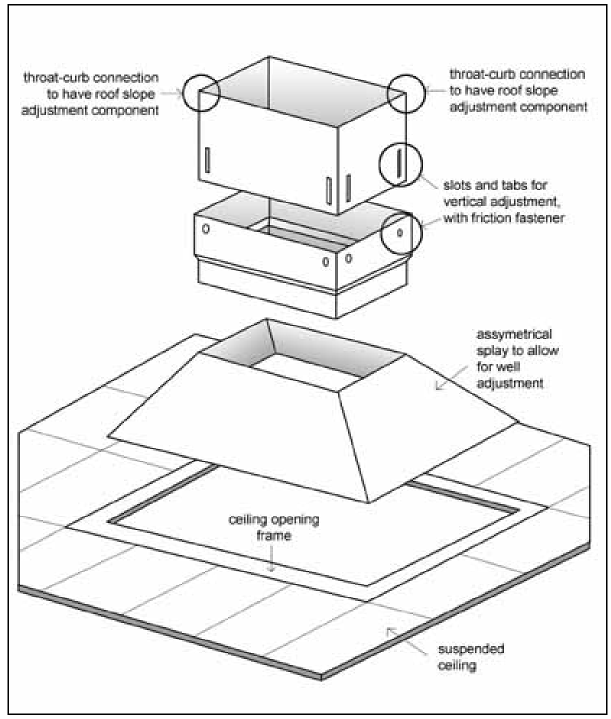

Figure 33. Adjustable Splay; Fixed-Metal Throat

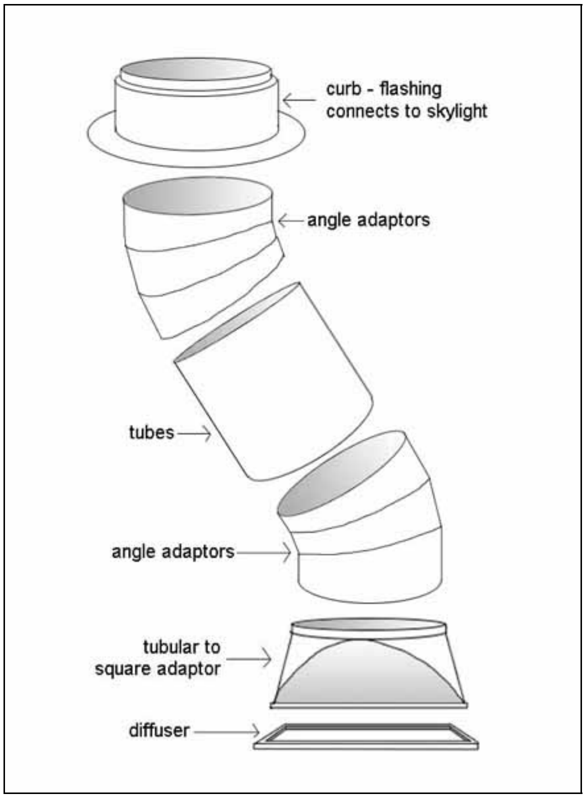

Figure 34. Fixed Splay, Tubular Adjustable Throat

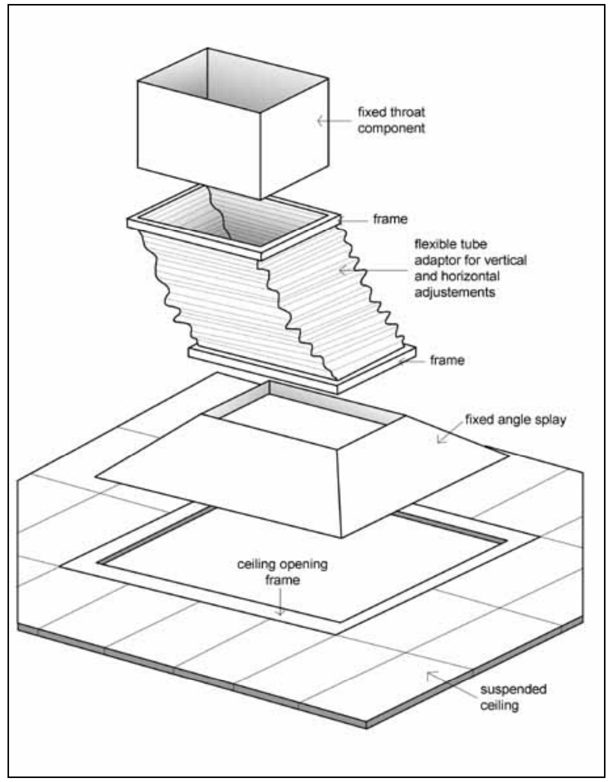

Figure 35. Fixed Splay; Fixed Throat, Flex Connector

Products

- Integrated Ceiling Design Summary Research Report (5.4.2)
- Design Guidelines for Skylights with Suspended Ceilings (5.4.6)

Market Connections

PRESENTATIONS

- *American Association of Manufacturers (AAMA),* Tucson, January 2002. Presentation on impact of integrated ceiling project on skylight market, use of software to improve skylighting design, and proposed Title 24 code change proposals. High level of interest from skylight manufacturers about the photometrics and its applicability for marketing their products.
- *California utilities.* The Institute made visits or contacts with each of the California IOUs and SMUD during 2001-2002 to brief them on the PIER objectives, anticipated products and schedule. NBI and project team members will visit each of these utilities at the end of 2003 to provide the efficiency program staff with completed PIER products and to discuss the transfer of the results into their programs. The IOU staff has indicated that the Savings by Design statewide program will be the best mechanism for integration of the majority of the PIER results.

- *IESNA Annual Conference.* August 2002. Presented paper, "Skylights as Luminaires: PIER Skylight Photometric Test Results." Paper was published in the IESNA Annual Conference Proceedings.
- *National Fenestration Rating Council* (NFRC). Annual Meeting, Tucson, June 2003. Presentation on U-factor and SHGC testing and code issues. Discussion points included: why commercial skylighting is important and how it differs from residential skylighting; the importance of measuring heat flux through the side of light wells; the impact of light wells on SHGC; the effect of skylight shape on angle-dependent visible transmittance and that projecting skylights are more efficient at transferring light than flat skylights; why SHGC should not be regulated in isolation from visible transmittance; and why visible transmittance is more important than U-factor for skylights. There are two potential outcomes of this presentation: 1) NFRC may reconsider their rating system for tubular daylighting devices; 2) U-factor results may have some effect on how NFRC rates skylights. NRFC has published a copy of E5's presentation on their website. E5 has also contacted the developers of SkyVision, after identifying that SkyVision may make it possible for NFRC to model projecting skylights for rating purposes.
- *Pacific Energy Center.* June 2003. E5 results presented at a training session titled "Integrated Skylights and Electric Lighting in Commercial Ceiling Systems." November 2002: E2 and E5 results presented at general training on skylighting design.
- *Pacific Energy Center training***.** San Francisco, June 2002. A training session on the use of the PIER photometric files was presented in conjunction with LightFair at the PG&E Pacific Energy Center.
- *SkyCalc training at Southern California Edison's Customer Technology Applications Center (CTAC).* E5 results included in spring 2003 and fall 2002 training sessions on SkyCalc program by Heschong Mahone Group, and will likely continue to be part of ongoing presentations.

CODES, STANDARDS AND DESIGN GUIDELINES

- *Title 24 2005 Standards Update—Roof/Ceiling Insulation.* With funding from the Commission, Element 5 drafted a proposed change to Title 24's Section 118—the requirement for placement of roof/ceiling insulation in nonresidential and high-rise residential buildings. As a direct result of Project 5.2's field results and energy and cost analyses, this proposal recommended the elimination of the allowance of insulation on dropped ceilings. This proposal would effectively prohibit lay-in insulation with dropped ceilings except for spaces with plenum heights greater than 12 ft. The proposal encountered little resistance, the Commission staff has supported it, and adoption is anticipated.
- *Title 24 2005 Standards Update—Daylit Zone Definition and Skylight Spacing Criterion.* Element 5's photometric and haze studies led to a proposal for a revised definition of the daylit zone and a proposal for a revised spacing criterion for skylights in the Title 24 2005 Standards update. If adopted (as it seems likely they will be), these changes will result in improved daylighting quality. The development of these two proposals was funded primarily by PG&E, but E5's PIER work on skylight testing provided key data, analysis and metrics.

- The proposed revision to Section 143c addresses the minimum skylight area for large enclosed spaces in low-rise buildings. Skylights with integrated controls are proposed to be required in some building types larger than 25,000 square feet such as warehouses and big-box retail. The visible transmittance test data allowed for the identification of a metric for diffusion that was considered necessary to develop an enforceable standard.
- The proposed revision to Section 131c addresses the definition of the daylight zone. Based on the PIER photometric testing of skylights, the spacing criterion (SC) would be revised from 2.0 to 1.4. The skylight testing project identified that the current daylit zone was too far apart and gave the wrong signal about the correct spacing of skylights to maintain lighting uniformity.
- The proposal defined a diffusion metric (haze) that would be required for obtaining energy credits for using skylights (Section 146), and would also be prescriptively required in Section 143(c).

PUBLICATIONS

- *IESNA*. August 2002. "Skylights as Luminaires: PIER Skylight Photometric Test Results" paper was published in the 2002 IESNA Annual Conference Proceedings.
- *New Buildings Institute-PIER website.* The skylight photometric tests are available for the public to download from the Institute PIER website.
- *NFRC.* July 2003. NFRC published E5's presentation (described above) on their website. To download PDF file, click on "PIER Skylight Testing" at www.nfrc.org/meetings.html.

NETWORKING AND COLLABORATION

- *ASHRAE.* ASHRAE's Subcommittee on Skylights has indicated interest in using PIER photometric results and thermal testing results in its future work to improve rating systems and manufacturing standards.
- *California investor owned utilities.* E5 is discussing case study projects that use modular light wells with the managers of the CA IOU's emerging technologies programs.
- *Ceiling grid manufacturers.* The team has been sharing findings with ceiling grid manufacturers to encourage their interest in developing a modular light well
- *Chain retailer* (name confidential). A large retailer has used the photometric data to evaluate lighting designs, including skylight and electric lighting integration and vertical illumination on displays.
- *IESNA.* Through his membership on the IESNA computer committee, Jon McHugh has suggested updating the IESNA's LM63 "standard Format for Electronic Transfer of Photometric data" to contain predefined keywords so that skylight-specific information is contained in the file header. This allows one to make lighting predictions with the photometric files for other locations and other times of the year than when the test data was collected. This proposal has been submitted to the IESNA Computer Committee.
- *Lighting software.* Lighting Analysts, a lighting software manufacturer, intends to include the photometric files in their AGI-32 software. Other lighting software manufacturers,

including the producers of SkyVision, have indicated interest in incorporating PIER photometric results in their products (see paragraph below on National Research Council of Canada).

- *NFRC.* See NFRC entry under "Presentations." In addition to providing information about the limitations of the current tubular daylighting device (TDD) rating protocol, E5 is providing NFRC additional information on current skylight test methods and how to better model skylights.
- *National Research Council of Canada.* E5 identified that the SkyVision skylighting design software created by the National Research Council of Canada (NRC) could be the appropriate tool for rating skylight performance. The Element leader has suggested that SkyVision developers contact the National Fenestration Rating Council (NFRC), which they plan to do after validating their model. NRC Staff is on the E5 TAG, and may be able to use some of the PIER skylight test data to validate their algorithms.
- *Other researchers.* Element 5 has exchanged methodologies and research tools with researchers at the Lighting Research Center, the LightRight Consortium, Natural Research Canada, the Florida Solar Energy Center, and Lawrence Berkeley National Laboratory.
- *Skylight manufacturers.* Several skylight manufacturers are considering product design modifications. One manufacturer is considering the ongoing use of the PIER project's photometric test facility. Some manufacturers have purchased additional photometric testing from Element 5's subcontractor. One manufacturer is building a prototype modular light well.
- *Steering committee industry connections.* Significant market impact occurred via the Element's TAG. In particular, at a meeting of this project's steering committee (a TAG subcommittee), the Element's findings were presented to major acoustic tile manufacturers (representing 95% of the T-bar market), major retail chain-store construction representatives, skylight manufacturers, and lighting software developers. This group helped define the direction of the guidelines, including indicating a preference for the specification to be included in the guideline instead of existing as a stand-alone document.
- *Utility incentives.* Element 5 has communicated with California utilities about the possibility of offering incentives to develop modular skylight well systems.

5.5. Conclusions and Recommendations

5.5.1. Conclusions

- *Lay-in insulation.* T-bar ceilings are ineffective as a pressure or infiltration barrier in a building. Therefore lay-in insulation is less effective at providing good thermal performance of the envelope as compared with insulation at a pressure boundary such as a hard ceiling or roof deck. In most situations, it is cost effective to move the insulation to the roof deck.

- *Skylight testing.*
    - *SHGC***.** The addition of a light well underneath a skylight reduces the solar heat gain of that skylight substantially, but not by as much as previous research indicated. This may indicate that insulating the skylight well is justified; further research should be done to determine if it is cost effective to insulate light wells.
    - *SHGC and U-factor.* When skylights and light wells are rated together, as with tubular daylighting devices or other types of combined skylight/light wells, there should be separate rating procedures for residential and commercial systems due to the dramatic differences in thermal load, occupancy hours and types, construction methods and ceiling configurations between these sectors.
    - *U-factor.* NFRC test methods need to be updated for projecting skylights. The current method of using a flat CTS (calibration transfer standard) results in erroneous results. Projecting skylights can be tested using the prior area weighted method for measuring the air film resistances. Also, building simulation algorithms should include the capability to account for the ratio of surface area to projected area. Currently simulation models assume this ratio is always 1.0. Making this change would allow better modeling of the air film heat transfer coefficients on projecting skylights.
    - *Visible transmittance.* The visible transmittance of domed skylights is fairly constant over a range of solar angles. This has implications for the modeling of domed skylights: they should be modeled using a constant visible light transmittance model rather than the more complex models that are currently used. The angular transmittance algorithms in building simulation software should be updated to account for different skylight shapes.
    - *Visible transmittance.* The ASTM D1003 test method for haze provides an adequate method for predicting the diffusion of skylight glazing.
    - *Photometrics.* The research team developed a method for testing the photometrics of skylights; this method uses a much smaller enclosure than previously believed could be used. The enclosure size was reduced by one-quarter, substantially lowering the cost of testing skylights. The research team has applied the photometric data to IESNA's LM63-1995 format. This has proven to be advantageous for predicting the luminous performance of skylights. It also allows greater prediction of skylights for uniform lighting and for highlighting objects. The shortcoming of this method is that it cannot be applied to clear skylights or skylighting systems that do not substantially diffuse light.
    - *Photometrics.* The test methodology developed in this project should be adopted by IESNA as part of their test standards. The IESNA LM63 "standard Format for Electronic Transfer of Photometric data" should be updated to contain predefined keywords so that skylight-specific information is contained in the file header. This allows one to make lighting predictions with the photometric files for other locations and other times of the year than when the test data was collected. This proposal has been submitted to the IESNA Computer Committee.

- *Skylight rating systems***.** E5's findings have been presented to the NFRC. As a result, NFRC is considering reevaluating their rating system for tubular skylights (also known as tubular daylighting devices, or TDDs). Also, the U-factor results may have some effect on how NFRC rates skylights. E5 has also contacted the developers of SkyVision and identified that their product may solve the modeling problem. The project leader also provided Energy Star program staff with the research and modeling results.

- *Integrated ceiling system design.*
  - *Splayed skylights are desirable for aesthetic reasons (people typically prefer a coffered ceiling).* Also, the splay allows skylights to be spaced further apart, thereby reducing installation costs and minimizing risks associated with roof penetrations.
  - *Modular light wells are desirable due to cost and performance predictability and better finish appearance.*
  - *Light wells substantially reduce the solar gain through the bottom of the light well, but a substantial fraction of heat goes sideways through the light well.* Further research is needed to validate the cost effectiveness of insulating the skylight well.
  - *There is a market interest and demand for modular skylight products and design recommendations.*

5.5.2. Commercialization Potential Or Commercialization Initiated

- *Photometrics***.** Some skylight manufacturers purchased additional photometric testing services and will use the data to market their skylights to major clients. One skylight manufacturer has set up a photometric test facility based on the design developed in this PIER project. They intend to use the test facility for product development and marketing materials (photometric files).
- *Lighting software.* Lighting Analysts, a lighting software manufacturer, intends to include the photometric files in their AGI-32 software. Other lighting software manufacturers, including the producers of SkyVision, have indicated interest in incorporating PIER photometric results in their products.
- *Integrated ceiling system.*
  - *The potential market for modular skylight-well products includes the building types that can take advantage of daylight benefits and that require the use of suspended ceiling systems.* These building types, which are low-rise commercial buildings such as offices, retail spaces, grocery stores, and schools, make up 54% of all new and retrofit construction in California. With an estimated annual commercial construction market of 157 million ft^2 in California, this results in a potential market of the target building types of 84.8 million ft^2 a year. Between 35 and 100 percent of all built floor space, depending upon building sector, is directly below a roof and could potentially be installed with skylights.
  - *Nationally, new construction of office, retail and educational space represents about 509.9 million ft^2 a year; therefore, there is a potential national market for skylight installations of 346.7 million sq. ft. of floor area annually.*

- *Several T-bar ceiling manufacturers expressed interest in developing modular light wells, but are not yet revealing design or market details about their intentions.*
- *One skylight manufacturer is developing a modular light well product.*
- *Several California utilities are interested in developing a pilot program that would promote modular skylight wells.*

5.5.3. Recommendations

- *Future research on modeling lay-in insulation.* Assumptions about the air infiltration rates across suspended acoustic tile ceilings have a large impact on a model's outcome. Similarly, the energy impacts of envelope tightness on air exchange rates is not entirely clear, especially given increased concern about indoor air quality. This area would benefit from further research. For example, research on the interaction between T-bar ceilings or their alternatives and fixed damper settings on small HVAC units could provide insights that yield energy savings and indoor air quality benefits.
- *Photometric testing.* The research team recommends a follow-on effort to persuade IESNA to adopt the photometric test standard. This effort would include outlining the test method and adopting certain keywords in the IESNA LM63 data format.
- *SHGC testing.* There is need for further research on the impact of sun angle on the SHGC of skylights and light wells. Further research should occur also on the SHGC of tubular daylighting devices. And further research is needed to test the SHGC of insulated light wells to help decide if it is cost effective to require insulated light wells.
- *Photometric testing.* It is probably not cost effective to measure skylights for every sun angle. A follow-on effort could determine if there is a predictive method that would allow one to take a limited number of photometric measurements and extrapolate that to the full range of skylight orientations and sun positions. This would probably involve analysis of the current data as well as some additional testing.
- *Market outreach possibilities.*
  - Develop a shorter "Brochure" on Integrated Ceiling Design. Architects would respond well to a short (8-page?) graphic and photo rich summary of the Design Guidelines' topics and recommendations. This could reference the Design Guidelines and be more widely distributed to encourage adoption of skylights and photo controls in commercial buildings.
  - Include information about skylights in reference books such as the *Time-Saver Standards for Architectural Design Data.*
  - Develop a separate numbering for skylight wells as part of the CSI's construction-specification numbering system**.**
  - Include a chapter on making splays in T-bar ceilings in the CISCA (Ceiling and Interior Systems Construction Association) *Ceilings and Systems Handbook.*

5.5.4. Benefits to California

Productivity and Interior Environments (Element 2 above) addresses daylight energy savings associated with an increased use of skylighting and lighting controls in California.

The potential market specific to modular skylight-well products includes the building types that can take advantage of daylight benefits and that require the use of suspended ceiling systems. These building types - low-rise commercial buildings such as offices, retail spaces, grocery stores, and schools - make up 54% of all new and retrofit construction in California. With an estimated total annual commercial construction market of 156 million ft^2 in California, this results in a potential market of the target building types of 84.8 million ft^2 a year. Of the potential target buildings, 16.5 million ft^2 a year are constructed with T-bar ceilings located under the roof and could be impacted by the use of the Design Guidelines.

Based on this market size for the Design Guidelines, first year electricity savings of 1,614 MWh are expected based on a 10% market penetration. Using an increase of market penetration of 1% per year over the next ten years, the cumulative electricity savings over the next ten years will be 115,429 MWh equal to a cumulative cost savings of 16 million dollars.

6.0 Integrated Design of Residential Ducting & Air Flow Systems (Element 6)

6.1. Introduction

Recent studies have demonstrated that residential duct systems are often badly installed, leaky or otherwise dysfunctional. One problem is the common practice of installing ducts with ductboard plenums and flex duct insulated to R-4.2 (code requirement) or sometimes R-6 where it is hottest: in the attic spaces of houses, above the required R-30 or R-38 ceiling insulation. There are practical and economic reasons for this practice, but until now little work had been done to develop realistic alternatives that would bring the ductwork within the conditioned building envelope.

This Element was designed to take an integrated approach to solving this and related ducting and air flow problems in California residences, and to develop solutions acceptable to the building industry.

6.2. Element Objectives

The Element began with dual objectives:

- Identify and evaluate alternative construction methods that would bring residential ductwork into the conditioned space; and
- Measure leakage and backdrafting in new California homes to determine if tightening the building envelope was increasing backdrafting.

A significant issue arose early in Program Year 1. The researcher developed a backdrafting test procedure for application to furnaces and water heaters, but in 80% of California homes, it turns out, these appliances are located in the garage or attic, outside the conditioned space. Additionally, a TAG member noted that extensive testing by Southern California Gas Company and other gas companies have not identified backdrafting problems. Therefore, the research team, with input from the PAC and TAG, concluded that depressurization-induced backdrafting is not a significant issue in California. The project team then modified the backdrafting test protocol to adapt it to hearth products, either solid fuel or gas fuel that are found in California homes. The team, however, was unable to identify homes that are significantly tighter than conventional homes built to current standards. The lack of such homes in the field test would have made it difficult for the researcher to draw conclusions from the test results.

After consultation with the Commission, the Program Advisory Committee (PAC) and the E6 Technical Advisory Group (TAG), the Element's work was re-scoped to focus on how to get ducts into the conditioned space.

The revised overall objective of Element 6 was to provide descriptions and data sufficient to:

- Allow the California Energy Commission to evaluate means of including ducts in homes' conditioned space for future revisions of the energy code; and
- Inform builders about the construction changes needed to build homes with ducts in conditioned space, while giving good estimates of likely costs and benefits.

Project Team and Technical Advisory Group (TAG)

Element 6 was led by Roger Hedrick of GARD Analytics. Other research team members were ConSol and Xenergy.

GARD Analytics and New Buildings Institute would like to acknowledge the invaluable guidance and advice provided by members of Element 6's TAG, which included:

- Rick Chitwood, Chitwood Energy Management
- Iain Walker, Lawrence Berkeley National Laboratory
- Joe Lstiburek, Building Science Corporation
- Bruce Wilcox, Berkeley Solar Group
- Jamie Lyons, Energetics, Inc.
- Marshall Hunt, Pacific Gas and Electric Company
- Robert Hemphill, GTI (withdrew from TAG after backdrafting research was eliminated)
- Daryl Hosler, Southern California Gas Company (withdrew from TAG after backdrafting research was eliminated)

6.3. Development of Alternative Construction Approaches (Project 6.3)

6.3.1. Introduction

This project comprised both the first and last tasks of this Element's work. Preliminary research on construction methods provided the foundation for subsequent projects. The Element's final product, "Home Builders Guide to Ducts in Conditioned Space (Builder's Guide)" was developed at the end of the contract term but falls within this Project 6.3.

Background and Overview

This project developed detailed descriptions of three approaches to getting ducts in conditioned space:

Unvented conditioned attic ("Cathedralized Attic");

Dropped ceiling ("Dropped Ceiling"); and

Conditioned mechanical space in the attic ("Plenum Truss").

The descriptions focus on the construction techniques and details that production builders need to successfully incorporate each approach. Specific details needed for typical single-story, two-story and townhouse homes were developed.

To date, relatively few homes in California have been built with ducts in conditioned space. Most California homes are built with a slab on grade and the duct system in the attic. There are some exceptions: Pulte Homes, for example, working with the U.S. Department of Energy's Building America Program, has been building homes in Arizona, Nevada and now California that have the ducts and air handler in an unvented conditioned attic. A few homes have also been built using the Dropped Ceiling approach, mostly in the southeast United States, again in cooperation with Building America. Finally, some Dropped Ceiling homes have been built in the Shasta, California, area with insulation and HVAC work done by Rick Chitwood.

6.3.2. Project Objectives

The project objectives were to identify and develop complete descriptions of three alternative construction approaches to building homes with ducts in conditioned space in order to give builders sufficient detail to successfully modify their existing home designs.

6.3.3. Approach

- *Literature search (Task 6.3.1).* The researcher conducted a literature search to identify recent residential projects constructed with ducts in conditioned space. Four publication sources were located that describe such projects: National Association of Home Builders Research Center; Building Science Corporation; Steven Winters Associates; and Home Energy magazine. The findings from this literature search are detailed in the "Literature Search Summary Report" (deliverable 6.3.1).
- *Interviews (Task 6.3.2).* Thirteen builders and researchers associated with the projects identified in the literature were interviewed to obtain complete descriptions of the designs used, and to collect detailed information on construction details, benefits, problems, and suggestions for improvements. Details from these interviews can be found in the report, "Interviews with Builders and Researchers" (deliverable 6.3.2).
- *Identification of Representative House Designs (Task 6.3.3).* The research team worked with California builders to select a number of home designs that represent typical houses currently being built in California. The designs were selected on the basis of subcontractor ConSol's experience with performing energy analyses in homes across the state for many different builders. They determined that these designs represent the market well, as segmented by type and floor area. The typical home designs selected include one-story detached houses, two-story detached houses, and two-story townhomes. These houses have conventional duct systems in an unconditioned attic. Most of the designs are slab on grade, although one design has a partial crawlspace. These designs are described in detail, with accompanying architectural drawings, in "Representative House Designs Summary Report" (deliverable 6.3.3).
- *Description of Alternative Construction Approaches (Task 6.3.4).* The research team identified and described the techniques that can be used to construct California houses with ducts located in conditioned space. In the guidelines produced as part of this project, "Home Builders Guide to Ducts in Conditioned Space" (deliverable 6.3.4), the techniques are applied to the three typical California production house designs identified in Task 6.3.3. These guidelines were designed to provide builders, contractors and subcontractors with sufficient detail that they could modify other existing house designs and build them successfully with ducts in conditioned space.

6.3.4. Technical Outcomes

- Nine representative California home designs were identified: three designs each of one-story, two-story, and townhouse floor plans. From those nine designs, the researcher selected three (one each of the one-story, two-story and townhouse floor plans) to serve as the baseline designs for the remaining research and analysis. Table 8 summarizes the representative characteristics of the nine designs.

Table 8. Major Characteristics of the Representative Home Designs

Design #	Type	Design Name	Floor Area (ft²)	Bed-rooms	Bath-rooms
1	1 Story	Gainsborough West (2)	1733	3	2
2	1 Story	Terra Linda	1746	3	2
3	1 Story	Los Olivos	3079	4	3
4	2 Story	Gainsborough West (1)	2231	4	3
5	2 Story	Mayfair/ Oak Glen II	3148	6	3
6	2 Story	Windmere Village 10	3194	5	3½
7	Townhome	Georgetown, Unit B	1584	3	3
8	Townhome	Sansovino, Unit 2	1216	2	2
9	Townhome	Avendale P-3, Plan 2	1570	3	2½

- Three approaches to constructing ducts inside the conditioned space were developed. Comprehensive documentation was created for each of the three approaches as applied to each representative home. These descriptive materials were designed to provide sufficient information to allow production builders to successfully modify their current designs and build them with ducts in conditioned space. The descriptions were used throughout E6's subsequent projects, and are intended to provide a basis for the Commission's future code-change evaluations. The three approaches are summarized here, with construction techniques described in detail in "Building Homes with Ducts in Conditioned Space—A Guide for Builders" (deliverable 6.3.4).
  - The *Cathedralized Attic* approach is applied to houses with conventional pitched attics. The roof deck is air sealed to provide the primary air barrier (ridge and soffit vents are not used). The ceiling insulation is moved to the roof level and installed immediately below the roof deck (see Figure 36). With the air and thermal barriers moved to the roof, the attic is brought into conditioned space. The HVAC system is then installed in the attic as it normally is. Houses built with this approach have generally used interior register locations.

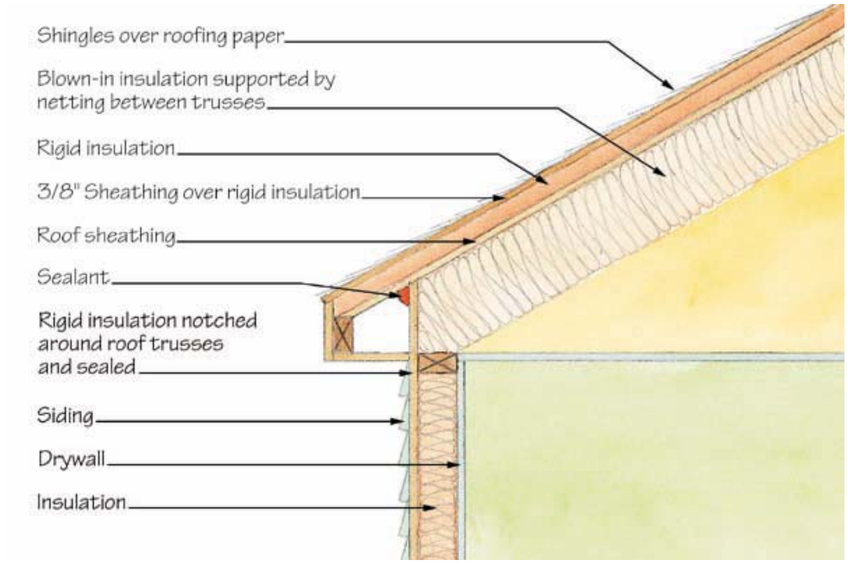

Figure 36. Insulating the Roof of a Cathedralized Attic

- The *Dropped Ceiling* approach is applied to houses with high ceilings, 9 ft to 10 ft. In hallways and other ancillary spaces, a dropped ceiling is installed at 8 ft high, with the ducts installed in the space between. By providing an air barrier at the 9 ft or 10 ft ceiling height, the duct space is brought into conditioned space. Supply registers are located on interior walls, adjacent to the dropped ceiling (see Figure 37).

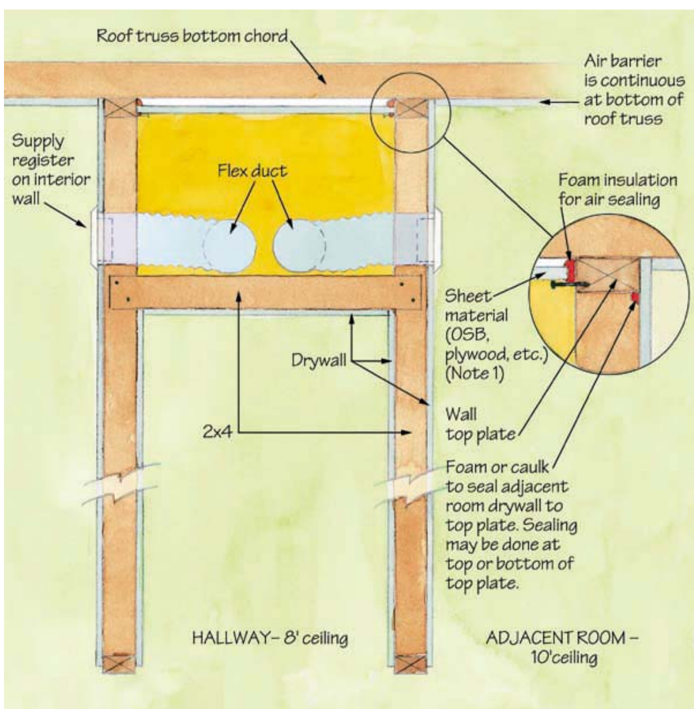

Figure 37. Dropped Ceiling Construction

Sheet material may be nailed to underside of roof trusses or laid loosely on horizontal nails. A tight fit is not required, but foam insulation or caulk must seal completely. Foam insulation will help secure the sheet material in place.

- The *Plenum Truss* approach is also applied to houses with conventional attics. Two alternative designs have been developed and tested (see Figure 38), and shown to work well. One of these alternative designs, the modified scissors truss, is used to provide a space between the ceiling and the bottom chord of the trusses. Sheet material, such as fiberboard, is installed on the bottom chord of the trusses, and sealed to provide the air barrier. Insulation is then installed above. The space between the bottom chord of the trusses and the ceiling is then inside conditioned space, and used for HVAC system installation. The conditioned duct space may not extend to the full width of the attic, so again interior supply register locations are used.

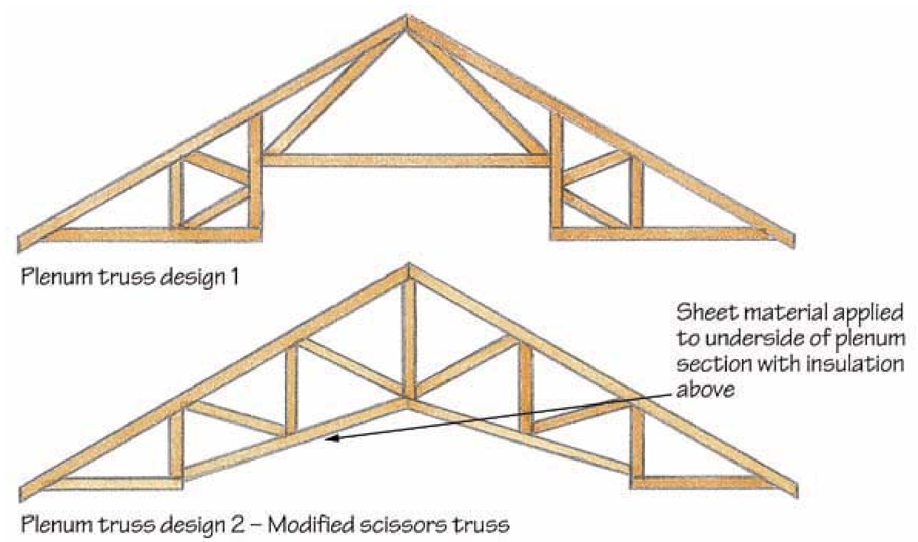

Figure 38. Plenum Truss Designs

- Guidelines were developed ("Home Builders Guide to Ducts in Conditioned Space" deliverable 6.3.4) that describe how builders can modify their home designs to incorporate the recommended approaches to putting ducts in conditioned space. These guidelines describe construction techniques, provide technical diagrams, address market barriers, and give summarized cost and savings information.

Products

- Literature Search Summary Report (6.3.1)
- Interview with Builders and Researchers (6.3.2)
- Representative House Designs Summary Report (6.3.3)
- Home Builders Guide to Ducts in Conditioned Space (6.3.4)

6.4. Identification & Approach to Resolution of Market Barriers (Project 6.4)

6.4.1. Introduction

Background and Overview

The full descriptions of the alternative approaches developed under Project 6.3 were used to identify market barriers that will need to be overcome for each approach to be successfully adopted by production builders in California.

6.4.2. Project Objectives

The objective of this project was to identify market barriers that will need to be overcome for builders to successfully implement the three approaches to putting ducts in conditioned space.

6.4.3. Approach

- Market barriers were identified from the interviews conducted for Project 6.3, and the issues associated with each market barrier were thoroughly described for builders, code officials and the Commission.
- A series of strategies for overcoming each identified market barrier was developed, with input from affected parties (i.e., builders, code officials, and the Commission).

6.4.4. Technical Outcomes

- *"Market Barriers – Identification and Approaches to Overcome Them"* (deliverable 6.4.1 and 6.4.2), identifies barriers to the market acceptance of building homes with ducts in conditioned space, and provides strategies that may be used to overcome these barriers. Overcoming the barriers may require the involvement of government agencies in addition to building contractors and subcontractors.

  The market barriers fall into two general groups, technical and commercial, which are described briefly here; see the report referenced above for a full discussion of barriers and recommended solutions.

- *Technical issues* involve difficulties in actually constructing homes with ducts in conditioned space that have the desired duct system performance. Technical barriers include:
  - *Retraining subcontractors.* Framing, for example, must be done differently to provide a dropped ceiling.
  - *Code issues.* For example, the requirement that attics be ventilated would prohibit the use of the conditioned unvented attic approach.
  - *Limitations on use of asphalt shingles.* An unvented attic used with an asphalt-shingle roof will in most cases void the shingle manufacturer's warranty.
  - *Energy credits.* The Title 24 Alternative Compliance Manual (ACM) procedures are not currently designed to address ducts in conditioned space.
  - *Measurement issues.* Test methods are needed that adequately characterize the efficiency gains achieved.

- *Duct access.* The Dropped Ceiling approach, in particular, creates a fairly small space for installing ductwork, and that space, once sealed in drywall, is difficult or impossible to access for repair or inspection.
- *Equipment sizing issues.* HVAC equipment is already typically oversized by 50% to 100% or more; the increased distribution efficiency that results from putting ducts in conditioned space exacerbates this oversizing, possibly resulting in reduced equipment efficiency and reduced comfort due to short cycling, as well as higher than necessary installation costs.

- *Commercial issues* involve problems that reduce consumer demand for homes with ducts in conditioned space. Commercial barriers include:
  - *Additional cost.* Houses with ducts in conditioned space will likely cost more to build, although this increase may be offset by reduced ductwork costs and the downsizing of HVAC equipment.
  - *Loss of floor space.* With the Dropped Ceiling approach, the air handler is usually located in a closet inside the conditioned space, decreasing usable floor space.
  - *Interior register locations.* Consumers accustomed to supply registers on the exterior walls may be uncomfortable with interior supply locations.
- *"Technical Information Package—Code Officials and Consumers"* (deliverable 6.4.2c&d) provides information to educate building code officials and consumers about the benefits of ducts in conditioned space.
  - *Code Officials:* The code official's portion of this report provides information that builders can present to a code official when requesting a variance to build a house using the Cathedralized Attic approach. This approach conflicts with most building code requirements that attics be ventilated. There are three reasons for this code requirement: 1) In cold climates, attic venting limits condensation of moisture from warm indoor air on cold roof surfaces; 2) Attic venting helps prevent ice dam formation; and 3) Attic venting helps lower the temperature of roofing materials in hot climates. The "Code Official's Guide" explains how each of these issues can be successfully addressed in other ways without attic venting.
  - *Consumers:* The consumer section of this report is intended to be developed into a brochure and distributed to consumers. It explains to homeowners the benefits of placing ducts in conditioned space, such as saving 8% to 15% on annual electricity bills for cooling. The goal of this marketing piece is to help stimulate demand for this feature in new houses.
- *"Technical Information Report"* (deliverable 6.4.2) summarizes the recommended approaches and describes associated costs, savings and market barriers. It includes cost data from Project 6.5 and energy savings data from Project 6.6. This report was specifically developed as a resource for the Commission and technical audiences.

Products

- Market Barriers—Identification and Approaches to Overcome Them (6.4.2)
- Homeowners Benefits to Ducts in Conditioned Space (6.4.2d)

- Technical Information Report – including cost and savings info for code officials and future code development (6.4.2e)

6.5. Develop Cost Data (Project 6.5)

6.5.1. Introduction

Background and Overview

One of this Element's goals was to develop integrated design solutions to ducting and air flow problems in California residences that would be acceptable to the building industry. As part of this process of developing feasible and effective alternatives, the researcher developed data comparing the cost of conventional construction with the cost of the three proposed approaches to putting ducts in conditioned space.

6.5.2. Project Objectives

This project's objective was to develop cost differences from conventional practice for each approach as applied to each of the three house styles: single-story, two-story and townhouse.

6.5.3. Approach

Using the detailed descriptions of the three alternative approaches and representative home designs developed in Project 6.3, initial cost differences from conventional practices were developed for each approach as applied to each of three house styles: single-story, two-story, and townhouse. This resulted in nine cost variants. Cost differences include changes in a number of construction elements, such as framing, air sealing, insulation, duct construction, and HVAC components.

Costs were developed in three ways:

1. Costing using standard cost-estimating guides and component costs determined from interviews with subcontractors and material suppliers. These costs are based on three houses, previously described in "Representative House Designs Summary Report" (deliverable 6.3.3).
2. Cost estimates prepared by production builders. Three production home builders estimated the cost impacts of modifying two of their designs currently in production to build them with ducts in conditioned space.
3. Cost estimates from a builder currently using the Cathedralized Attic approach and from the researcher who developed the Plenum Truss approach.

6.5.4. Technical Outcomes

The report "Cost Differences for Houses Built with Ducts in Conditioned Space" (6.5.2) provides the detailed results of the cost investigation. The three different methods of developing costs provided a wide range of values, which are summarized in Table 9.

Table 9. Construction Cost Estimate Summary ($)

	CATHEDRALIZED ATTIC		DROPPED CEILING	PLENUM TRUSS	
	Standard Ducts	Compact Ducts	Standard Ducts	Standard Ducts	Compact Ducts
Component Estimates (from standard cost-estimating guides and interviews with subcontractors and material suppliers)					
Design 2, R-30	1,233	695	763	4,371	3,834
Design 2, R-38	1,335	798	763	4,371	3,834
Design 5, R-30	1,239	-775	-486	5,833	3,819
Design 5, R-38	1,334	-680	-486	5,833	3,819
Design 8, R-30	–	1,168	360	–	2,398
Design 8, R-38	–	1,206	360	–	2,398
Production Builder Estimates					
House 1	786	–	1,936	1,486	–
House 2	773	–	1,923	1,473	–
House 3	–	–	2,966	–	–
House 4	–	–	3,012	–	–
House 5	1,073	–	1,431	–	–
House 6	938	–	1,250	–	–
Builder Costs—Cathedralized Attic					
Builder Large	–	1,120	–	–	–
Builder Small	–	1,540	–	–	–
Research Estimate—Plenum Truss					
Researcher	–	–	–	325	–

Cathedralized Attic. Cost estimates for the Cathedralized Attic are the most consistent, ranging from a savings of nearly $800 to a cost increase of about $1,200, increasing to $1,500 when pressure relief jump ducts and an outdoor air intake are included. Use of a compact duct system offers significant cost savings, which are included in these costs. When the savings from the compact duct system are not included, the cost estimates are all between $773 and $1,335, a remarkably tight grouping.

*Dropped Ceiling***.** Cost estimates for the Dropped Ceiling approach vary widely between the production builders' estimates and the component-based estimates. One source of the difference may be the compact duct-system savings included in the component-based estimates, but these savings are not large enough to explain all the difference. The builders may be assuming that the top of the dropped ceiling will be drywalled. If so, this may result in a significant cost increase, as well as schedule and subcontractor coordination problems. But drywalling the top of the dropped ceiling is not necessary; the component-based approach assumes the use of low-cost plywood with foam sealant. For the purpose of the final cost report, the researcher used professional judgment in conjunction with this wide range of estimates and represented the cost impact as $0 – $800.

Plenum Truss. Cost estimates for the Plenum Truss approach have the largest spread, from $300 to nearly $6,000. Costs for this approach appear to be closely tied to the size of the house. The variation in costs appears to be due to variations in the estimated cost for framing the floor of the ceiling plenum, which is by far the largest cost component for this approach. The component-based estimates for the floor framing alone exceed the total cost estimates from the production builders and the researcher. For the purpose of the final cost report, the researcher used professional judgment in conjunction with this wide range of estimates and represented the cost impact as $2,000 – $4,000.

SUMMARY OF CONSTRUCTION COST IMPACTS

The section above showed the detailed cost impacts of each approach for each of the three example houses. Table 10 below gives a rough summary of the construction cost change, in dollars and as a percent of total construction cost. These costs are subject to significant variation with different house designs and other factors, such as labor rates. These are also costs to the contractor, so the effect of the final cost to the consumer will be greater.

Table 10. Cost Premium Best Estimate (Cost and as Percent of Total Construction Cost)

House Design	Cathedralized Attic		Dropped Ceiling		Plenum Truss	
	%	$	%	$	$	%
One-Story Single Family	0.5%	$800	0.5%	$700	$4,000	3%
Two-Story Single Family	0%	$0	0%	$0	$4,000	1.5%
Townhouse	1%	$400	0.4%	$1,000	$2,000	2%

For the two-story single family house built with the Cathedralized Attic or Dropped Ceiling approach, the overall cost impact is $0. In this larger house with its extensive duct system, the change to a compact duct system results in large savings. The other two house designs (one-story detached and townhouse) also have savings from the change to a compact duct system, but since the houses are smaller, the savings are smaller as well. The relatively high cost for the

Plenum Truss approach is primarily due to the need for extensive additional framing of the ceiling below the attic.

Table 10 does not reflect any savings related to reducing the capacity of the central heating and cooling equipment. Although all three approaches result in a reduction in the required equipment capacity, the change may not always be great enough to allow the next smaller size unit to be selected. Careful design calculations should be used to determine the equipment size required. If the capacity can be reduced, the additional savings may well result in an overall cost reduction for building the house with the ducts in conditioned space.

Products

- Cost Differences for Houses Built with Ducts in Conditioned Space – included in "Cost and Savings for Houses Built with Ducts in Conditioned Space: Technical Information Report" (6.4.2-e)

6.6. Estimate of Energy Savings of Various Approaches (Project 6.6)

6.6.1. Introduction

Background and Overview

This project addresses one of the primary objectives of this Element's work: to provide a statistically reliable estimate of the energy savings in California houses if ducts were put in the conditioned space, and to project those savings estimates into the future assuming that the proposed construction approaches were implemented.

6.6.2. Project Objectives

The project objective was to estimate the energy savings and demand reductions for each approach and home type, located in four California climate zones with high rates of new construction.

6.6.3. Approach

- *Develop test procedures (Task 6.6.1).* The researcher specified test procedures to be used in evaluating the performance of duct systems located in conditioned space. Two tests were specified, one for air leakage and the other for thermal conduction. The air leakage test was specified for use in completing Task 6.6.2. The thermal conduction test was intended to be a production-level test for enforcement use to assure that a home that nominally has the ducts in conditioned space has actually been constructed that way. The details of these test procedures are described in "Test Procedures Summary Report" (deliverable 6.6.1).
- *Conduct tests of homes (Task 6.6.2).* "Tests of Homes with Ducts in Conditioned Space" (deliverable 6.6.2) describes the testing that the research team conducted of California homes built with ducts in conditioned space. This testing was the first step in the process of estimating the energy, energy demand and energy cost savings that can be expected for houses built with ducts in conditioned space. The report describes the houses tested, the testing performed and the data collected.

  Seventeen houses were tested. Thirteen used the Cathedralized Attic approach and four used the Dropped Ceiling approach. No houses were identified that used the Plenum

Truss approach (while the Plenum Truss approach may be a viable approach, the researcher was only able to identify a couple of houses in Florida built that way).

The testing conducted at the test sites consisted of four primary test procedures:

- Duct leakage,
- Duct leakage to outdoors,
- Delta-Q test of duct leakage, and
- Measurement of temperature change of supply air as it passes through the ducts.

- *Correlate distribution system efficiency (Task 6.6.3).* The test results from the tested houses were examined for correlations between the house characteristics (particularly the approach used to bring the ducts into conditioned space), and the test results.
- *Calculate energy savings (Task 6.6.4).* Three representative house designs were modeled using a variant of DOE-2 with duct leakage modeling functions added. Two baseline variants were developed: a “normal” leakage case using duct leakage of 22% of system flow, and “low” leakage case using leakage of 6% of system flow. Simulations were performed using weather data for 13 California climate zones. The house envelope characteristics (wall insulation, roof insulation, glazing U-factor and solar heat gain coefficient) were adjusted for each climate zone as specified in Title 24, Prescriptive Package D. Expected energy savings were calculated, including the energy and demand savings for each approach compared to the high or low leakage base cases, both in energy units and as percentage savings. With three houses and 13 locations, a total of 195 DOE-2 runs were performed.

6.6.4. Technical Outcomes

- *Duct leakage tests – hatch closed.* Table 11 summarizes the results of the duct leakage tests, including total duct leakage and leakage to the outside with the attic hatch closed. The fraction of total duct leakage that goes to outside is also shown. In all cases, duct leakage is quite low. While the average percent leakage to the outside for all tested houses was 55%, there was a distinct difference between homes with Dropped Ceilings (33% average) and homes with Cathedralized Attics (61% average).

Table 11. Duct Leakage Test Results with Attic Hatch Closed

House ID	Type	Duct Leakage (cfm @ 25 Pa)	Leak to Outside (cfm @ 25 Pa)	Percent of Leak to Outside
Banning A	Cathedralized Attic	28	17	61%
Banning A	Cathedralized Attic	42	15	36%
Banning A	Cathedralized Attic	28	17	61%
Banning A	Cathedralized Attic	52	38	73%
Banning B	Cathedralized Attic	49	30	61%
Banning A	Cathedralized Attic	41	29	71%
Banning A	Cathedralized Attic	47	22	47%
Banning A	Cathedralized Attic	49	40	82%
Banning A	Cathedralized Attic	46	27	59%
Banning A	Cathedralized Attic	48	21	44%
Cottonwood	Dropped Ceiling	41	6	15%
El Dorado Hills	Cathedralized Attic	91	70	77%
Livermore	Cathedralized Attic	50	32	64%
Mt. Shasta A	Dropped Ceiling	76	30	39%
Mt. Shasta B	Dropped Ceiling	68	22	32%
Mt. Shasta C	Dropped Ceiling	55	25	45%
Redding	Cathedralized Attic	68	44	65%
All Tested Houses: Average[1]		52	29	55%

Minimum[1]	28	6	15%
Maximum[1]	91	70	82%
Dropped Ceiling: Average[1]	60	21	33%
Minimum[1]	41	6	15%
Maximum[1]	76	30	45%
Cathedralized Attic: Average[1]	49	31	61%
Minimum[1]	28	15	36%
Maximum[1]	91	70	82%

[1]The three Average (and Minimum and Maximum) values may represent different houses.

- *Duct leakage tests – hatch open.* Data were collected from four houses for duct leakage and duct leakage to the outside with the attic hatch open. As can be seen from the data in Table 12, the hatch status made little difference in the leakage values. Opening the attic hatch increased duct leakage slightly in most cases, and decreased leakage to the outside in two cases. The changes, however, are too small to be considered significant.

Table 12. Duct Leakage Test Results with Attic Hatch Open

		Duct Leakage (cfm @ 25 Pa)		Leak to Outside (cfm @ 25 Pa)	
House ID	Type	Closed	Open	Closed	Open
El Dorado Hills	Cathedralized Attic	91	94	70	70
Livermore	Cathedralized Attic	50	50	32	31
Mt. Shasta B	Dropped Ceiling	68	71	22	22
Mt. Shasta C	Dropped Ceiling	55	56	25	24

- *Delta-Q tests.* The Delta-Q test results were not useful. Of the 15 houses tested, only 3 had apparently valid results. Of the others:
  - three had curve-fit R^2 values (a measure of the quality of the fitted line) less than 0.25;
  - five had a negative leakage on either the supply side, the return side, or both; and
  - four had both negative leakage and low R^2 values.

The researcher discussed these results with an experienced user of the test, who stated that such results are not uncommon when the ducts have low leakage. When the leakage values are low, they approach the magnitude of the uncertainties in the calculation procedure, and cause the effects seen.

- *Temperature change of supply air.* The temperature change was extremely low, essentially in the undetectable range, so conductive losses couldn't be measured. Instead, the researcher did some calculations of the conductive losses. Based on seasonal temperature values from ASHRAE Standard 152, and the temperatures measured in the duct spaces of the tested houses, along with reductions in duct length of 30%, the conduction losses should be decreased by a factor of about 3.
- *Distribution system efficiency correlation.* The number and variation in houses tested turned out to be much smaller than was anticipated when this task was planned, but one correlation did become apparent. The results of the duct leakage to outdoors, in percentage of total leakage, was 61% for the Cathedralized Attic houses, and was 33% for the Dropped Ceiling houses, nearly a 2:1 ratio. This result may be explained by the smaller surface area of the duct space with the Dropped Ceiling approach compared to the surface area of the entire attic for the Cathedralized Attic approach.
- *Energy savings.* The energy savings for each climate zone were combined into a single statewide average. The first two tables that follow show these savings results compared to the high-leakage base case (Table 13) and low-leakage base case (Table 14). Table 15 shows the minimum, maximum and average savings per construction approach for each housing type, duct leakage and climate zone.
    - Estimated annual electric energy savings range from a low of 1% (176 kWh) for a townhouse built with the Plenum Truss design to a high of 19% (5420 kWh) for a single-story detached house built with the Dropped Ceiling design.
    - Annual net energy cost savings per housing unit range from no savings for a townhouse using the Cathedralized Attic approach to a high of $1,285 for a two-story detached house using the Dropped Ceiling approach.
    - Annual savings vary greatly by climate zone and on whether the house uses normal leakage ducting (22% of system airflow) or a low leakage duct system (6% of system airflow).
    - Heating energy increases slightly with the Cathedralized Attic approach and, to a lesser extent, the Plenum Truss approach. This is due to the increase in insulated envelope area that results from moving the insulation up to the roof (Cathedralized Attic) or up to an intermediate location between the attic floor and roof (Plenum Truss).

Table 13. Average and Maximum Energy Savings vs. High-Leakage (22%) Base Case

Approach	House		Cooling Electric	Total Electric	Peak Electric	Total Gas
			(kWh)	(kWh)	(kW)	(therms)
Cathedralized Attic	Two Story	Avg	3,527	3,521	1	-40
		Max	7,735	7,618	3	-4
	One Story	Avg	2,145	2,155	1	-8
		Max	5,215	5,186	2	12
	Townhouse	Avg	865	877	0	-18
		Max	2,227	2,168	1	-3
Dropped Ceiling	Two Story	Avg	3,427	3,415	1	24
		Max	8,263	8,145	4	70
	One Story	Avg	2,032	2,029	1	35
		Max	5,479	5,420	2	81
	Townhouse	Avg	799	805	0	8
		Max	2,344	2,285	1	23
Plenum Truss	Two Story	Avg	3,313	3,300	1	-4
		Max	7,852	7,735	3	11
	One Story	Avg	1,907	1,898	1	24
		Max	5,186	5,157	2	57
	Townhouse	Avg	768	769	0	-3
		Max	2,227	2,168	1	3

Table 14. Average and Maximum Energy Savings vs. Low-Leakage (6%) Base Case

Approach	House		Cooling Electric	Total Electric	Peak Electric	Total Gas
			(kWh)	(kWh)	(kW)	(therms)
Cathedralized Attic	Two Story	Avg	1,154	1,137	0	-67
		Max	2,285	2,197	1	-4
	One Story	Avg	767	767	0	-38
		Max	1,641	1,611	0	-5
	Townhouse	Avg	301	309	0	-27
		Max	674	645	0	-3
Dropped Ceiling	Two Story	Avg	1,055	1,031	0	-3
		Max	2,813	2,725	1	0
	One Story	Avg	654	642	0	5
		Max	1,904	1,846	1	9
	Townhouse	Avg	235	237	0	-1
		Max	791	762	0	0
Plenum Truss	Two Story	Avg	940	916	0	-32
		Max	2,403	2,315	1	-1
	One Story	Avg	528	510	0	-6
		Max	1,611	1,582	1	1
	Townhouse	Avg	205	201	0	-11
		Max	674	645	0	-1

Table 15. Range of Energy Savings by Housing Type, Duct Leakage and Climate Zone (CZ)

Cathedralized Attic							
HOUSE TYPE		TWO-STORY		ONE-STORY		TOWNHOUSE	
DUCT LEAKAGE		LOW	NORMAL	LOW	NORMAL	LOW	NORMAL
Elec. (KWh per house)	Ave	1,137	3,521	767	2,155	309	877
	Max	2,197	7,618	1,611	5,186	645	2,168
	Max CZ	15	15	15	15	15	15
	Min	732	2,139	469	1,231	234	674
	Min CZ	2	2	2	2	2	2
Nat Gas (Therm per house)E	Ave	-67	-40	-38	-8	-27	-18
	Max	-4	-4	-5	-4	-3	-3
	Max CZ	15	15	15	15	15	12
	Min	-138	-68	-76	-68	-53	-28
	Min CZ	2 & 11	2	11	2	2	2
Dropped Ceiling							
HOUSE TYPE		TWO-STORY		ONE-STORY		TOWNHOUSE	
DUCT LEAKAGE		LOW	NORMAL	LOW	NORMAL	LOW	NORMAL
Elec. (KWh per house)	Ave	1,031	3,415	642	2,029	237	805
	Max	2,725	8,145	1,846	5,420	762	2,285
	Max CZ	15	15	15	15	15	15
	Min	557	1,963	293	996	175	557
	Min CZ	2	2	3	3	2,3,5	3 & 5
Nat Gas	Ave	-3	24	5	35	-1	8
	Max	0	70	9	81	0	23
	Max CZ	6,7,10,15	11	5	2	6,7,9,10,15	2

	Min	-7	0	1	2	-3	0
	Min CZ	2	6 & 15	15	15	11	15
Plenum Truss							
HOUSE TYPE		TWO-STORY		ONE-STORY		TOWNHOUSE	
DUCT LEAKAGE		LOW	NORMAL	LOW	NORMAL	LOW	NORMAL
Elec. (KWh per house)	Ave	916	3,300	510	1,898	201	769
	Max	2,315	7,735	1,582	5,157	645	2,168
	Max CZ	15	15	15	15	15	15
	Min	498	1,904	234	938	117	557
	Min CZ	2	2	2,3	3	2	2 & 3
Nat Gas	Ave	-32	-4	-6	24	-11	-3
	Max	-1	11	1	57	-1	3
	Max CZ	15	11	6,7,9,15	11	-1	11
	Min	-18	-16	-4	2	-10	-7
	Min CZ	2	3	11	15	2	5

- *Energy cost savings.* Once energy savings were determined, energy costs savings were estimated based on residential gas and electric rates of major utilities in California. Weighting factors based on housing starts were used to calculate state average energy cost savings. Table 17 shows these results, along with the maximum savings value from any climate zone.
- *Cost Effectiveness.* All three approaches are cost effective in almost all housing types and climate zones with normal leakage ducting and vary with low leakage housing types. Table 16 gives a simple overview of the cost effectiveness results per approach based on a less than 7 year payback to homeowners.

Table 16. Cost Effectiveness of Duct Placement Construction Approaches

Approach	Normal Leakage (22%)	Low Leakage (6%)
Cathedralized	Yes	Some Single Family No for Townhouses
Dropped	Yes	Most Single Family Some Townhouses
Plenum	Yes - some single family	Generally No

Table 17. Statewide Average and Maximum Energy Cost Savings

			vs. High Leakage Base			vs. Low Leakage Base		
Approach	House		Elec. ($)	Gas ($)	Total ($)	Elec. ($)	Gas ($)	Total ($)
Cathedral-ized Attic	Two Story	Avg	780	-33	748	253	-56	198
		Max	1,202	-4	1,198	419	-4	411
	One Story	Avg	474	-6	468	170	-32	138
		Max	818	10	814	254	-5	249
	Townhouse	Avg	207	-15	192	73	-22	51
		Max	342	-3	339	114	-3	105
Dropped Ceiling	Two Story	Avg	752	21	773	226	-3	223
		Max	1,285	59	1,285	430	0	430
	One Story	Avg	444	29	473	140	4	144
		Max	855	69	857	291	7	292
	Townhouse	Avg	189	6	196	56	-1	55
		Max	361	20	361	120	0	120
Plenum Truss	Two Story	Avg	729	-3	725	202	-27	175
		Max	1,221	9	1,220	365	-1	364
	One Story	Avg	415	20	435	111	-5	106
		Max	814	48	816	250	1	251
	Townhouse	Avg	181	-2	179	48	-9	38
		Max	342	3	341	102	-1	101

As shown in Table 13 through Table 17, significant energy savings and energy cost savings can be achieved by building houses with ducts in conditioned space. The savings vary dramatically by size of the house and by climate, although the approach used has less impact. One difference between the approaches is that the Cathedralized Attic approach and, to a lesser extent, the Plenum Truss approach, cause slight increases in heating energy. This is due to the increase in insulated envelope area that results from moving the insulation up to the roof (Cathedralized Attic) or up to an intermediate location between the attic floor and roof (Plenum Truss).

Products

- Tests of Homes with Ducts in Conditioned Space (6.6.2)
- Energy Savings for Homes with Ducts in Conditioned Space - included in "Cost and Savings for Houses Built with Ducts in Conditioned Space: Technical Information Report" (6.4.2-e)

Market Connections

PRESENTATIONS

- *ASHRAE Annual Meeting.* Kansas City, June 2003. Discussed draft of "Building Homes with Ducts in Conditioned Space—A Guide for Builders" (draft) at meeting of the TC 6.3 committee on Central Forced Air and Cooling Systems, attended by approximately 30 members.
- *California utilities.* Team members are involved in IESNA and ASHRAE and will present E7 information for consideration to technical committees regarding outdoor lighting energy baselines and the predominance of specific equipment. This information will provide input to key lighting design guides such as the IESNA handbooks and recommended practice guidelines, the ASHRAE/IESNA 90.1 lighting standards, and the Advanced Lighting Guidelines.

PUBLICATIONS

- *ASHRAE Handbook***.** E6 provided information that will be included in the updated ASHRAE Systems and Equipment Handbook (Chapter 9, duct design), to be published in 2004.
- *Building Industry Institute.* The Building Industry Institute (BII) is a program of the California Building Industry Association that develops and administers research and educational programs for home builders, developers and the general public. BII's website provides a series of protocols on topics such as air sealing, HVAC design and installation, and insulation. Rob Hammon, an E6 subcontractor, is closely involved with BII and expects that E6's research and findings will inform the development of a BII protocol on ducts in conditioned space; he has indicated that BII may be interested in publishing the Guide for Builders on their website (www.thebii.org).
- *DOE Building America.* Guide for Builders to be distributed online through this widely used website on residential construction. Primary users of website are residential builders and energy efficiency managers.

CODES, STANDARDS AND GUIDELINES

- *Title 24 Code Development***.** E6's "Technical Information Report" (6.4.2) provides technical data to support Title 24 code development for placing ducts inside conditioned space in residential construction. Supporting data includes market barriers and methods for overcoming them; cost/benefit data; and methods for verifying compliance.
- *Influence on Local Codes.* Once completed and disseminated within the market, "Building Homes with Ducts in Conditioned Space—A Guide for Builders" and the "Technical Information Package—Code Officials and Consumers" will potentially have a significant impact on how homes are designed and built in California. One early example: In the spring of 2003, Pulte Homes wanted to use the Cathedralized Attic approach in a new development in Beaumont, California, but was meeting resistance from the building department, which was concerned about roof venting issues. Pulte consulted with Roger Hedrick, provided the code official with E6 data and reports, and as a result gained approval for their construction methods. In an email to Roger Hedrick, a Pulte employee in charge of the Beaumont development said, "...your reports and your feedback has been extremely helpful in our efforts to reach approval in the City of Beaumont."

NETWORKING AND COLLABORATION

- *Research and Construction Industry.* In the course of this research, the project team worked or was in contact with most of the researchers, consultants and home builders who have experience with the issues related to placing ducts in conditioned space, including: Pulte Homes; Steven Winters Associates; Joe Lstiburek of Building Science Corporation; Rick Chitwood of Chitwood Energy Management; and Jamie Lyons of National Association of Home Builders Research Center. In addition, TAG members were active in helping guide the research, and it is expected that they will help promote the findings to the residential homebuilding community. TAG members included Joe Lstiburek, Rick Chitwood and Jamie Lyons from above, as well as Rob Hammon of ConSol, Geof Syphers of Xenergy, Marshall Hunt of Pacific Gas & Electric, Iain Walker of Lawrence Berkeley National Laboratory, and Bruce Wilcox of Berkeley Solar Group.

6.7. Conclusions and Recommendations

6.7.1. Conclusions

Building houses with ducts in conditioned space is technically feasible and can be done at fairly small cost increments with valuable returns in energy savings.

- *Of the three recommended approaches, the Dropped Ceiling and Cathedralized Attic designs will result in the lowest construction cost increase, ranging from zero to 1%*. The Plenum Truss approach is estimated to add between 1.5% and 3% to construction costs. In addition, the three approaches may, in some cases, allow the heating and cooling equipment to be downsized, which could offset some of the construction cost increases or even result in an overall decrease in construction costs.
- *Estimated annual electric energy savings range from a low of 1% (176 kWh) for a townhouse built with the Plenum Truss design to a high of 19% (5420 kWh)* for a single-story detached house built with the Dropped Ceiling design.

- *Annual net energy cost savings range from none for a townhouse using the Cathedralized Attic approach to a high of $1,285* for a two-story detached house using the Dropped Ceiling approach.
- *Heating energy increases slightly with the Cathedralized Attic* approach and, to a lesser extent, the Plenum Truss approach. This is due to the increase in insulated envelope area that results from moving the insulation up to the roof (Cathedralized Attic) or up to an intermediate location between the attic floor and roof (Plenum Truss).
- *Annual savings vary greatly* by climate zone and on whether the house uses normal leakage ducting (22% of system airflow) or a low leakage duct system (6% of system airflow).
- *All three approaches are cost effective in almost all housing types and climate zones with normal leakage ducting.* For low duct leakage houses, the Dropped Ceiling approach is cost effective in most of the single family and some of the townhouse types, the Cathedralized Attic is only cost effective in some of the single family types, and the Plenum Truss approach is not cost effective. Cost effective is defined here as having a payback to the homeowner of less than 7 years.
- *To date, building houses with ducts in conditioned space has been done on a very small scale, but given the advantages of this approach it seems likely that this practice will increase at a modest rate***.** Commission support for the approach could significantly accelerate that increase.

6.7.2. Commercialization Potential Or Commercialization Initiated

Homes with ducts in conditioned space are already being built in a few places, and the findings and guidelines produced by Element 6 will likely increase the rate at which this approach is accepted by the homebuilding industry.

Commercialization of a new practice in the residential construction industry is a slow process due to the many players and distributed channels of information and education. In California particularly, the residential construction industry struggles with language diversity as a market barrier to implementation of new technologies. The assumptions for statewide energy savings of this practice are thus based on extremely low rates of penetration. Increased market penetration/commercialization can occur but is highly dependent on the success of third party entities such as utilities and major home building companies adopting the practice as standard or required. At this time, continued promotion and exposure to the building industry and utility market will increase this alternative construction method.

6.7.3. Recommendations

It is recommended that the Commission support the use of ducts in conditioned space in new home construction.

To move the homebuilding market toward adopting the approaches described in this report, it will be important for the Commission to capitalize on the materials produced by E6, and to identify target audiences and effective distribution channels for these materials. The change to building ducts in conditioned space would seem to be a natural fit with the utility programs used to train builders in reducing duct leakage.

Building ducts in conditioned space should also be included in Title 24 as an optional energy credit, with the caveat that the duct system be leak-tested and tested for leakage to the outdoors. This is an effective method for energy savings and should be an alternative for builders to meet the whole building energy targets.

To expand on the energy savings calculations conducted as part of this research, it is recommended that additional research is pursued that uses actual measurements to compare energy savings. This would ideally entail a side-by-side testing of houses with and without ducts in conditioned space. In particular, the temperature inside the conditioned duct space of actual houses should be monitored along with the outdoor temperature to better understand the dynamic behavior of the house.

6.7.4. Benefits to California

First year savings of 266 MWh and ten year cumulative savings of 178,768 MWh are expected from the adoption of the ducts in conditioned space building techniques. There is a minor ten year penalty in gas consumption of 364,000 therms.

These numbers are based on the California new construction market of 155,000 houses per year and a 0.1% penetration the first year ramping to a 10% penetration in year 10. The savings estimates are based on the current averages of 30% of housing built with low leakage ducts and 70% built with normal leakage ducts.

The ten year cumulative electric energy savings is $23.2 million with a small increase in gas use equal to $328,000 resulting in a net energy cumulative savings of $22.9 million.

7.0 California Outdoor Lighting Baseline Assessment (Element 7)

7.1. Introduction

This research project was the first major study of nighttime lighting in California. Prior to this study, there had been little data on outdoor lighting conditions and practices in California, and even less information on energy use or the extent of good or bad lighting practices. Many energy codes outside of California regulate outdoor lighting practices, but before California could consider similar regulation, the current nature of commercial outdoor lighting needed to be investigated and analyzed. This is particularly important because trends in outdoor lighting practices appear to be moving toward ever-greater numbers of fixtures and brighter lamps, using significantly more energy for the same task with little or no additional benefit.

7.1.1. Element Objectives

This Element's objectives were to:

- Fill gaps in knowledge about outdoor lighting in California by identifying current design practices and estimating the energy demand and consumption of current statewide practices;
- Provide outdoor lighting baseline information to inform the 2005 Title 25 Standards development; and
- Provide a framework for future investigations into outdoor lighting practices in California.

7.1.2. Project Team and Technical Advisory Group (TAG)

Element 7 was led by Dr. Roger Wright, Matt Brost and Sam Pierce of RLW Analytics, Inc. with support from Ramona Peet. Primary subcontractors were Clanton Engineering and M. Neils Engineering.

RLW Analytics and New Buildings Institute would like to acknowledge the invaluable guidance and advice provided by members of Element 7's TAG, which included:

- Jim Benya, IALD, FIES, LC, PE, Lighting Designer, Jim Benya Lighting Design
- Bill Daiber, Sales Representative, San Diego Gas and Electric Company
- Loren Gardener, Chief Building Official, City of Davis
- Wes Hiratsuka, Engineer, City of Sacramento
- Bill Hughes, Retired, formerly in charge of street lighting for the City of Portland, Oregon
- Steve Johnson, Building Technologies, Lawrence Berkeley National Laboratory
- Ian Lewin, PhD, FIES, Lighting Scientist/Researcher, Lighting Science Inc.
- Crawford Lipsley, Vice President, Holophane Division of Lithonia Lighting
- Terry McGowan, FIES, LC, Executive Director, Lighting Research Office/EPRI

7.2. Background Review and Project Work Plan (Project 7.2)

7.2.1. Project Objectives

This project's objective was to develop a detailed project workplan.

7.2.2. Approach

The researchers reviewed all relevant current literature on nighttime exterior lighting, and assembled this information to provide a ready reference resource for the project. The researchers reviewed the following sources:

- Research on nighttime visibility including lighting levels, lighting uniformity, visual adaptation, reaction time, and effects of spectral distribution on mesopic and scotopic vision sensitivity
- Research on light trespass evaluation methods
- IESNA recommended practices
- IESNA statements on light pollution and trespass
- CIE recommended practices and standards
- CIE mesopic lumen evaluation criteria
- Existing local and proposed model exterior lighting ordinances
- California Title 24
- Evaluation of sky brightness

7.2.3. Technical Outcomes

The background information provided by this project was used to develop the research plan. The project team produced an annotated bibliography of relevant studies on outdoor lighting (deliverable 7.2.1) that should be useful to other researchers investigating this topic.

Products

- Annotated Bibliography and Summary (7.2.1)

7.3. Initial Market Characterization (Project 7.3)

7.3.1. Project Objectives

The project objectives were to:

- Carry out a telephone survey of about 1000 buildings to assess the current type of outdoor lighting applications and develop a proxy for the amount of each type present at each site.
- Analyze data from the market characterization by building type and outdoor lighting function.
- Characterize the information according to function and "expected" intensity of use.
- Use resulting information to plan subsequent stages of the study.
- Use the initial market characterization as a data-leveraging approach to extrapolate the subsequent fieldwork to the statewide population.

7.3.2. Approach

The researchers conducted telephone surveys of 1000 businesses in California. The surveys were required in order to develop a sample frame from which to select a sample of 300 buildings for the statewide assessment task. The 1000 surveys also served as the mechanism for extrapolating the findings from the statewide assessment back to the population of commercial/industrial buildings in California.

The target population studied was the outdoor lighting associated with existing commercial, industrial, and multi-tenant apartment buildings in California. The surveys included both existing and new construction, but did not address roadway lighting or billboard lighting. To optimize the relative precision of statewide estimates of energy use and other factors, a method was devised that would allow sampling of locations with large amounts of outdoor lighting with higher inclusion probabilities than locations with small amounts of outdoor lighting and at the same time would maintain manageable travel distances between sites. Using the idea that the amount of outdoor lighting associated with existing commercial and industrial buildings in a geographic area is likely to be directly related to the amount of commercial activity in a geographic area, a stratified sampling plan was developed based on zip codes in California using measures of commercial activity by zip code.

7.3.3. Technical Outcomes

- From the initial 1000 telephone surveys, the researchers recruited a sample of 300 buildings to participate in the site surveys subsequently conducted as part of Project 7.5.

Products

- Methodology Used for Sample Design (7.3.1)
- Copy of Phone Survey Instrument (7.3.2)
- Phone Survey Tracking Report (7.3.3)
- Summary of Phone Survey Responses (7.3.4)

7.4. Critical Analysis (Project 7.4)

7.4.1. Project Objectives

This project's objectives were to:

- Collect technical data on the amount, prevalence and quality of the outdoor lighting, the associated energy consumption, the visibility at low levels of illuminance, light pollution, light trespass and outdoor lighting practices.
- Develop a uniform and useful outdoor lighting assessment tool.
- Develop a set of useful, widely recognized metrics for an exterior lighting assessment.
- Expand the knowledge of exterior lighting energy performance.

7.4.2. Approach

- *Sample design.* The researchers used responses to the telephone survey in Project 7.3 to identify buildings for this project. A sample of 50 buildings was selected so that a broad range of outdoor lighting applications and technologies could be examined. This allowed for the outdoor lighting assessment tool developed in this project to be as useful and versatile as possible.

- *Data collection.* Initially, the project team completed 10 pilot onsite visits. These first onsite visits represented an assorted set of building types, outdoor lighting functions, and densities of anticipated outdoor lighting loads to capture the diversity of outdoor lighting applications. The data from these 10 sites provided the framework for designing the outdoor lighting assessment tool.

  The first wave of onsite data collection took place in the greater Sacramento metropolitan area. Ultimately a total of 49 pilot site surveys were completed (one federal facility declined to participate at the last minute due to security concerns related to the September 11, 2001 terrorist attacks).

- *Data analysis***.** The researchers analyzed the issues and characteristics listed below for each of the 49 sample sites using the data collected during the onsite visits.

  1. Purpose for outdoor lighting (safety, security, aesthetics, community-driven issues, advertising, etc.)
  2. Proximity to other areas (adjacent to low density residential, located on major commercial street, within sensitive distance to observatories, etc.)
  3. Activity use of outdoor area
  4. Illuminance levels and uniformity
  5. Glare potential
  6. Equipment distribution characteristics
  7. Sky brightness prediction
  8. Light source type
  9. Conformance with existing recommended practices
  10. Control strategies of lighting (photocontrols, scheduling, motion sensing, etc.)
  11. Energy usage (connected load and energy profile)

7.4.3. Technical Outcomes

- *An "Outdoor Lighting Assessment Tool" was developed for use in this study and potentially by researchers conducting future studies of outdoor lighting.*

  The data collected and analyzed at the 49 sample sites was used to design a useful outdoor lighting assessment tool. This tool was used in subsequent projects of this Element to conduct the statewide outdoor lighting assessment.

- *A comprehensive database of site information was developed.*

  Using the data from the pilot site visits, an MS Access database was developed that would eventually contain the site information for all the buildings surveyed by this Element. This site information in the database includes overall site area; building type; site user questionnaire on outdoor lighting types, use schedules, controls, and subjective comments; lighting area "Functional Use Areas"; weather conditions and surrounding information; luminaire information; sign information; glare ratio measurements; light trespass measurements; and outdoor lighting measurements for illumination and uniformity.

- *Several lessons were learned throughout the course of conducting the phone and onsite surveys:*
    - Continuous oversight by a single individual is required during data collection to monitor the data collected and to answer questions regarding unique situations. This is necessary to ensure consistent interpretations, because the surveyors are exposed to countless "non-conforming" situations.
    - The onsite survey instrument and database that houses the onsite survey data must be designed to be flexible enough to capture many outdoor lighting applications. Even though pilot tests of 50 buildings were used to design the survey instrument, the researchers still encountered unanticipated outdoor lighting applications that necessitated either revisions to the instrument or special handling in the database.
    - The illuminance measurement grids should be defined at night right before the readings are taken. During the pilot test of the onsite survey instrument, the researchers were defining the placement of the illuminance measurement grids as a part of the daytime component of the onsite survey. When the surveyors returned at night to take the measurements, they often found cars or other objects obstructing the grids defined during the day, requiring the grids to be redefined.

Products

- Final Report for Pilot Onsite Visits (7.4.3)
- Site Survey Instrument (7.4.4)

7.5. Survey and Analytical Methodology (Project 7.5)

7.5.1. Project Objectives

This project's objective was to use the knowledge developed in the Critical Analysis Project to develop a practical and repeatable survey methodology for characterizing outdoor lighting.

7.5.2. Approach

The research team developed a data collection and analysis tool that:

- Provides a survey instrument and electronic data-input form for surveying the outdoor lighting at a given site;
- Creates a database of the characteristics of the sample sites;
- Provides the computational analysis to convert the survey inputs for each site into an estimate of the associated energy use and key environmental impacts at the site; and
- Provides the statistical tools for extrapolating the findings to the state, and for calculating the appropriate measures of statistical precision.

The components of this tool are described in the Technical Outcomes section below.

7.5.3. Technical Outcomes

- *The research team developed a reference manual to support the surveyors in the field.*

The manual included fixture, lamp type, and wattage identification information; daytime and nighttime survey procedures; and a luminaire catalogue with pictures and descriptions of 41 lighting fixtures likely to be found in the field, along with a unique identification number for each. The manual is included as an appendix to the "California Outdoor Lighting Baseline Assessment" (product 7.7.2c).

- *An onsite survey instrument was developed that forms the framework for the surveyor's discussion with the site contact about lighting types and lighting use schedules.*

  The instrument provided a clear format for recording the required daytime and nighttime onsite data. Data collected using this instrument included information about the building, exterior lighting schedules and controls, functional use areas, luminaires, signage, lighting zones, glare and trespass. It also included illumination grid measurements and a "Nighttime Subjective Lighting Evaluation." The instrument is included as an appendix to the "California Outdoor Lighting Baseline Assessment."

- *All data collected using the Onsite Survey Instrument was combined into an MS Access database.*

  This data consolidation involved multiple components: definition of data tables; development of a practical data entry tool; data entry; and quality control of entered data. Each of these components is discussed in detail in the "California Outdoor Lighting Baseline Assessment."

Products

- Site Survey Training Materials (7.5.2)

7.6. Statewide Assessment (Project 7.6)

7.6.1. Project Objectives

This Project's objectives were to build on the survey methodology to provide a statewide, statistically representative baseline survey of outdoor lighting. Specific objectives were to:

- Use the onsite survey methodology developed in the preceding project to collect data for the 300 selected buildings;
- Use the analytical tools to assess the energy and environmental impacts of selected changes in efficiency, operation, illumination levels or controls;
- Analyze the potential energy savings of cost-effective efficiency improvements; and
- Extrapolate the findings to the total statewide population.

7.6.2. Approach

Data collection required visiting more than 300 sites throughout California. This was accomplished with teams of trained site surveyors using the "Onsite Survey Instrument" developed as part of the Survey and Analytical Methodology Project (7.5). This instrument was designed to allow data collected from a vast range of unique site circumstances to be compiled effectively into a single database.

Two visits were required for each site. First, the surveyor visited during the day to solicit information from the person responsible for outdoor lighting and to inspect replacement lamps for type and wattage. The surveyor returned after dark to take illuminance readings and administer the "Nighttime Subjective Lighting Evaluation" to site users. These evaluations were also completed by each site surveyor. The data collection spanned three consecutive months during the late winter and early spring of 2002. During this time, the team project manager provided continuous technical support via phone and email to the field teams. This single point of coordination proved to be essential in developing consistency and thoroughness in the vast amount of data collected from diverse sites ranging from ski resorts to RV sales facilities.

7.6.3. Technical Outcomes

The research findings are summarized below. For the complete results, including 84 figures and tables that present all the findings, see the "California Outdoor Lighting Baseline Assessment" (7.7.2).

OUTDOOR LIGHTING ENERGY CONSUMPTION

- *California C/I (commercial/industrial non-roadway) outdoor lighting annual energy consumption is estimated to be 3,067 GWh equal to roughly 1.35% of the total statewide annual energy consumption.*

  The non-roadway outdoor lighting surveyed through this project resulted in a statewide estimate of 3,067 GWh. The percent of total state energy consumption aligns well with other estimates of outdoor lighting (LBNL; General Electric) and is based on the 2001 energy use of 227,087 GWh reported by the California Independent System Operator (ISO).

- *Commercial outdoor lighting accounts for 3% of nighttime energy use and 2.63% of nighttime peak demand.*

  The total 2001 annual nighttime energy consumption for the state of California was 101,773 GWh, according to the ISO. The maximum peak demand from commercial outdoor lighting is 809 MW, and occurs in the winter from 7 PM to 8 PM. This winter peak is slightly higher than the summer peak due to the operation of winter resorts (closed during the summer) and due to school recreation areas not in use in the summer. The commercial outdoor lighting peak demand is 2.63% of the total California system load of 30,788 MW for that hour, calculated using California ISO data (the peak demand in February 2002, for the hour ending at 8 PM).

- *Parking lots, walkways and signage account for 75% of the outdoor lighting energy use.*

  These three "functional use areas" (FUA) dominate the outdoor lighting energy use, keeping in mind that roadways were not a part of this study. Table 18 below shows the overall energy use for the FUAs in the study with the top three areas represent the following percents of the total energy use: parking lots 31.5%, walkways 22.4%, and signage 20.3%.

Table 18: Statewide Energy Usage by Functional Use Area (FUA)

The error bound provides an indication of the confidence level associated with each result. The size of the error bound is the result of estimating the statewide results using a relatively small sample size (303 sites) and by the variation in the data. For functional use areas such as Parking, the sample size is large and the associated error bound is relatively small. For Gas Station Canopies, the sample size is relatively small and the error bound correspondingly large.

FUA	Energy Usage (GWh)	Error Bound (GWh)	% Energy Use
Parking	967.3	270	31.5%
Pedestrian & Walkway	685.6	283	22.4%
Signage	622.6	213	20.3%
Security	207.9	96	6.8%
Storage	159.5	72	5.2%
Outdoor Retail Sales	140.2	157	4.6%
Internal Roadway	74.4	49	2.4%
Recreation	47.6	44	1.6%
Façade & Aesthetic	43.5	27	1.4%
Entry	40.0	12	1.3%
Landscape	39.9	17	1.3%
Gas Station Canopy	29.8	30	1.0%
ATM	6.8	8	0.2%
Undeveloped	1.9	3	0.1%
Commercial Outdoor Patio	0.5	1	0.0%
Total Energy Usage	**3,067**	**N/A**	
Error Bound for all FUAs	N/A	687	

ENERGY SAVINGS

- *A broad "what if" lamp replacement scenario would save approximately 204 GWh, a 7% reduction in the annual commercial outdoor lighting energy consumption in California.*

  E7's primary objective was establishing the type and energy use of existing outdoor lighting. The team also estimated the energy savings potential of a broad "what if" scenario that assumes replacing all of California's high pressure sodium (HPS) lamps with metal halide (MH) lamps. This general estimate does not incorporate a cost/benefit or technical analysis of the assumptions. The scenario is included to demonstrate the type of measure-specific energy impact analysis that can be done using this database. This lamp replacement scenario would save approximately 204 GWh annually, a 7% reduction in the annual commercial outdoor lighting energy consumption.

Note: The energy savings from lamp replacement strategies may not be as large as expected. The PIER report proposes a theoretical scenario where all existing HPS lamps are replaced with MH lamps, and estimates a potential savings of 33% from this strategy for the referenced lamps. This estimate is based on the understanding that less power is required to achieve equal brightness lumens from MH lamps as compared to HPS lamps. However, as there is a large efficacy versus wattage effect, an estimate of 10–15% savings may be more appropriate. In addition, there are unanswered theoretical questions about whether the source for the brightness measure referenced in the "California Outdoor Lighting Baseline Assessment" is valid for use in parking lots.[6] If this measure is not valid, replacing HPS lamps with MH lamps would still achieve energy savings, but at the expense of visual performance. A new PIER project is further exploring the specifics of visual, technical and energy implications of lamp selections for parking lots. Go to www.archenergy.com/lrp/lightingperf_standards/project_5_3.htm for information and outcomes.

Lighting Controls

- *More than 85% of the commercial outdoor lighting has an electronic or electromechanical control.*

  This was a particularly important and surprising finding. Frequently, site surveyors found lighting that was activated by a photocell at dusk and de-activated by a timer in the late evening. Only 13.4% of the lighting encountered was controlled manually. Recreation areas were most likely to use manual controls (66%). Electronic methods (photocells and time clocks) were the control strategy of choice for gas station canopies and storage areas (97.8% and 96.4% respectively). Only 6.2% of parking areas relied on manual controls for the lighting.

Additional Research

- *After concluding the original surveys, the team conducted additional surveys of gas station canopies and car dealerships, substantially enhancing the data for these two areas.*

  The original data set included only seven sites with gas station canopies and four outdoor retail sales sites (car dealerships). This affected the ability to evaluate the impact of the proposed outdoor lighting standards to any degree of confidence for these two areas. As a result, after the completion of E7's research, the team supplemented these two important functional use areas with additional site visits. The data for these sites were incorporated into the database, substantially enhancing the quality of reporting for these two areas. This additional work was made possible, in part, by additional Commission funding administered through the PIER program. The details of this additional research are presented in an Appendix to E7's final report.

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[6] See Dr. S.M. Berman, "Energy Efficiency Consequences of Scotopic Sensitivity," Journal of the Illuminating Engineering Society, Winter 1992.

FIXTURES AND LAMPS

- *The "California Outdoor Lighting Baseline Assessment" provides extensive data on the types of lamps and fixtures installed at each site. Here are a few of the findings:*

  Percentage of total lamps installed by building type:

  - 57.7% of all lamps in apartments and condominiums are compact fluorescent lamps
  - 28.1% of all lamps in small retail are high pressure sodium lamps
  - 30.7% of all lamps in small offices are incandescent lamps, indicating there is significant room for improvement in this building type

  Distribution of lamps across functional use areas (FUA):

  - Incandescent lamps represent 30.8% of all lamps installed across all FUAs
  - High pressure sodium lamps are the most frequently used lamps for security areas (41.2%)

  Distribution of lamp types by FUA:

  - 50.7% of mercury vapor lamps are in parking lots
  - 70.1% of incandescent lamps are used to illuminate pedestrian areas and walkways
  - 68.1% of low pressure sodium lamps are used to light parking lots

  Percentage of FUAs with a certain lamp type:

  - Mercury vapor lamps are found in 14% of parking lots and 19.1% of storage areas
  - 48.3% of parking lots have high pressure sodium lamps
  - Incandescent lamps are utilized in almost 70% of building entrances

  Percentage of FUAs having certain fixture types:

  - 38.7% of parking lots are equipped with "shoebox" style fixtures (identified as type A in the final report)
  - Wall packs (type P) are the next most common fixture for parking lots at 19.3%
  - The most common fixture type for façade and aesthetic is the PAR lamp holder (type U) at 33%
  - The most commonly found fixture type for all FUAs is the "wall pack" at 18%, followed by the "shoe box" at 14.5%
  - The "barnyard" fixtures (type E) are represented in most of the functional use areas. These fixtures frequently have inefficient mercury vapor lamps.

  Percentage of FUAs illuminated by each fixture type:

  - 64.2% of Gas Station Canopy Areas are illuminated using "drop lens canopy" lights (type N)

- 35.8% of the areas are illuminated using "small dropped lens canopy" lights (type O), "fluorescent wrap" (type AA), and "dropped lens downlight" for smaller lamps (DD).
- Internal roadways are significant users of "pole-mounted globe area lights" (type CC) which are a concern to "night sky" proponents

LIGHTING POWER DENSITY (LPD)

- *The "California Outdoor Lighting Baseline Assessment" provides extensive data on LPD levels by building type, functional use area and lighting zone.*

  Because the study resulted in so much useful LPD data, only one table is reproduced here. Table 19 illustrates the percent of total area that has an installed wattage within certain LPD ranges. The calculations include both non-lit as well as lit areas. Categories with very small sample sizes should be considered as case studies rather than as an indication of statewide design practice.

Table 19. Site Lighting Power Density (LPD) by Building Type

	% of Area (ft²)						
Building Type	**Non-lit Sites**	**> 0 to 0.0049 (W/ft²)**	**0.005 to 0.0099 (W/ft²)**	**0.01 to 0.049 (W/ft²)**	**0.05 to 0.099 (W/ft²)**	**> = 0.1 (W/ft²)**	**Sample Size**
Apartments & Condos	-	50.2%	15.4%	16.5%	13.5%	4.3%	15
Assembly	-	-	-	47.3%	26.3%	26.4%	11
Full Service Restaurant	-	-	-	81.3%	-	18.7%	7
Grocery	-	53.9%	-	-	31.0%	15.1%	3
Hospital	-	-	-	6.5%	58.9%	34.5%	8
Hotel	-	-	48.5%	-	39.0%	12.6%	4
Industrial	0.7%	71.4%	18.9%	4.5%	2.8%	1.7%	31
Large Office	-	-	-	26.4%	39.5%	34.1%	26
Large Retail	1.5%	-	-	9.8%	50.3%	38.4%	15
Large Schools	-	-	-	100.0%	-	-	2
Recreation	0.1%	60.1%	-	-	19.6%	20.2%	7
Small Office	-	19.0%	1.6%	44.2%	25.9%	9.4%	102
Small Retail	0.1%	6.3%	-	-	30.6%	63.0%	42
Small School	-	-	18.7%	12.1%	69.2%	-	6
University	-	-	-	99.1%	0.8%	0.2%	8
Warehouse	5.0%	-	-	78.7%	16.4%	-	16
All Building Types	**0.7%**	**34.5%**	**9.7%**	**21.2%**	**20.1%**	**13.8%**	**303**

- *Using the LPD data amassed by this study, projections can be developed for many lighting applications and configurations, yielding substantial information for the design and regulatory communities.*

Table 19 and the complete LPD results in the "California Outdoor Lighting Baseline Assessment" provide an opportunity to evaluate the energy savings available from enhancements in commercial outdoor lighting design practices. For example, the data in the final report indicate that an LPD of less than 0.10 W/ft^2 for parking is common and adequate. The energy savings of converting over-lit parking to this standard could be calculated. Similar projections could be developed for many other lighting applications and configurations, yielding valuable information for the design and regulatory communities.

SUBJECTIVE ASSESSMENTS

The site survey included a Nighttime Subjective Lighting Evaluation, a series of questions asked of site users and the surveyors. For a detailed breakdown of the responses, see the "California Outdoor Lighting Baseline Assessment." The statements included here are a recap of some of the more significant findings.

- *The lighting was considered comfortable by 70.6% of respondents. More than 50% of respondents found security lighting to be adequate. The subjective evaluation of glare at each site revealed that slightly more than 40% of sites were considered somewhat or very "glary."*

  The lighting was considered comfortable by 70.6% of respondents. More than 50% of respondents found security lighting to be adequate. When asked to compare site lighting to lighting at similar areas, more than 55% concluded that lighting at other similar sites is about the same, although 43% of respondents considered university lighting worse than lighting at similar areas.

- *For the sites using fluorescent lighting in the parking lot, 85.7% of respondents found the site lighting to be comfortable and also a good example of security lighting.*

  Most of the site evaluations were conducted in the parking lots of the sites visited. The respondents at sites utilizing low pressure sodium lamps in the parking lot were more likely to answer no to the question regarding the ability to identify an object's color. Surprisingly, the percentage of respondents who considered the lighting quality at these sites to be about the same as similar areas, is roughly the same as for other lamp types.

  The site surveyors' subjective impression tended toward "worse" as the lamp wattage increased and when comparing non-cutoff to cutoff fixtures. Similarly, the glare ratio increased with increases in lamp wattage and the use of non-cutoff fixtures. These results are detailed in the "California Outdoor Lighting Baseline Assessment" (7.7.2).

Products

- Final Data Collection Instrument (7.6.2)
- Final Training Material (7.6.3)
- Outdoor Lighting Analysis Database (7.6.5)
- California Outdoor Lighting Baseline Assessment (7.7.2)

Market Connections

CODES AND STANDARDS

- *Outdoor lighting standards.* The PIER Outdoor Lighting Baseline Assessment informed the development of new standards for outdoor lighting under Title 24.
- *International Dark-Sky Association (IDA).* PIER results are contributing to the outdoor standards in IDA's voluntary national Model Lighting Ordinance.

PRESENTATIONS

- *ACEEE Summer Study.* August 2002. Presentation and paper by the Institute and RLW on research and results. Audience: energy efficiency building sciences professionals.
- *California utilities.* Team members are involved in IESNA and ASHRAE and will present E7 information for consideration to technical committees regarding outdoor lighting energy baselines and the predominance of specific equipment. This information will provide input to key lighting design guides such as the IESNA handbooks and recommended practice guidelines, the ASHRAE/IESNA 90.1 lighting standards, and the Advanced Lighting Guidelines.
- *GlobalShop Retail Conference.* Chicago, March 2001. Presentation by New Buildings Institute at major retail industry conference. Emphasized the research objectives of E2, E5 and E7.
- *LightFair.* Las Vegas, May 2001. Presentation to over 200 lighting industry professionals.

PUBLICATIONS

- *ACEEE Summer Study.* August 2002. Paper by the Institute and RLW on research and results. Audience: energy efficiency building sciences professionals.
- *Building Standards Magazine.* February 2002. Article by subcontractor Nancy Clanton, titled "Brighter Not Necessarily Better at Night," featured E7 research. Audience: building construction industry. Article also posted on website www.lighting.com.

7.7. Conclusions and Recommendations

7.7.1. Conclusions

The results of this survey, which are described in the Outcomes section of Project 7.6 above, will provide a basis for ongoing discussions of program and code options for addressing outdoor lighting energy use. The baseline findings, survey methodology, energy metrics and environmental assessment are already influencing nationwide discussions of exterior lighting. Some examples follow.

- *California outdoor lighting standard.* California Senate bill SB5X was signed into law in 2001. It provided that the Commission could develop standards for and regulate outdoor lighting. Previously, the Commission was restricted to regulating lighting only for conditioned space. A new 2005 Title 24 Standard for Outdoor Lighting was proposed that used the PIER data as one resource in the development of its requirements. These Standards will be adopted as updates to Title 24, Part 6, and are currently scheduled for effective dates in late 2005 or 2006.
- *Model Lighting Ordinance.* A consortium of lighting experts and entities, lead by the International Dark-Sky Association (IDA) is developing a Model Lighting Ordinance (MLO). The MLO Task Force was formed in early December 2001. As the Commission

develops a scientific basis for outdoor lighting regulation, based in part on this PIER research, the MLO Task Force will incorporate results as appropriate to the outdoor lighting section of their national model ordinance. The intent of the MLO for outdoor lighting will be to restrict unnecessary and improper uses of outdoor lighting through a combination of cutoff requirements, height limitations, power density limits, and other factors that still permit the interpretation and application of Illuminating Engineers Society of North America (IESNA) recommendations by individual lighting designers, engineers and others. The work will be based on IESNA, CIE (International Commission on Illumination) and other applicable standards to the maximum extent possible.

- *Lighting industry design guidelines and standards.* Results of this work may also feed into key lighting design guides such as the IESNA handbooks and recommended practice guidelines, the ASHRAE/IESNA 90.1 lighting standards, and the Advanced Lighting Guidelines.
- *Further outdoor lighting research.* The assessment methodology described in this report is highly valuable as a repeatable protocol for the establishment of outdoor lighting baselines. Combined with the interest and activity of transferring this research into programs, policies and practices this survey method will play a key role in reducing outdoor lighting energy use.
- *Washington State and City of Seattle outdoor lighting standards.* In Washington, both Seattle and the State have had exterior lighting requirements since 1980. Both codes prohibit trading between interior and exterior lighting and categorize exterior lighting into two broad groups: facade lighting and all else. The wattage allowances are applied to the square foot of illuminated area. A representative from the City of Seattle is an advisor to this PIER research and is providing valuable feedback on the application of their code approach. This project's findings, in turn, will provide expanded category definitions and characteristics beyond the current "all else" grouping in Washington, including such areas of high interest as gas station and parking lot lighting.

7.7.2. Commercialization Potential Or Commercialization Initiated

There is some potential for the survey method and tools to be commercialized, but they are currently publicly available. The survey itself does not have commercialization potential.

7.7.3. Recommendations

ADDITIONAL OPPORTUNITIES

- The development of correlations between LPD and illuminance values, including associated information of lamp type, pole height, and lighting zone, would also provide valuable insight into the outdoor lighting design practices in California.
- The statewide results provide an opportunity to evaluate the energy savings available from enhancements in commercial outdoor lighting design practices. For example, the data indicate that lighting power densities (LPD) of less than 0.10 W/ft^2 for parking are both common and adequate. The impact available from various strategies to convert over-lit parking to this standard could be calculated. The opportunity exists to develop similar projections for many other lighting applications and configurations, yielding substantial information for the design and regulatory communities.

7.7.4. Benefits to California

Energy Benefits

Quantifying outdoor lighting's energy consumption and demand provides the State of California and utilities with a foundation for establishing regulatory and voluntary approaches to modifying energy use in this sector. Potential energy savings are described in the Technical Outcomes section of Project 7.6 above.

Other Benefits

This research has created an excellent foundation for more specific studies by providing a repeatable methodology for targeted data collection and by establishing a set of results from which to design more specific inquiries.

8.0 Glossary

Acronym	*Term*
AAMA	American Association of Manufacturers
ABG	Advanced Building Guidelines
ACEEE	American Council for an Energy Efficient Economy
ACM	Alternative Compliance Manual
AEC	Architectural Energy Corporation
AIA	American Institute of Architects
ARI	Air-Conditioning and Refrigeration Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BII	Building Industry Institute
CASE	PG&E's Codes and Standards Enhancement initiative
CEE	Consortium for Energy Efficiency
cfm	Cubic feet per minute
CHPS	Coalition for High Performance Schools
CIE	International Commission on Illumination
CISCA	Ceiling and Interior Systems Construction Association
DCV	Demand-control ventilation
DX	Direct expansion
EDR	Energy Design Resources
EMCS	Energy management and control system
EMS	Energy management system
EVT	Effective visible transmittance
Ft^2	Square feet
FSEC	Florida Solar Energy Center
FUA	Functional use areas
FUSD	Fresno Unified School District
GWh	Gigawatt-hour
HECAC	High-efficiency commercial air-conditioning (a CEE initiative)

Acronym	*Term*
HMG	Heschong Mahone Group
HPS	High pressure sodium
HVAC	Heating, ventilating and air conditioning
IDA	International Dark-Sky Association
IESNA	Illuminating Engineering Society of North America
ISO	Independent System Operator
kWh	Kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory
LPD	Lighting power density
MBSS	Model-based statistical sampling
MDL	MicroDataLogger
MH	Metal halide
MLO	Model lighting ordinance
MW	Megawatt
NBI	New Buildings Institute
NFRC	National Fenestration Rating Council
NRC	National Research Council of Canada
NRNC	California Statewide Non-Residential New Construction database
O&M	Operations and maintenance
PAC	Program advisory committee
PECI	Portland Energy Conservation, Inc.
PG&E	Pacific Gas & Electric Company
PIER	Public Interest Energy Research
SC	Spacing criterion
SF	Square feet
SHGC	Solar heat gain coefficient
SIC	Standard Industrial Classification code
SSCTS	Skylight Solar Calorimeter Test System

Acronym	*Term*
TAG	Technical advisory group
TDD	Tubular daylighting device
TXV	Thermostatic expansion valves
UCB	University of California at Berkeley
VAV	Variable air volume
VSD	Variable-speed drive

9.0 Attachments

This section lists the attachments to the final report of the PIER Program *Integrated Energy Systems: Productivity and Building Science Program* (the program), Contract Number 400-99-013, conducted by New Buildings Institute, Inc.

The final report and these attachments are intended to provide a complete record of the objectives, methods, findings and accomplishments of the *Integrated Energy Systems: Productivity and Building Science Program.* The report content, and particularly the attachments, are highly applicable to architects, designers, contractors, building owners and operators, manufacturers, researchers, and the energy efficiency community.

This list of attachments is organized into two sections:

- **Summary Attachments**, which include key final products such as design guidelines and final research reports; and
- **Technical Attachments**, which include technical reports, survey methods and databases.

These attachments are part of report 500-03-082. To obtain copies of these attachments or other reports produced within this contract, or for 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. All research products are also available through New Buildings Institute at www.newbuildings.org.

9.1. Summary Attachments

Element	Attachment #500-03-082-	Attachment Name	Contents	Product #
1	A-1	Market Connection Report	Summarizes the market activities, connections, and influences of the PIER program.	None
	A-2	Project Brochures	Brief tri-fold brochures for each research element that promote their research results and products.	None
2	A-3	Daylighting in Schools: Reanalysis Report	Full report on the Daylighting in Schools: Reanalysis Study.	2.2.5
	A-4	Summary of Daylighting in Schools: Reanalysis Report	Summary of the full report (7 pages).	2.2.5x
	A-5	Daylight & Retail Sales: Replication Study	Daylight & Retail Sales final report.	2.3.7
	A-6	Daylight & Retail Sales: Replication Study—Appendices	Appendices to Daylight & Retail Sales final report.	2.3.7
	A-7	Windows & Classrooms	Healthy Schools final report. Complete title: Windows & Classrooms: A Study of Student Performance and the Indoor Environment.	2.4.10
	A-8	Windows & Classrooms—Appendices	Appendices to Windows & Classrooms report.	2.4.10
	A-9	Windows & Offices:	Healthy Offices final report. Full title: Windows & Offices: A Study of Office Worker Performance and the Indoor Environment.	2.6.10
	A-10	Windows & Offices—Appendices	Appendices to Windows & Offices report.	2.6.10
3	A-11	Advanced VAV System Design Guide	Design guide for improving performance of VAV systems in large commercial buildings.	3.6.2
4	A-12	Small Commercial HVAC System Design Guide	Design guide for improving performance of small package HVAC units.	4.7.5
5	A-13	Design Guidelines for Skylights with	Best practices for designing modular skylight/light-well systems with	5.4.6-b

Element	Attachment #500-03-082-	Attachment Name	Contents	Product #
		Suspended Ceilings	suspended ceilings	
	A-14	Ceiling Insulation Report	Summary of Data Collection and Analysis Results on Lay-in Ceiling Insulation	5.2.6
	A-15	Photometric Files	1. Intro to Photometric Files 2. Photometric Files – IESNA Format (zipped) 3. Photometric Reports (zipped) 4. Summary of Photometric Files 5. Presentation on Photometrics	5.3.5-b
6	A-16	Home Builders Guide to Ducts in Conditioned Space	Recommended approaches for modifying house designs to locate ductwork within conditioned space.	6.3.4
	A-17	Homeowners Benefits to Ducts in Conditioned Space	Short brochure to educate consumers about the benefits of ducts in conditioned space.	6.4.2-d
7	A-18	CA Outdoor Lighting Baseline Assessment	Full report on California outdoor lighting characteristics including areas of use, lamp type, and energy consumption.	7.7.2
	A-19	CA Outdoor Lighting Baseline Assessment—Appendices	Appendices to full report.	7.7.2

9.2. Technical Attachments

Element	Attachment #500-03-082	Attachment Name	Contents	Product #
3	A-20	Large HVAC Building Survey Info	1. Database of new CA commercial buildings over 100,000 ft²	3.2.1
			2. Summary of Site Screening Interviews	3.2.2
			3. Onsite Inspection Report for 21 Sites	3.2.4
	A-21	Large HVAC Field and Baseline Data	1. Field Data Collection (3 items: Site Survey Data Form; Site Survey Letter; Site Survey Schedule)	3.2.3
			2. Sensitivity Analysis	3.3.1
			3. Solutions Report	3.3.3
	A-22	Large HVAC Energy Impact Report	Statewide Energy Impact Report	3.4.1
4	A-23	Small HVAC Field and Survey Info.	1. Background Research Results Summary	4.3.1
			2. Description of the Field Methods	4.4.1
			3. Survey Method and Questionnaires (5 items: survey form; functional performance test; spot power measurement; economic survey; kW survey.)	4.4.2
	A-24	Small HVAC Database of Monitored Info	Database of compiled information from the field surveys.	4.4.3
	A-25	Small HVAC Problems & Potential Savings Reports	1. Summary of problems with each surveyed building	4.5.1
			2. Statewide Energy Impacts	4.5.3
5	A-26	Ceiling Insulation Survey Info	1. Site Visit Protocol	5.2.2b
			2. Report on Phone Surveys (200 Buildings)	5.2.3
			3. Insulation Cost and Application Study	5.2.5
	A-27	Skylight Photometric & Thermal Reports	1. Construction and Calibration of Skylight Photometric Test Facility	5.3.5
			2. Photometric Testing Lessons Learned	5.3.2x

Element	Attachment #500-03-082	Attachment Name	Contents	Product #
			3. Skylight Test Chamber Design Report: Skylight U-factor Tests	5.3.2 a
			4. Summary of U-Value Test vs. Model	5.3.2-b
			5. Summary of SHGC Test vs. Model	5.3.3-b
			6. Summary of VLT Test	5.3.4
			7. Summary of VLT Angle Test vs. Model	5.3.4-b
	A-28	Integrated Ceiling Research Report	Integrated Ceiling Research Report.	5.4.2
6	A-29	Residential Duct Placement Field Test and Research Reports	1. Tests of Homes with Ducts in Conditioned Space	6.6.2-b
			2. Literature Search	6.3.1
			3. Interview with Builders and Researchers	6.3.2
			4. Representative House Designs Summary Report	6.3.3
	A-30	Residential Duct Placement: Market Barriers	Identifies market barriers to locating ducts in conditioned space and approaches to overcoming the barriers	6.4.2-b
	A-31	Cost & Savings for Houses Built with Ducts in Conditioned Space: Technical Information Report	1. Information for technical audiences and Title 24 code updates. Summarizes recommended approaches and describes costs and savings.	6.4.2-e
			2. Building Code Official's Briefing Document Variance for Attic Venting due to "Cathedralized Attic"	6.4.2-c
7	A-32	Outdoor Lighting Survey Reports	1. Annotated Bibliography and Summary	7.2.1
			2. Sample Design	7.3.1
			3. Phone Survey Instrument	7.3.2
			4. Phone Survey Tracking Report	7.3.3
			5. Summary of Phone Survey Responses	7.3.4
			6. Summary Trip Report: 40 Pilot Outdoor Lighting Surveys	7.4.4
			7. Surveyor Training Presentation (.ppt)	7.5.2
			8. On-Site Survey Instrument	7.6.2
	A-33	CA Outdoor Lighting Baseline Database	CA Outdoor Lighting Analysis Database This attachment is 86 MB and is only available by direct mailing. Please contact NBI or CEC for a copy.	7.6.5