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Commercial-Sector Conservation Technologies

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COMMERCIAL-SECTOR CONSERVATION TECHNOLOGIES

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ABSTRACT

This report describes and documents **selected** commercial-sector energy conservation technologies and strategies with special emphasis on their application in the Pacific Gas and Electric and the Southern California Edison service territories. The primary topics are space cooling (equipment, loads, systems), air transport, refrigeration, electric motors, electric lighting, and daylighting and fenestration. The report presents cost, energy and power savings, lifetime, product reliability, and related information for each of these topics. Documentation, with field performance data where possible, is also included. Secondary topics, (covered in substantially less detail) are energy management and control systems, natural gas cooking, and natural gas space heating equipment. Gaps in information and future research needs are also highlighted.

Keywords: Energy Conservation, Commercial Buildings, Office Buildings, Cooling, Ventilation, Refrigeration, Electric Motors, Lighting Systems, Daylighting, Energy Management Systems, Air Conditioning, Cooling Systems, Ballasts, Fluorescent Lamps, Light Bulbs, Skylights, Ventilation Systems, Refrigerators

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CHAPTER 1

INTRODUCTION

Chapter 1

Introduction

1.1 PURPOSE AND SCOPE

California's energy utilities and state regulatory agencies have long recognized the importance of the commercial sector as an energy user and the potential that this sector holds for energy and power conservation. The commercial sector accounts for nearly 29 percent of the state's total electric energy consumption and 32 percent of its peak electricity requirements. Projects such as the Southern California Edison (SCE) Hardware Rebate Program and the Pacific Gas and Electric (PG&E) Customized Rebate Program for Large Businesses have captured some of the conservation potential. However, the proliferation of conservation technologies and strategies, the limited data on commercial stock characteristics, and the lack of field-monitored performance information have hampered efforts to more accurately and fully describe commercial conservation potential.

This report reviews, evaluates, and documents information on **selected** existing and emerging conservation technologies and strategies applicable to both new and existing California commercial buildings. We emphasize electric end uses but briefly discuss natural gas heating, cooking, and cooling.

Wherever possible we have supplemented the technical descriptions of conservation measures with discussions of the effects of operation and maintenance activities on their performance. In addition, we have used case studies to illuminate the performance of measures and strategies. However, there are few long-term performance studies and much of the case study information, if available, includes little on the performance of specific types of equipment.

We designed this report for use by a wide range of utility audiences. It provides guidance and recommendations to energy management planners, commercial surveys designers, and commercial-sector field representatives and auditors. The detailed cost, savings, and other data for specific technologies also should help refine and update the inputs to the utility "conservation-potential/forecasting" models. Finally, the report will help utilities integrate conservation research with conservation programs.

A key element of the report is the extensive documentation of our analysis including sources, gaps in information, and conclusions. This is essential because conservation technologies are changing rapidly and many gaps exist in our understanding of current building stock characteristics. We have tried to be as complete as possible in presentation of material so that the user can understand the origin of our assumptions and the paths to our conclusions. Furthermore, the level and style of documentation will permit future users to update and expand on our work with relative ease.

1.2 COVERAGE

By mutual agreement with both utilities we have concentrated on only a portion of the commercial sector end uses, building-types, and conservation measures. Nevertheless they represent a substantial fraction of both total electric energy and power use for SCE and PG&E. We also have examined a few natural gas end uses, all classified as secondary topics.

Some of the questions we asked in our selection process included:

- Does the end use account for a significant large fraction of the total commercial sector electricity use?
- Is the energy intensity of the end use high?
- Is either the EUI or total electricity use of an end use projected to increase substantially between 1982 and 2000?
- Do our preliminary analyses or other conservation potentials studies suggest a large, uncaptured conservation potential?
- Are there good prospects that the conservation measures or strategies within the end use can be carried out?
- Are there new or innovative conservation technologies or strategies likely to be available by 2000?
- Were there enough data available, especially from monitored performance of buildings, to warrant further investigation?

Based on these factors and discussions with both PG&E and SCE we selected five primary topics and three secondary topics.* Figures 1-1 through 1-4 illustrate the primary topic areas of this report: cooling and ventilation, refrigeration, and lighting. The shaded portions of the pie charts are the end uses that are considered in the greatest detail. Portions of unshaded end uses are briefly discussed, in the appendices.

Primary Topics:

- **Chapter 2 Cooling and Air Transport**
- **Chapter 3 Refrigeration**
- **Chapter 4 Motor Efficiency**
- **Chapter 5 Electric Lighting**
- **Chapter 6 Daylighting and Fenestration**

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* Progress reports containing details of our selection process were provided to PG&E on November 15, 1983 and to SCE on November 18, 1983.

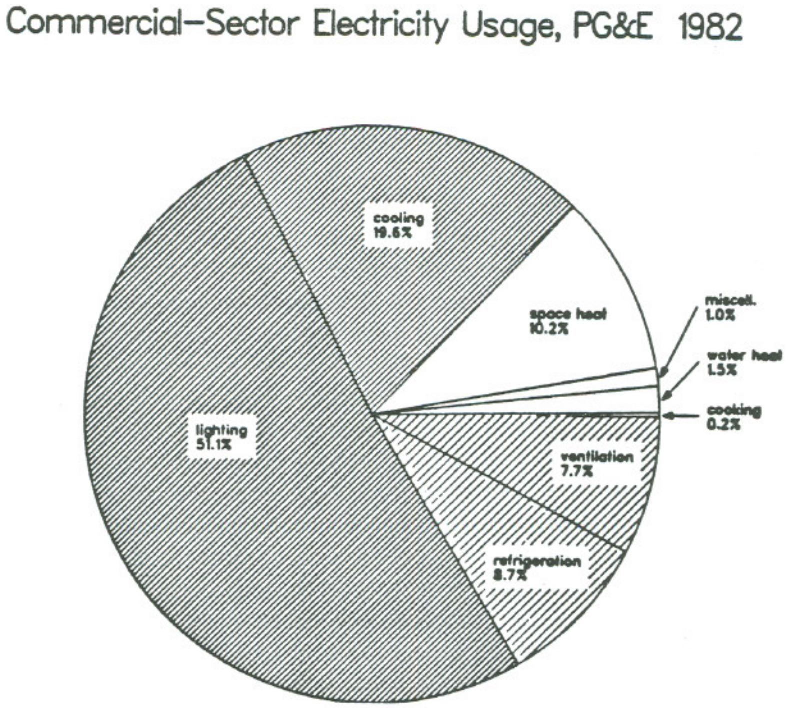

Figure 1-1. Commercial-Sector Electricity Usage, PG&E 1982. Total electricity usage is 19,424,295 kWh.

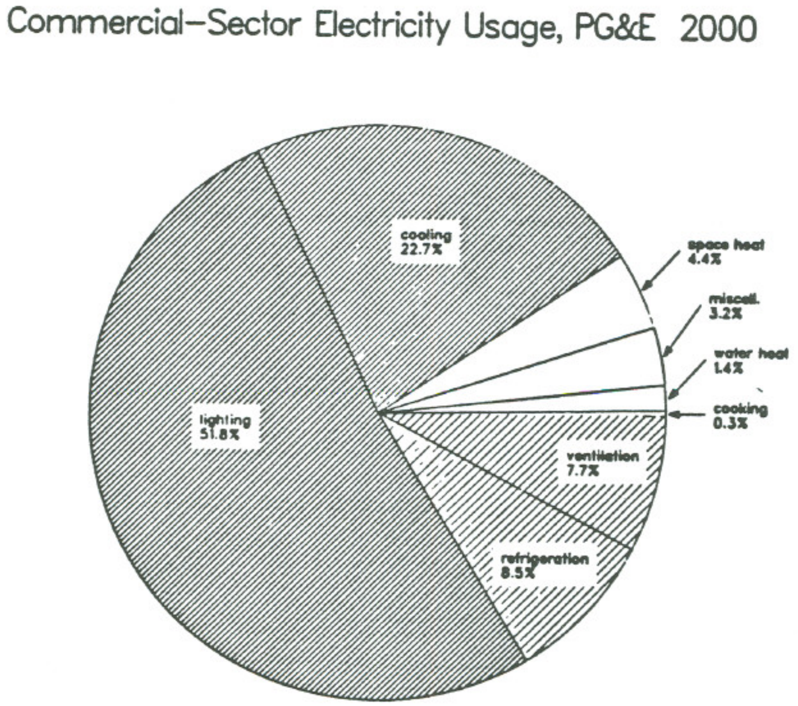

Figure 1-2. Commercial-Sector Electricity Usage, PG&E 2000. Total electricity usage is 22,220,230 kWh.

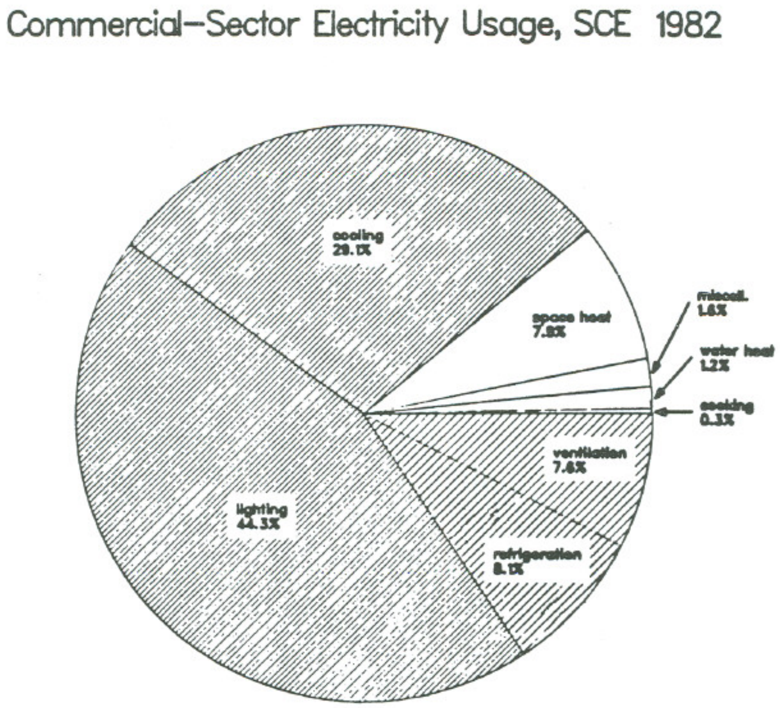

Figure 1-3. Commercial-Sector Electricity Usage, SCE 1982. Total electricity usage is 18,075,496 kWh.

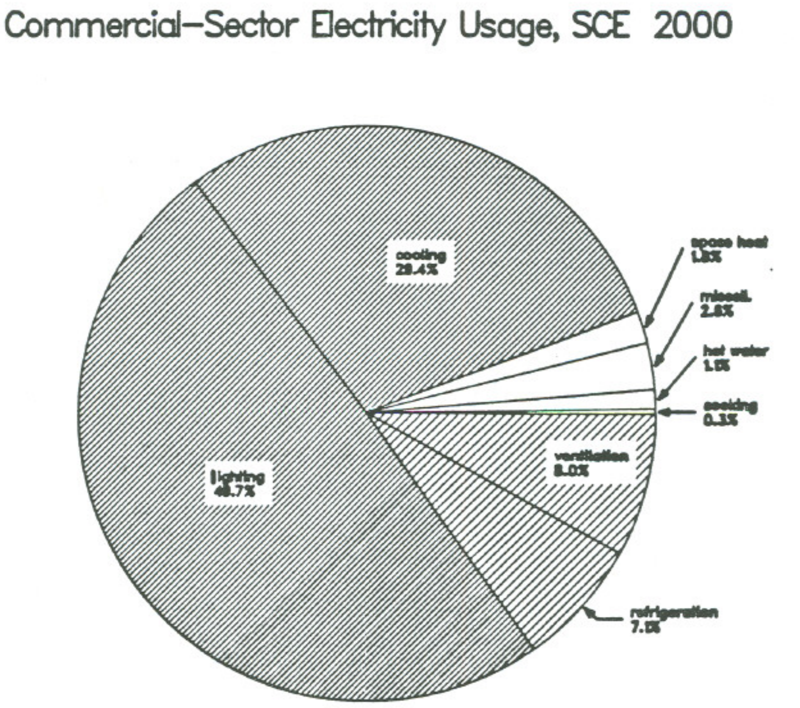

Figure 1-4. Commercial-Sector Electricity Usage, SCE 2000. Total electricity usage is 23,220,755 kWh.

Secondary Topics

- Appendix A Natural Gas Space Heating Equipment
- Appendix B Natural Gas Cooking in the PG&E Service Territory
- Appendix C Energy Management and Control Systems

1.3 RESEARCH APPROACH

The evaluations of conservation measures are based on a wide range of resources and analytical techniques. We began with standard literature searches and supplemented that material with manufacturers' product literature and information gleaned from conferences. For several end uses, such as electric lighting and daylighting, other research at the Lawrence Berkeley Laboratory provided significant material. Wherever possible we used published and unpublished data from field measurements of commercial building performance, laboratory tests of equipment, and site visits by the project staff.

The building energy-analysis computer simulation tool, DOE-2, was also used for portions of the daylighting and fenestration (Chapter 6), and the cooling/air transport (Chapter 2) analyses. We used the computer model in those instances where empirical data were lacking or where the combined effects of building characteristics, weather, equipment type, and other complicating factors made direct analyses impossible. Details of the building "prototypes" and analytical approach are contained in the chapters.

Our goal for each of the primary subject areas was to provide data and evaluations of the following characteristics for each conservation technology or strategy:

- Energy performance
- Costs (installation, operating, and maintenance)
- Lifetimes
- Reliability
- Applicability
- Relation to other measures
- Documented practical experience
- Side-effects
- Operator/occupant response
- Relation to California Title-24 Non-Residential and ASHRAE 90 Standards

1.4 QUANTIFYING THE SAVINGS

Because of the heterogeneous nature of the various end uses and conservation measures, we have not used a single energy performance indicator for all measures. Instead, we provided the most appropriate and useful indicator for each of the technologies or strategies. Consequently, some energy and power savings estimates are expressed in percentage savings, others in an absolute reduction in energy use per square foot, and still others in the resultant energy use independent of the baseline condition. This multi-indicator approach admittedly complicates comparison of energy savings across end uses and building types, but we believe it is a more accurate and useful means of describing specific conservation potential.

1.5 HOW TO USE THE REPORT

Each chapter of this report has been divided into three sections, each of which presents a different level of detail on the conservation measures and strategies. For those readers interested in a quick overview of of the technologies the summary tables, at the beginning of each chapter, contain a concise tabulation of costs, energy and power savings, lifetime, applicability, and additional comments. These summary tables are followed by one to three page summary sheets, which contain a general description of the technology, its applicability, energy performance, costs, reliability/lifetime, utility system impacts, user impacts, availability, experience, and comments and caveats (qualifications).* The summary sheets support and amplify the material in the summary tables. If the reader wants a more detailed discussion of how the conservation measures fit into each end use this is provided in the narrative section of each chapter.

The three appendices contain shorter discussion of special areas of interest. A list of abbreviations and a glossary of technical terminology follow the appendices.

1.6 LIMITATIONS OF THE REPORT

The following chapters contain much information on commercial-sector conservation technologies. Nonetheless, many gaps remain. Data gaps for each end use are discussed within the narrative section of each chapter. Here we highlight some of the general gaps including: 1) uncertain data quality and availability; 2) technical issues of building and measure performance; 3) the limited scope of our computer analyses, and 4) uncertainty about peak and load shaping impacts of conservation measures.

Data quality and availability

In many instances we have not tapped all the utility data sources relevant to conservation potential estimates; in particular the audit and rebate program results have not been used. These could be a source of important case study information on conservation measure performance and cost, and stock characteristics.

Cost (and reasons for cost variation) remain a problem area. Variations result from such factors as discount pricing and variations in labor costs. Similarly, although most new-product performance is well-defined under test conditions, there is little documentation of in-place operating experience. Product lifetimes and operating costs for many of the emerging technologies are also major unknowns. There is a need for monitored data on the long-term operating characteristics of these strategies. Finally, There is a major gap in our knowledge of how both newly constructed and existing buildings are operated and controlled. Case study evaluation of buildings, perhaps with some short-term diagnostic monitoring, is one way to begin to fill this gap.

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* No summary sheets were include in Chapter 6, Daylighting and Fenestration. The chapter concentrates more on energy conservation design strategies rather than energy conservation hardware, consequently summary sheets were not developed.

Technical issues

Various technical issues such as the relationship between lighting levels, lighting design, and visual performance, require further research.

Computer simulations

As noted above, we have used the DOE-2 simulation model to calculate cooling, air transport, and daylighting energy and power savings. However, we only considered three locations, Fresno, Los Angeles, and San Francisco. We feel that these sites are sufficiently representative of variations in California climate to bracket the range of conditions. Site specific conservation analyses would probably require simulations for other locations.

Our computer simulations concentrated on variations in shell features and weather (see Appendix 2-A and Chapter 6 for more details). Future parametric computer simulations should also address more system types and different operating conditions. Finally, the simulations work were not anchored to buildings that have been submetered and examined in detail through on-site performance case studies.

Peak and Load Shaping

Utility conservation programs are not only concerned with conservation of energy but are also directed toward peak load reductions and load shaping. Nonetheless, the impacts of conservation measures and strategies on utility peak demand and load shape is often difficult to determine. All commercial buildings, even with in a small geographic area, will not peak at the same time, and an individual building's peak may not correspond to the utility system peak. In addition, the zones of a multiple zone system will peak at different times of the day, depending on building design (e.g. thermal mass), operating schedules, start-up characteristics, and orientation. Consequently it is very difficult to accurately determine what specific load shape or peak impacts can be expected from a given conservation measure.

Similar uncertainties exist from a building design viewpoint. Although we have assumed that building designers will downsize cooling equipment to credit peak savings from decreased internal loads (e.g. daylighting), in practice the unproven aspects of these load reductions may limit the downsizing.

1.7 GENERAL CONCLUSIONS AND OBSERVATIONS

The major conclusions and observations for each of the end uses can be found in the "Key Finding" section of each chapter. There are, however, several general conclusions and observations that cut across individual end use categories. These include:

- The best strategies for reducing peak electricity usage are **not** necessarily those that save the most energy. Utility information/incentive programs and penetration models need to reflect the economic trade-offs of energy savings versus peak savings. In addition we found that there is often little or no reliable information on the peak shaving or load profile impacts of specific conservation measures.
- Usually, it is misleading to think of a single maximum technically-feasible ("max-tech") conservation option for a given end use and building type. There are often enough variations in building characteristics, equipment, location, and equipment usage patterns within an end

use or building type category to make the single-option approach misleading. The effect on site-specific conservation program design and implementation may be more pronounced than on more broad range forecasting estimates.

- Good building operation and management can yield larger energy and power savings than hardware measures alone. It is difficult or impossible to obtain reliable and detailed building operating data. Where such data are available it is often difficult to quantify savings because of an uncertain starting point (or baseline) from which to measure savings.
- Existing baseline EUI estimates and stock characteristics have been developed primarily for demand forecasting purposes. If these values are to serve as a basis for technology-specific potentials estimates, conservation program design, or efforts to track conservation progress, there is a need for more refinement in these estimates. Similarly, the building and end use categories are poorly matched for determining conservation potential. Categories based on HVAC systems, effective glazing apertures, usage patterns, or comfort conditions are often substantially more useful for energy conservation programs.
- Notwithstanding new stringent ASHRAE and Title-24 standards for new commercial buildings, there is still a large potential for both energy and power savings in the commercial sector. This is especially the case for existing commercial buildings, which are not covered by the new standards.

1.8 CONSERVATION OPPORTUNITIES

We have identified many commercial-sector conservation opportunities. Some of these opportunities have already been recognized by utility conservation planners and program designers and there are programs underway or being planned which will address them. However, we feel that they are significant enough that they should be reemphasized.

Training and Data Collection:

- Conservation incentives as well as audits should emphasize better building management, control, and maintenance, not just the installation of new, conservation hardware.
- The utilities should promote building operator training programs and continuing feedback on building performance.
- Engineering services, independent of retrofits, modelled on efforts such as utility lighting design assistance programs, should be expanded to optimizing controls and air distribution system balancing.
- "Close the feedback loop" among designers, engineers, and operators:
  - Set customer guidelines for specifying "building commissioning" services.
  - Encourage building-specific operation manuals.
  - Publicize detailed case studies.
  - Sponsor 1-2 year return visits for Architect/Engineering firms,
    along with building operators, vendors, and independent
    technical mediator.

- Commercial-sector surveys need more details of building stock and equipment to improve conservation potentials analysis, provide more accurate program guidance, and track progress toward conservation goals. Some specific recommendation include:
    - Combination of surveys with on-site analysis, monitoring , and linkage to other data sources such as audits, rebates, and EMCS as data loggers.
    - More detailed survey questions with follow up field observation and measurement of existing equipment such as:

      Variable-air-volume (VAV) vs. constant-volume
      Fan CFM and outside air percentage
      Economizer presence and operation
      Thermostat set-points
      Major equipment schedules
      Lighting power-density and hours of operation
      Refrigeration equipment characteristics
      Fenestration features
    - Consideration of a multi-year plan for the improved characterization of commercial building stock.
    - Providing for customer contacts during the construction of new buildings. This would allow collection of data on construction practices and equipment installation.

Hardware:

- Installation of economizers is a dominant HVAC energy efficiency strategy in all weather zones.
- Title 24 (office) non-residential standards challenge but do not exhaust state-of-the-art conservation possibilities. Additional opportunities for utility technical assistance and incentives include:
    - Promoting equipment efficiency standards better than ASHRAE 90 and Title-24 requirements.
    - Peak load-shifting and other demand management.
    - Assistance in effective lighting design (including daylighting/fenestration) that is below 1.5 W/ft^2 with good visual performance, comfort, and aesthetics.
- Commercial building renovations offer major opportunities for technical assistance and incentives. Special attention should be directed toward improved lighting design and controls and HVAC distribution and controls.
- Labeling programs for replacement equipment including motors, refrigerators, compressors, chillers, cooking equipment, and reach-in refrigerators might be considered as a supplement to existing commercial incentive programs. For equipment usually replaced at breakdown, a

pre-tagging system, perhaps modelled after the agricultural pump replacement program, should also be examined.

- Utility-subsidized EMCS installations, in particular, can provide useful monitored data for program feedback, conservation assessment, end use analysis, and electric load profiles.

CHAPTER 2

COOLING AND AIR TRANSPORT

Table 2-1
SUMMARY TABLE - SPACE COOLING: EQUIPMENT TECHNOLOGIES

Measure	Applicability (R=Retrofit;N=New)	Base Conditions	Climate Zone (if appl.)	% Reduction (*) in cooling usage: Annual Energy	% Reduction (*) in cooling usage: Peak Demand	Costs ($/ft^2)	Lifetime (years)	Comments
High efficiency mechanical cooling equipment	N. Also replacement on failure. All building types and climate zones.	1. <11 tons, air cooled condenser included. Base COP=2.0-2.4.	ALL	20-50%	20-50%	0.70-1.70	10-20	Assuming similar part load curves. See table in summary sheet for COP's of different equipment at rated conditions. Low end of base COP range is ASHRAE 90/75 standard, and can be taken to be typical of existing buildings. High end of base COP range is ASHRAE 90/84 standard, and can be taken to be typical of new buildings. Savings are based on COP of "best" available equipment (see Table 2-8). Costs stated are entire equipment costs. Incremental costs for high performance equipment over standard equipment are small.
		2. Water chillers, 50-2000 tons, condensing equipment not included. Air cooled (base COP=2.1-2.5)		15-25%	15-25%	0.40-1.40	20-30	
		Water cooled (base COP=3.2-4.0)		10-25%	10-25%			
		3. Absorption chillers (heat operated). Condensing equip. not included. Base COP=0.4-0.7.		10-50%	N/A	0.50-2.00	20-30	
Part load COP improvement	N,R. Especially applicable to water chillers, and buildings with multiple zone systems.	Building with most operating hours well below design conditions.	ALL	15-30%	0	N/A	10-30	Costs vary with type of control and equipment selected, and system size. Savings vary according to load profile.
Gas fired absorption chillers	N. Larger buildings with chilled water systems.	Building with electric chiller COP of 4.0, replaced with absorption chiller COP of 0.48-0.68 (ASHRAE 90/84 standards).	ALL	-100%- -180% (**)	100%	0.50-2.00	20-30	Cost savings will depend on relative prices of fuel and electricity. Energy savings estimates assume a heat rate of 10,500 Btu/kWh. (**): Energy consumption (different fuels) will increase since gas equipment COPs are lower than comparable electric equipment.
Double bundle chillers	N. Larger buildings. Buildings with high space heating or hot water requirements.	Building *without* an economizer, or with load shedding economizer controls.	ALL	Due to COP penalty, energy and peak consumption may increase by 10-30%.		0.10-0.50	20-30	Benefits of recovered heat must be traded off against typically lower COP. Savings will be higher in buildings with high thermal loads and/or storage capability. Costs are incremental costs over standard equipment.
Raise evaporating/ Lower condensing temperatures. (Reset)	N,R. All building types and climate zones. Easiest to implement with chillers and cooling towers.	40°F evap temp.	ALL	3-10%	0	N/A	10-25	Raising evaporating temperatures may have to be traded off against increases in fan usage. Savings based on 5° reset (annual avg.) on either evap. or cond. temp. Reset may only be possible during non-peak periods (no peak demand savings).

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* Base case cooling energy use varies from 1 to 7 kWh/ft^2-yr, and peak demand varies from 1 to 6 W/ft^2, depending on building configuration, operating schedule, and climate.

Table 2-2
SUMMARY TABLE - SPACE COOLING: EQUIPMENT TECHNOLOGIES

Measure	Applicability (R=Retrofit;N=New)	Base Conditions	Climate Zone (if appl.)	% Reduction (*) in cooling usage		Costs ($/ft^2)	Lifetime (years)	Comments
				Annual Energy	Peak Demand			
Outside air economizer	N (required by code in Calif.). R (unless space limitations prevent installation). All bldg. types and climate zones. May not be suitable for buildings with continuous outside air or tight humidity requirements.	Building operating during daytime hours. No significant process loads (e.g. computer equipment). NOTE: No annual peak savings, since economizer can not be used on hottest days.	SF	40-80%	0			% savings tend to be in the low end of the range for bldgs with 1. VAV systems 2. Daytime operation only 3. No reset control. Initial base line usage, and therefore absolute savings (improving economics) tend to be higher in buildings: 1. with higher internal loads 2. more fenestration (higher solar loads). Costs are extremely site specific. Little data available on lifetime. Costs are higher per ft^2 for smaller systems.
			LA	15-65%	0	0.05-0.50	10-20	
			FRESNO	30-45%	0			
Direct and indirect evaporative cooling	N,R. All building types and climate zones. Direct evap cooling not suitable for spaces requiring tight humidity control.	Building with dry bulb economizer.	SF	30-50%	0			% savings indicated is from base case *with economizer*. Base cooling EUI's in SF are considerably lower than those in LA, and those in LA lower than those in FR. Absolute savings will generally be higher in central valley areas. Some form of water treatment is required.
			LA	5-30%	0	0.50-1.10	5-20	
			FRESNO	10-20%	0			
Cooling tower cooling (Strainer cycle)	N,R. Larger buildings, with chilled water systems and cooling towers.	Building *without* economizer.	ALL	0-10%	0	N/A	5-20	Savings will be higher in buildings with high process loads and significant night cooling requirements, and in arid climates.
Off-peak ice storage	N,R. Larger buildings.	Full storage, system sized to meet all cooling loads on the peak day with storage.		0	100%	1.00-4.00	20-30	Energy consumption may increase, due to low evaporating temps. Energy consumption shifted off-peak. Costs stated are storage system costs. Reduced chiller first costs may completely offset storage system first costs.
		Partial storage, system sized to meet all cooling loads on the peak day with chiller running continuously.	ALL	0	40-70%	0.50-2.00		
Off-peak chilled water storage	N,R. Retrofits may be limited by storage space constraints. Larger buildings.	Full storage, system sized to meet all cooling loads on the peak day with storage.		0	100%	0.50-3.40	20-30	Evaporating temps. same as in conventional system. Relatively large space requirements. Energy consumption shifted off-peak. Costs stated are storage system costs. Reduced chiller first costs may completely offset storage system first costs.
		Partial storage, system sized to meet all cooling loads on the peak day with chiller running continuously.	ALL	0	40-70%	0.25-1.60		

* Base case cooling energy use varies from 1 to 7 kWh/ft^2-yr, and peak demand varies from 1 to 6 W/ft^2, depending on building configuration, operating schedule, and climate.

Table 2-3
SUMMARY TABLE - SPACE COOLING: EQUIPMENT TECHNOLOGIES

Measure	Applicability (R=Retrofit;N=New)	Base Conditions	Climate Zone (if appl.)	% Reduction in cooling usage Annual Energy	% Reduction in cooling usage Peak Demand	Costs ($/ft²)	Lifetime (years)	Comments
Phase change materials	N,R. Any building suited for ice or chilled water storage. May be more suited to retrofits since less space is required.	Not applicable	ALL	**	**	Relatively high	**	This is a relatively new and untested technology. Savings vary depending on type of material. See the summary sheet for more detail.
Mass storage and night venting	N. Buildings designed with large amounts of exposed thermal mass, or hollow core slabs.	Buildings not occupied at night.	ALL	**	**	Difficult to estimate.	**	Savings in cooling consumption must be traded off against fan energy consumption during night venting periods. See summary sheet for more detail.
Ground and ground-water source heat pumps	N. Buildings with access to large ground area or ground water aquifer (typically rural areas). Not suited for large urban areas.	Not applicable	ALL	**	**	HIGH	**	See summary sheet for more detail. Energy performance difficult to estimate and highly variable. This technology has limited potential.
Desiccant cooling systems	Generally, not applicable in California.	Not applicable	NONE	NONE	NONE	HIGH	**	This technology is suited for hot, humid climates (not California). Development still in the research phase. See summary sheet.
HVAC system modifications	Described in Section 2.4							

** See individual summary sheets for specifics on these technologies.

Table 2-4

SUMMARY TABLE - SPACE COOLING: LOAD REDUCTION MEASURES

Measure	Applicability (N=New, R=Retrofit)	Base Conditions	Climate Zone	Cooling Reduction		Cost (\$/ft^2)	Lifetime (years)	Comments
				Annual Energy kWh/ft^2-yr	Peak Demand W/ft^2			
Heat gain reductions from equipment	R.	Assume energy conservation measures produce a 2 kWh/ft^2-yr reduction in lighting energy use and a 1 kWh/ft^2-yr reduction in air transport energy use.	SF	0.16-0.91	0.24-0.49	-	-	Cooling savings result from energy savings in *other* end-uses. No costs are shown because these are secondary savings. Variations in savings are primarily due to variation in cooling system efficiency.
			LA	0.33-0.94	"	-	-	
			FR	0.39-1.16	"	-	-	
Heat-removing luminaires	N. Used with fluorescent fixtures in clean environments.	Assume lighting power density of 2 W/ft^2, and office building schedule.	SF	0.05-0.16	0.02-0.03	0.05-0.15	20 - 30	The luminaires lower lamp temperature and affect lamp performance; effects can be positive or negative. This technology is covered in the "Venting Heat Gains" summary sheet.
			LA	0.16-0.27	"	"	"	
			FR	0.11-0.27	"	"	"	
Roof insulation	N, R. Most applicable during new construction or reroofing, although can be done at other times for some roofs.	Initial roof is horizontal, R-8, solar absorptivity =0.7. Assume R-11 is added so total is R-19. 4 story building.						Energy savings are greater for roofs that are initially poorly insulated. Heating and air transport savings should also be considered. Savings and costs are per ft^2 floor area (*not* roof area), to be consistent with other table entries.
		Buildings with Economizers:	SF	0.00-0.00	0.09-0.18	0.08-0.16	15 - 30	
			LA	0.01-0.01	"	"	"	
			FR	0.06-0.12	"	"	"	
		Buildings without Economizers:	SF	-0.01	0.09-0.18	0.08-0.16	15 - 30	
			LA	0.01-0.02	"	"	"	
			FR	0.06-0.12	"	"	"	
Light colored roofs	N, R. Especially applicable for horizontal roofs (less aesthetic impact). Not applicable in dirty environments.	Initial roof is horizontal, R-8, solar absorptivity=0.7. Coating gives solar absorptivity=0.25. 4 story building.						Generally more effective than insulation for saving cooling energy. Saves more energy on poorly insulated roofs. Savings and costs are per ft^2 floor area (*not* roof area), to be consistent with other table entries.
		Buildings with Economizers:	SF	0.01-0.03	0.08-0.16	0.05-0.15	10 - 25	
			LA	0.05-0.10	"	"	"	
			FR	0.10-0.20	"	"	"	
		Buildings without Economizers:	SF	0.07-0.14	0.08-0.16	0.05-0.15	10 - 25	
			LA	0.08-0.16	"	"	"	
			FR	0.11-0.23	"	"	"	

Table 2-5

SUMMARY TABLE - SPACE COOLING: LOAD REDUCTION MEASURES

Measure	Applicability (N=New, R=Retrofit)	Base Conditions	Climate Zone	Cooling Reduction Annual Energy kWh/ft^2-yr	Cooling Reduction Peak Demand W/ft^2	Cost ($/$ft^2$)	Lifetime (years)	Comments
Roof-spray cooling	N, R. Most applicable to buildings with horizontal roofs.	Roof is horizontal, R-8, solar absorptivity=0.7. 4 story building.						Savings are largest for poorly insulated, dark roofs. Water usage can be significant, and the water cost is not included in the given cost figure; for the case presented, water use is 5 - 11 gallons/ft^2 of floor area per year. (20-45 gallons per ft^2 of roof area.) Pumping is required for buildings taller than a few stories, but pumping energy use is small, 5 x 10^{-5} kWh/gallon/story.
		Buildings with Economizers:	SF	0.02-0.04	0.14-0.28	0.06-0.13	10 - 25	
			LA	0.07-0.15	"	"	"	
			FR	0.16-0.32	"	"	"	
		Buildings without Economizers:	SF	0.11-0.22	0.14-0.28	0.06-0.13	10 - 25	
			LA	0.12-0.25	"	"	"	
			FR	0.18-0.35	"	"	"	
Reducing outside-air ventilation	R. Applicable for overventilated buildings. Only saves cooling energy for buildings with economizers.	Reduce outside air intake by 0.05 cfm/ft^2 of floor area.	SF	0.00-0.00	0.05-0.10	0.00-0.01	20 - 30	There are also heating savings from this measure.
			LA	0.01-0.02	0.08-0.15	"	"	
			FR	0.03-0.06	0.11-0.23	"	"	
Air-to-Air heat exchangers	N. Most applicable to buildings with large outside air requirements. Usually difficult to retrofit.	0.15 cfm/ft^2 outside air ventilation, 70% heat exchanger effectiveness.	SF	0.00-0.01	0.15-0.30	0.08-0.23	10 - 25	There are also heating savings from this measure.
			LA	0.02-0.05	0.19-0.38	"	"	
			FR	0.06-0.13	0.23-0.45	"	"	
Increasing cooling thermostat settings	N, R. Applicable in buildings where increased interior temperatures will not adversely affect comfort.	Increase thermostat setting from 75°F to 78°F. Moderate to poorly insulated building.						Occupant comfort must be considered. Heating savings result from increased heat storage for the nighttime cool-down period.
		Buildings with Economizers:	SF	0.15-0.30	0.03-0.09	0.00	1 - 30	
			LA	0.38-0.75	"	"	"	
			FR	0.23-0.45	"	"	"	
		Buildings without Economizers:	SF	0.38-0.75	0.03-0.09	0.00	1 - 30	
			LA	"	"	"	"	
			FR	"	"	"	"	

NOTE: Most energy savings estimates were derived from DOE-2 computer simulations of the office building module described in Appendix 2-A. The total savings in kWh were normalized to a square foot basis by dividing by the 16,000 ft^2 floor area of the office module. The variations in energy savings were calculated by assuming a range in cooling plant COPs of 2.0 - 4.0.

Table 2-6
SUMMARY TABLE - AIR TRANSPORT TECHNOLOGIES

Measure	Applicability (N=New, R=Retrofit)	Base Conditions	Climate Zone	% Reduction (*) in Air Transport		Cost ($/ft^2)	Lifetime (years)	Comments
				Annual Energy	Peak Demand			
Variable-Air-Volume (VAV) systems	N, R. Not applicable to buildings with high outside-air ventilation requirements. Cannot retrofit to systems with low-pressure ducts.	Retrofit of a dual-duct system. Savings and costs given for different types of main-fan flow control.						New construction costs are less than the case presented, and retrofits of systems other than dual-duct are more expensive. For new construction, variable-pitch fans become more competitive with the other fan control methods. VAV systems have impacts on the cooling energy use that can be positive or negative depending on the system compared against. See the summary sheet for more detail.
		Discharge Dampers:	All	18-35%	3%	0.20-0.50	10 - 20	
		Inlet Vanes:	All	40-60%	10%	0.24-0.56	10 - 20	
		Variable-Speed Drives:	All	68-80%	12%	0.40-0.90	10 - 20	
		Variable-Pitch Fans:	All	68-80%	12%	0.48-1.28	10 - 20	
Reducing fan air flow	R. Applicable to buildings with excessive air flow. No energy savings for VAV systems with efficient flow-control: variable-speed drives, or variable-pitch fans.	Assume air flow can be reduced 15%.						A significant portion of the cost is due to the energy audit necessary for determining the amount of air flow reduction possible. Heating and cooling impacts may be positive or negative depending on system type.
		Change Motor Pulley:	All	28-40%	28-40%	0.10-0.15	20 - 30	
		Duty-Cycle Motor:	All	15%	15%	0.10-0.15	5 - 20	
Fixing duct leaks	R. Substantial leakage is only found in buildings with low-pressure duct systems.	Assume leaks amounting to 10% of total flow are repaired, and fan air flow is reduced accordingly by changing the motor pulley size.	All	19-28%	19-28%	0.15-0.40	2 - 15	This measure also reduces noise from leaking ducts.
Miscellaneous pressure reduction measures	R. Applicable to existing systems with high pressure drops.	Assume the system pressure drop can be reduced from 5 - 50%.	All	5-50%	5-50%	0.20-1.20	10 - 30	These site-specific retrofit measures include installing turning vanes in square duct bends, and modifying fan fittings to reduce resistance in the index duct run.
Efficient air transport designs for new construction	N. Applicable for new construction.	Assume air flows can be reduced 20-40% and pressure drops reduced 25-50% when compared to existing buildings.	All	40-70%	40-70%	0.40-1.10	20 - 30	Savings and costs are relative to designs in existing buildings. In new designs, air flow requirements can be reduced by energy-conserving cooling design, and system pressure drops can be reduced by larger ducts and air-handling components.

* Base case air transport use varies from 2 to 9 kWh/ft^2-yr, and peak demand varies from 0.3 to 3 W/ft^2, depending on building configuration, operating schedule, and climate.

Table 2-7
SUMMARY TABLE - AIR TRANSPORT TECHNOLOGIES

Measure	Applicability (N=New, R=Retrofit)	Base Conditions	Climate Zone	% Reduction (*) in Air Transport Annual Energy	 Peak Demand	Cost ($\$/\text{ft}^2$)	Lifetime (years)	Comments
Fan shut-off during unoccupied hours	N, R. Applicable to buildings that run the air transport system during unoccupied hours.	Assume timeclock shuts air transport system down for 100 hours/week.	All	60%	0%	0.01-0.06	5 - 20	Comfort for service personnel during unoccupied hours can be achieved by fan cycling or low-speed operation.
Motion-Sensor control of ventilation	N, R. Most applicable to bathrooms in commercial buildings.	Assume motion-sensor causes an additional 4 - 10 hours of shut-off per day, on average.	All	17-40%*	0-25%*	0.70*	5 - 20	* - Costs and savings are based on the square footage that is controlled, not on the total building floor area. A building will not realize peak savings unless many bathrooms are independently controlled. Lighting should also be controlled by the motion-sensor. The percentage savings in lighting energy use will similar to the air transport savings.
Energy-efficient motors	N, R. Applicable during new construction or at time of motor failure. Early replacement is sometimes justified.	Assume replacement occurs at time of motor failure. 3 - 8% efficiency improvements are possible.	All	3-11%	3-11%	0.01-0.02	10 - 25	Cost is marginal cost above standard motor. Early replacement costs will be significantly greater. Efficiency improvements are greatest for small motors. See Chapter 4 for more details.

* Base case air transport use varies from 2 to 9 kWh/ft^2-yr, and peak demand varies from 0.3 to 3 W/ft^2, depending on building configuration, operating schedule, and climate.

Commercial Technology Summary Sheet

END-USE: Space Cooling

TECHNOLOGY: **High Efficiency Mechanical Cooling Equipment**

GENERAL DESCRIPTION: With today's improved cooling equipment, machines are available with significantly higher COPs than older machines, and higher than existing minimum standards set by ASHRAE and Title 24 (see Table 2-8).

PHYSICAL CHARACTERISTICS: Identical to standard equipment.

APPLICABILITY: All building types and sizes. Since old equipment must be replaced, this technology is less applicable to retrofits, except on equipment failure. No significant variation by climate zone.

ENERGY PERFORMANCE: Savings range from 15-60%, within the same equipment type (see table). Savings are dependent on *in place* equipment COP; ASHRAE 90/75 minimum standards may be typical of existing stock; ASHRAE 90/84 standards may be typical of new construction. Savings resulting from shifts between equipment types may be calculated from the figures given in the table.

COSTS: Incremental costs between standard and high efficiency equipment are small. Total installed costs will vary according to equipment type and size. For example, reciprocating chillers cost $200-$500/ton; centrifugal chillers cost $350-$600/ton. Installation costs are about 10% of equipment costs.

RELIABILITY/LIFETIME: No different from conventional equipment.

UTILITY SYSTEM IMPACTS: Reduction in peak demand (kW), reduction in energy consumption (kWh). Improving COP reduces full load input (kW) to machine, reducing peak load. Since most buildings peak during the summer due to air conditioning load, COP improvement reduces utility peak as well. Gas absorption units eliminate electric demand due to load of electric vapor compression machines (see Gas Absorption Chillers Summary Sheet).

USER IMPACTS: No known negative user impacts of high performance cooling equipment.

PRODUCT AVAILABILITY: Most equipment cited is widely available, although only one or two major manufacturers may market equipment with the "best" COP stated. Stated COPs may not be available over the entire size range.

EXPERIENCE: Several case studies state full load chiller input at 0.6 kW/ton (COP=5.8). Limited monitored data on actual on site performance as compared to manufacturer's specifications.

COMMENTS + CAVEATS: COP ratings are based primarily on manufacturers' claims (at standard rating conditions). Actual performance at full load may be higher or lower, depending on actual operating conditions (specifically evaporator and condenser temperatures). Relative performance between two machines subject to the same conditions in the same building should be similar to the figures stated.

The percentage savings assume similar part-load performance curves among machines. This probably understates the actual savings since newer, high performance machines tend to perform better at part load as well.

At least one chiller manufacturer has a product to upgrade an existing chiller, as opposed to replacing the entire unit (York CodeKit). Replacing units in existing buildings may be prohibitively expensive since buildings are often built around large mechanical equipment.

Table 2-8

Minimum[1] and "Best"[2] Full Load* Efficiencies of Cooling Equipment

TYPE, size range	Condensing Means[3]	Base Line ASHRAE-90 1975	Min.COP: Title 24/85 ASHRAE-90/84	Min.COP: Proposed ASHRAE-90/88	1984 "Best"[2] COP	Energy and Peak Demand* Savings (%), 1984 Best vs.		
						90-75	90-84	90-88
<65,000 Btu/h (5 tons)								
o Electrically Driven Air Conditioners[4]	Air	1.8	2.28[5]	2.34	3.69[8,9]	50	40	40
	Evap/Water	1.8	2.58[5]	2.64	3.37[9]	45	20	20
o Hydronic Heat Pumps Water Source, Cooling Mode	Water	1.8	2.64[5]	2.70	3.1[10]	40	15	10
>65,000 Btu/h (5 tons)								
o Electrically Driven Air Conditioners[6] (up to 134,000 Btu/h)	Air	2.0	2.4	2.49	3.49[9]	40	30	30
	Evap/Water	2.0	2.7	2.78	3.49[9]	40	20	20
o Electrically Driven Water Chillers[6]								
-Centrifugal (100-2000 tons), and Rotary/Screw (100-750 tons)	Air	2.2	2.34	2.40	3.0[11]	25	25	20
	Evap/Water	3.8	4.04	<250 tons 4.04	5.0[12,13]	25	20	20
				>250 tons 4.25	5.6[12,13]	30	30	25
-Reciprocating (50-250 tons)	Air	2.1	2.46	2.55	3.0[14]	30	20	15
	Evap/Water	3.2	3.51	3.64	4.2[15]	25	15	10
-Hydronic Heat Pump, Reciprocating	Water	2.0	2.75	2.87	3.1[10]	55	10	5
o Heat Driven Absorption Units (10-1500 tons)[7]								
-Direct fired: single stage	Evap/Water	0.40	0.48	0.48	0.67[16]	40	30	30
two stage					1.02[17]	60	50	50
-Indirect fired: single stage		0.65	0.68	0.68	0.71[16]	10	5	5
two stage					1.14[17]	40	40	40

* The COPs presented in this table are *full-load* efficiencies, based on ratings at Air-conditioning and Refrigerating Institute (ARI) standard rating conditions. Actual overall cooling performance will depend on actual evaporating and condensing temperatures and part-load equipment performance, along with input requirements to auxiliaries, including chilled water pumps, and condensing pumps and fans. The values in the table should be used for comparison purposes only. The reported savings estimates are approximate because they assume similar part-load performance between units.

NOTES for COP table

1. Title 24 Standards from: California Energy Commission, "Express Terms of Committee Proposed Energy Efficiency Standards," August 2, 1983.

   ASHRAE-90, 1984 and 1988 standards from: Battelle Pacific Northwest Laboratory, "Recommendations for Energy Conservation Standards and Guidelines for New Commercial Buildings, Vol II: Description of the Development Process," October, 1983.

2. "Best" efficiencies from a survey of selected sources, as specified.

3. Air - air cooled condenser. Condensing temperatures determined by ambient dry bulb temperatures.

   Evap/Water - evaporatively or water cooled condenser (typically an open cooling tower). Condensing temperatures determined by ambient wet bulb temperatures.

   ASHRAE-90 (1984) documentation estimates a 1.0 improvement in EER (0.3 improvement in COP) for water/evaporatively cooled equipment over comparable air cooled equipment.

4. Includes:

   Unitary (central) equipment,
   Cooling mode of unitary (central) and packaged terminal heat pumps
   (air and water source),
   Packaged terminal air conditioners (PTAC),
   Room air conditioners.

5. Title 24 standards not specified for equipment less than 65,000 Btu/hr.

6. COPs for electrically driven air conditioners include compressor, evaporator and condenser. COPs for water chilling packages do *not* include chilled water or condenser water pumps, or cooling tower fans. For hydronic heat pumps, COP *does* include supply fan motor efficiency if fan is included as a part of the heat pump.

7. Heat operated equipment COPs can not be directly compared to those for electric equipment, and gas fired equipment will also avoid demand charges. Some heat operated equipment also utilizes waste heat.

   Direct fired equipment is driven by gas or oil; indirect by steam, hot water. COPs are based on BTU output/BTU input; indirect units are based on the heat content of the steam or hot water input to the machine, *not* the BTU's of fuel required to produce the hot water or steam.

   ASHRAE has set standards only for single stage equipment. Two stage equipment can yield a significantly higher COP. Savings for two stage equipment are based on single effect base case.

   There is only one U.S. manufacturer (Trane) of two stage equipment. The high COP units are manufactured in Japan.

   Stated COPs *do not* include input to electric auxiliaries.

8. Only one unit surveyed had a COP this high. Next highest COP = 3.43.

9. From ASHRAE-90 (1984) documentation; survey of available equipment COPs. This document also includes data on the percent of equipment presently manufactured that will require redesign to meet the 1984 and 1988 standards.

10. McQuay Air Conditioning, Water Source Heat Pump, horizontal and vertical units. Equipment range: 9,000 Btu/hr (3/4 ton) at 10.9 EER, 242,000 Btu/hr (20 ton) at 10.0 EER. Units cited in table: 40,500 Btu/hr (3.4 ton) at 10.6 EER (3.1 COP), 204,000 Btu/hr (17 ton) at 10.5 EER (3.1 COP). Source: McQuay pamphlet A/SP 31-29.

11. Dunham-Bush Air Cooled Liquid Chiller with Screw Compressor. Unit cited: ARPCX (50, 60, 80 tons), 3.0 COP based on standard ARI rating condition 95^{O} entering air, 10^{O} chilled water rise, 44^{O} leaving water. Source: Dunham-Bush advertisement in *ASHRAE Product Specification File*, 1982.

12. Trane Centravac, 500 ton unit, compressor 050, with evaporator 2D, condenser 2D, rated at 44° leaving evaporator temp, 95° leaving condenser temp. At same rating conditions: 200 ton, COP 5.0; 315 ton, COP 5.6; 800 ton, COP 5.5; 1200 ton, COP 5.1; 1518 ton, COP 5.5. Source: Trane pamphlet PL-RF-CTV-000-DS-1-983.

13. Where double-bundle heat recovery is employed on centrifugal or screw compressor units, a lower COP is acceptable under ASHRAE-90, provided that the energy recovered exceeds the loss due to lower COP.

    For comparison purposes, the highest double bundle chiller surveyed has a COP of 4.2 (not including any offsetting heat recovery benefit). This is a Carrier Double Bundle Heat Reclaim Chiller. Unit cited: 15.9 tons capacity, 13.4 KW input, 4.2 COP. Range: up to 142.4 tons, 149.1 KW input, 3.4 COP. (Most units within size range have a COP of 3.0.) Source: Energyworks, *Energy Efficient Products and Systems*, p. 6.1, 1983.

14. McQuay Air Conditioning, Reciprocating Air Cooled Chiller, 35.9 ton summer cooling capacity, rated at 10.4 EER (3.0 COP). Available equipment in same category ranges from 12.5 tons (9.9 EER) to 126.7 tons (9.4 EER). Source: McQuay pamphlet A/SP 31-29.

15. McQuay Air Conditioning, Reciprocating Water Cooled Chiller, 26 ton summer cooling capacity, rated at 14.2 EER (4.2 COP). Available equipment in same category ranges from 7.9 tons (13.3 EER) to 127.5 tons (13.4 EER). Source: McQuay pamphlet A/SP 31-29.

16. Yazaki Gas and/or Water fired Single & Double Effect Chiller-Heaters, single effect mode. Gas fired unit is 70 ton unit (rated at 100 tons in double effect mode), requiring fuel input of 1,263,000 Btu/hr input (COP=0.67). Water fired is 70 ton unit (rated at 100 tons in double effect mode), requiring heat input of 1,120,000 Btu/hr input (COP=0.75). These units are modular (7.5, 10, 20 and 30 tons), and provide up to 150 tons total capacity. Source: Yazaki pamphlet 0184-11000.

17. Hitachi Paraflow Chiller-Heaters, two stage absorption units. Can be direct fired with gas, oil, or propane, or can utilize hot exhaust gas or steam (commercial or industrial applications). COP: Direct fired, 1.02 cooling, 0.90 heating; exhaust gas/heat recovery, 1.14 cooling, 0.95 heating. Source: Energyworks, *Energy Efficient Products and Systems*, p. 6.5, 1983.

Commercial Technology Summary Sheet

END-USE: Space Cooling

TECHNOLOGY: **Cooling Equipment Part-load Performance Improvement**

GENERAL DESCRIPTION: Depending on equipment type, cooling system COPs will vary with changes in cooling load over the day/year. In cases where COP degrades significantly at part load, improvements can be made by installing control systems to optimize operating conditions and performance by staging multiple machines or by increasing chilled water temperatures according to building cooling needs.

PHYSICAL CHARACTERISTICS: Control systems: generally a control box, mounted on wall near cooling equipment or on cooling equipment itself. (Space requirements are generally *not* a problem.)

APPLICABILITY: Part-load improvement is applicable to equipment which does *not* cycle on and off to meet part-load needs. (Cycling equipment typically operates at close to full load when it is running. See section 2.3.2, Measures of Equipment Performance.) Optimization strategies are typically applied to chilled water systems, and therefore larger buildings ($>$50,000 ft^2).

ENERGY PERFORMANCE: Depends on degree and duration of part load operation. For buildings with constant cooling load near or equal to full load, the savings are negligible. For buildings with most cooling hours away from design conditions, savings range between 15 and 30%. Savings are *not* dependent on climate zone, except to the extent that climate affects load profile. (Probably not a large variation in California.)

Part load improvement is most effective in buildings which operate most of the year at part load (particularly very low loads). Some examples: 1) Buildings with oversized equipment (due to intentional oversizing in original design or subsequent conservation actions to reduce cooling loads, e.g. delamping); 2) Buildings requiring cooling 24 hours a day (due to internal loads) which have high solar gains, placing most cooling hours away from design conditions.

COSTS: Control system costs decrease with installed cooling capacity. One control system can be connected to more than one chiller, with some modifications.

Costs are extremely variable with type of control selected.

RELIABILITY/LIFETIME: No known early failure problems. Should last as long as equipment being controlled.

UTILITY SYSTEM IMPACTS: No annual peak demand (KW) reduction. Energy consumption (KWH) savings during non-peak periods only.

USER IMPACTS: No known negative user impacts. Control software generally set up by installer, but can often be modified by building staff.

PRODUCT AVAILABILITY: Many chiller and control system manufacturers today market some kind of optimization control. Some examples (not exhaustive): York Turbomodulator, Trane Chiller Optimizer, Pacific Technology, Chillertrol.

EXPERIENCE: Pacific Gas and Electric demonstration project showed 20% savings during winter (low load) months. Annual savings should be less. [1]

COMMENTS + CAVEATS: In VAV systems, optimization strategies may increase fan energy consumption. The savings are highly dependent on cooling load profile, which is extremely building specific.

Notes

1. Pacific Gas and Electric, "Centrifugal Chiller Load Control Demonstration Project," No date or report number.

Commercial Technology Summary Sheet

END-USE: Space Cooling

TECHNOLOGY: **Gas fired absorption chillers**

GENERAL DESCRIPTION: One alternative to a vapor compression refrigeration cycle is an absorption refrigeration cycle. This cycle makes use of two liquids: an absorbent and a refrigerant. The absorbent has a strong affinity for refrigerant when cold and rejects the refrigerant when hot. This allows thermal energy (heat) to be used to produce a cooling effect, rather than electricity input to a compressor system.

Gas fired absorption chillers still have low COPs compared to electric vapor compression machines. These units can also be used to reduce peak electric demands.

Chillers are available in single and two stage models. In two stage equipment, the heat provided in the first stage generator is used in the second stage generator to drive off greater quantities of refrigerant vapor.

APPLICABILITY: Although these units are becoming available in smaller sizes, this technology is generally applied in larger buildings (with chilled water systems). Switching from electric to heat operated equipment is applicable to new construction or replacement on failure in existing buildings.

ENERGY PERFORMANCE: Table 2-9 gives proposed standards for absorption equipment, along with performance ratings of equipment that is presently available. (See also summary table for Full Load COP Improvement.) In order to compare these ratings with similar electric vapor compression machines, prices for different fuels must be compared, or electricity inputs converted to resource energy. For comparison, the "best" electric chiller available has a full load COP of 5.0 to 5.6.

Table 2-9
Absorption Equipment Performance Ratings

	Min.COP: Title 24/85 ASHRAE 90/84	1984 "Best" COP	% Savings "Best" vs. Standards
Direct Fired: single stage	0.48	0.67	30
two stage		1.02	50
Indirect Fired: single stage	0.68	0.71	5
two stage		1.14	40

According to manufacturers data, these units have good part load performance (i.e. part load COP is close to full load COP).

COSTS: Costs per square foot of building space will vary according to the building's peak cooling load. Installation costs will vary according to space constraints.

Estimated installed cost per ton: single stage: \$250-\$500/ton
two stage: \$300-\$700/ton

Larger units (1000 ton) are in the low end of the price range; smaller units (100 ton) are in the high end of the price range. [1]

At peak cooling loads of 350-500 ft^2/ton, costs are \$0.50-\$1.50/ft^2 for single stage equipment, and \$0.60-\$2.00/ft^2 for two stage equipment. [2]

RELIABILITY/LIFETIME: Estimated lifetime of absorption equipment: 20 years. This equipment may be subject to corrosion problems (brine solutions).

UTILITY SYSTEM IMPACTS: Peak demand (kW) and energy consumption (kWh) reductions. Gas consumption will increase.

USER IMPACTS: No known negative user impacts. If the building has a source of waste heat, this may be able to be used as an alternative to fuel consumption.

PRODUCT AVAILABILITY: These chillers are readily available today, although there are only a few distributors in the U.S. (These units are used extensively in Japan.) Equipment available in the U.S. includes that made by Hitachi, Yazaki, and Eshel.

Notes

1. Cost data are from J.E. Christian, "Central Cooling - Absorptive Chillers," Argonne National Laboratory, ANL/CES/TE 77-8, August 1977. Prices have been inflated to 1983 dollars.
2. The figures for peak cooling loads (chiller size) are based on building module simulation results.

Commercial Technology Summary Sheet

END-USE: Space Cooling

TECHNOLOGY: **Double Bundle Chillers**

GENERAL DESCRIPTION: Double Bundle Chillers (or auxiliary condensers) have the option of sending condenser heat to a heat exchanger to recover heat for space or domestic hot water heating rather than to a conventional cooling tower. This saves heating energy when a building requires heat at the same time it requires cooling.

PHYSICAL CHARACTERISTICS: Double bundle chillers are identical to conventional chillers except for an additional condenser "bundle", which allows isolation of the open cooling tower loop from the closed, heating water loop.

APPLICABILITY: Applicable in buildings where there is a significant heating load during chiller operation periods. Typically installed in larger buildings. Buildings using OSA for cooling (economizers) during heating periods may not be suited since chillers will not be running or will be running at low loads, and will be rejecting little heat. (Double bundle chillers which optimize between useful rejected heat and economizer savings are available.) Special cases where double bundle chillers are especially applicable :

1. Computer areas with dedicated cooling systems running 24 hrs/day
2. Buildings without economizers, for example, those with fan coil units.
3. Buildings with large domestic hot water usage (hospitals, hotels)
4. Buildings with hot water storage capability.

Double bundle chillers are not usually good candidates for retrofits, since hot water heating systems are seldom designed for a 10°F temperature difference, and this affects coil and pipe sizing.

ENERGY PERFORMANCE: Typically, the full load COPs of double bundle chillers are less than those of conventional centrifugal chillers (up to 30% lower). [1] Since hot water temperatures are generally higher than typical condensing temperatures, COP decreases. This penalty in chiller consumption must be traded off against avoided heating costs. Table 2-10 summarizes simulation results for a double bundle chiller in Los Angeles. These results show that most of the heat recovered is not usable.

COSTS: Cost premium over conventional chiller dependent on chiller being replaced and double bundle chiller chosen, and can range from \$50-\$200/ton. For Los Angeles building, this results in \$0.10-\$0.50/ft^2. Installation costs will also be higher (about 10%). Operation and maintenance costs (both materials and labor) are usually higher than those for a conventional system.

RELIABILITY/LIFETIME: Similar to conventional chillers.

UTILITY SYSTEM IMPACTS: No reduction in peak demand (kW). Increase in electricity consumption (kWh).

PRODUCT AVAILABILITY: Several large air-conditioning manufacturers have double-bundle chillers as part of their regular product line (e.g. York, Carrier, Trane). Conventional chillers can be modified for heat recovery by installing an additional heat exchanger in the condenser water loop.

EXPERIENCE: In one building in Harrisburg, PA, heat recovery has been used successfully all year round. (However, this particular building has an especially high computer load, as well as cold winter temperatures.) Summer peaks are met with an additional 800 ton conventional chiller (building cooling peak = 2800 tons). In this case, electricity prices are relatively *inexpensive* when compared to fuel costs.

The Wells Fargo Mortgage building in Santa Rosa, California utilizes heat recovery off of the computer cooling system to preheat domestic hot water. According to building engineers, this system can often meet all of the building's hot water needs. In this case, the heat exchanger bypasses an *air-cooled* condenser, possibly resulting in a net improvement in cooling equipment performance.

Notes

1. Freedman, Gilbert M., "Strategy/Criteria for Transition of a Central System from Heat Recovery to Conventional Heating and Refrigerating," *ASHRAE Journal*, December, 1981, pp 27-30. This article summarizes an approach to determining break-even points for heat recovery from large centrifugal refrigeration machines, based on energy costs and equipment performance. In general, the break even point occurs when

$$COP_h = \frac{r_e}{r_h} L\left(1 - \frac{COP}{COP'}\right)$$

COP = cooling COP of the heat recovery machine
COP'= cooling COP of the conventional machine
COP_h= heating COP of the heat recovery machine
r_e = unit cost of electricity
r_h = unit cost of heating ($/therm, $/lb steam)
L = heating value per unit of purchased heat (btu/therm, btu/lb)

Table 2-10
Double Bundle Chiller Simulation Results (Los Angeles) [1]

	No Economizer		With Economizer	
	Base System	Double Bundle	Base System	Double Bundle
COP at Rated Conditions	4.8	4.6	4.8	4.6
Cooling EUI $kWh/ft^2/yr$	3.42	4.34	1.54	1.93
Cooling EUI penalty		(0.92)	-	(0.39)
Useful Recovered Heat ($KBTU/ft^2/yr$) [2]	-	1.97	-	0.07
Wasted Recoverable Heat ($KBTU/ft^2/yr$) [3]	-	4.96	-	2.31

1. Base system is constant volume, variable temperature system.
2. Useful recovered heat is heat recovered that could be used to meet building heating needs. This system has no heat storage capacity, so that heat recovery has to be coincident with heating requirements in order to be "useful". Further, this simulation did not include heating requirements for domestic hot water. Savings will be higher in buildings with higher heating loads during cooling periods, and with water heating requirements. Actual fuel savings will depend on boiler efficiency.
3. "Wasted" recoverable heat is the difference between heat available to be recovered and "useful" recovered heat. This is heat produced by the chiller during non-heating periods.

RAISE EVAPORATOR/LOWER CONDENSING TEMPERATURES

Commercial Technology Summary Sheet

END-USE: Space Cooling

TECHNOLOGY: **Raise evaporator/lower condensing temperatures.**

GENERAL DESCRIPTION: Cooling equipment has a higher COP when evaporating and condensing temperatures are closer together, due to the laws of thermodynamics. These temperatures can be brought closer together by: 1) raising supply air/chilled water temperatures (note caveat, below), 2) lowering condensing temperatures by installing pre-coolers on air cooled condensers, switching from air cooled to evaporatively cooled condensers (cooling towers), or increasing fan speed and/or water flow in cooling towers.

PHYSICAL CHARACTERISTICS: This technique involves implementing control strategies as opposed to installing system hardware (with the exception of pre-coolers). Resetting supply air/chilled water temperatures is discussed in the Cooling Systems section; we discuss here only the second order effects of COP improvement.

APPLICABILITY: Applicable across all building types and climate zones. Typically a retrofit measure for poorly controlled and operated systems.

ENERGY PERFORMANCE: Savings vary according to type of existing cooling system and degrees of reset. (Depending on building and climate specifics, the degrees of reset will vary over the day and the year, making annual savings difficult to estimate.) The addition of pre-coolers to air cooled condensers or increased cooling tower fan and pump consumption will increase HVAC auxiliary electricity consumption (both peak and energy).

Table 2-11
Savings per Degree of Reset

Compressor Type	% Increase in COP per degree of reset	
	Evap. Temp.	Condensing Temp.
Absorption	0.5	0.8
Reciprocating	1.0	1.5
Centrifugal	1.7	0.5
Screw	2.3	2.3

Sources: *DOE-2 Reference Manual,* Part 1, Version 2.1, May 1981. Federal Energy Administration, *Guidelines for Saving Energy in Existing Buildings,* Engineers, Architects and Operators Manual, ECM 2, June, 1975.

COSTS: Variable, dependent on strategy. Difficult to estimate; dependent on building specific parameters.

RELIABILITY/LIFETIME: No known problems with reliability. Lifetime will be the same as that of standard control components (10-20 years) with proper calibration and maintenance.

UTILITY SYSTEM IMPACTS: Supply air/chilled water reset may only be possible during off-peak hours, resulting in energy consumption savings (kWh) only (no peak demand savings). Depending on the method of reducing condensing temperatures, there may be slight reductions in peak demand, but energy consumption savings will be dominant.

USER IMPACTS: As with all control systems, this technique requires regular maintenance, inspection and calibration. There should be no effect on occupant comfort. (In humid areas - unlike California - raising supply air temperatures could result in higher space humidity levels.)

PRODUCT AVAILABILITY: Widely available. Can be installed by knowledgeable building engineer, controls contractor or HVAC contractor.

COMMENTS + CAVEATS: Raising evaporator temperatures require a corresponding increase in fan flow, and therefore, energy consumption. Lowering condensing temperatures may increase HVAC auxiliary consumption (cooling tower pumps and fans, condenser fans).

Commercial Technology Summary Sheet

END-USE: Space Cooling

TECHNOLOGY: **Outside-Air Economizer Cycle**

GENERAL DESCRIPTION: When the outside air is cool enough, it can be brought into the space to help meet cooling loads instead of mechanically cooling interior air. Dry bulb economizers include outside and interior air temperature sensors, damper motors, motor controls, and (depending on installation) dampers (see section 2.3.3). Economizer cycles are required on all new commercial buildings by Title 24 and ASHRAE 90 standards. This project has not analyzed savings for enthalpy control on economizer cycles.

PHYSICAL CHARACTERISTICS: For smaller systems (package units), economizers can be bought "off the shelf." For larger applications, the controls and dampers are custom designed. Generally, one economizer control system will be required for each separate air distribution system.

APPLICABILITY: Most applicable to temperate climates (e.g. San Francisco Bay Area). Savings will be much smaller in extremely hot or humid areas. Also not applicable to spaces requiring 100% outside air for ventilation purposes (unless space is over ventilated). Applicable to all building types, new, retrofits, and renovations. There are some cases where economizers cannot be installed because there is not enough space to install an outside air damper large enough to bring in 100% outside air. It may not be possible to retrofit some package units with economizers (see Caveats).

ENERGY PERFORMANCE:

See Table 2-12, along with plots of monthly energy usage in Equipment Documentation section (2.3.3). These results are based on DOE-2 simulations for office building module (see Appendix 2-A).

Percentage savings will be higher in buildings 1) in mild climate zones, 2) with systems which reset supply air temperatures, 3) with lower internal loads or large glass areas, and 4) with higher minimum supply air temperatures.

COSTS: Cost per ton of peak cooling capacity or square foot of building space decreases quickly with cooling system size and building size. Costs are highly variable in larger buildings due to variations in system configuration.

Costs per ton:	5-10 tons:	\$75-\$175/ton
(of peak cooling cap.)	15-20 tons:	\$50-\$75/ton
	25-100 tons:	\$25-\$50/ton
Costs per ft^2:	5-10 tons:	\$0.15-\$0.50/ft^2
(based on 350-500 ft^2/ton,	15-20 tons:	\$0.10-\$0.20/ft^2
results from module)	25-100 tons:	\$0.05-\$0.15/ft^2

RELIABILITY/LIFETIME: Dampers, motors, and sensors can be damaged or broken. Unless the unit is inspected, there is no obvious evidence of economizer malfunction (except increase in energy bill). Requires frequent checks for proper operation. Enthalpy controls have a history of premature failure. (Due to these problems, and generally low humidity in Calif. - making extra savings small - enthalpy controls have not been considered here in depth.)

UTILITY SYSTEM IMPACTS: Energy consumption savings (kWh) only. No reduction in peak demand (kW). (Peak occurs on warmest days, when economizer will not be operating.) There may be reductions in peak during cooler months (Oct-April). These reductions will not coincide with utility system or building annual peak.

USER IMPACTS: May increase maintenance requirements (as noted).

PRODUCT AVAILABILITY: Widely available, many installations, state and nation wide. Most HVAC contractors can install as a retrofit or new construction. Required by California Title 24.

COMMENTS + CAVEATS: Not suitable for areas where precise humidity control is required. Savings will vary according to building hours, external and internal loads, and supply air temperatures.

Economizers may not be suited for retrofits of package units. Compressors in package units may burn out unless some type of protection is provided (low lock-out temperature).

Table 2-12

System Configuration and Climate Variations - Dry Bulb Economizer

BUILDING/SYSTEM CONFIGURATION [1]	PERCENT SAVINGS WITH ECONOMIZER [2]		
	Los Angeles	San Francisco	Fresno
2.7 w/ft^2 lighting			
Supply air min = 55^{O} Economizer lockout = 72^{O}	55%	77%	42%
Supply air min = 55^{O} Economizer lockout = 68^{O}	50%	74%	39%
Supply air min = 60^{O} Economizer lockout = 72^{O}	61%	77%	44%
1.7 w/ft^2 lighting			
Supply air min = 55^{O} Economizer lockout = 72^{O}	60%	-	-

1. All systems are constant volume, variable temperature systems. Savings will be considerably less with variable-air-volume systems. Building operates on an 8 AM to 5 PM schedule. (See documentation, sections 2.3.3 and 2.4.3)
2. Percent savings are based on a base case which is same configuration without an economizer. Blank spaces indicate no simulation run. Savings include reductions in chiller, cooling tower pump and fan, and chilled water circulation pump consumption.

Commercial Technology Summary Sheet

END-USE: Space Cooling

TECHNOLOGY: **Evaporative Cooling**: Direct, Indirect and combination systems.

GENERAL DESCRIPTION: An evaporative cooling process removes heat by evaporating water. An air stream can be cooled if some of its heat is used to evaporate water (sensible heat exchanged for latent heat). The cooling potential of this process is limited by the water content of the air stream; the closer the stream is to saturation, the less the potential for increasing the latent heat content of the air stream. As a result, evaporative cooling techniques are most suited to warm, dry climate zones. Essentially all areas of California can make use of evaporative cooling during some part of the cooling season (which is year round for most commercial buildings).

Since evaporative cooling systems require 100% outside air intake capability, systems will (should) be set up with economizer controls. All savings figures are savings above those resulting from economizer control alone. Further, any building not suited for economizer control will generally not be suited for evaporative cooling. Buildings requiring 100% outside air at all times are good targets for evaporative cooling, due to savings at high ambient temperatures.

PHYSICAL CHARACTERISTICS:

There are three basic types of evaporative cooling systems for commercial buildings:

1. *Direct:* The air stream is brought in direct contact with water (from sprayers, or by passing the air through a wetted media). As the air stream uses its heat to evaporate the water, the sensible heat of the stream drops, lowering the dry bulb temperature, but increasing the moisture content of the air (humidity ratio). The most common is the wetted media type. It requires a water pump and water supply or water treatment to prevent scaling and algae buildup.
2. *Indirect:* Using a heat exchanger, the air supplied to the building is sensibly cooled by passing it by a separate stream which has been cooled using the direct process. Although there is a penalty in dry bulb temperature drop due to heat exchange, the building air stream is sensibly cooled only, and the humidity ratio (water content) does not change. The most typical configuration consists of a set of plastic heat exchanger tubes covered with cloth wicks. The building air is sent through the tubes (dry side) while outside air is passed over the tubes, which are sprayed with water. An indirect cooler requires an additional (wet side) fan, and a water pump. Again, some form of water treatment or bleed-off is required to prevent algae build up on the tubes, which decreases heat exchange efficiency.
3. *Combination* (two stage cooler): The building air stream is sensibly cooled through an indirect cooler (reducing dry bulb temperature only), and is then further cooled (and moisture added) with a direct cooler.

APPLICABILITY: Evaporative cooling is applicable to any building which requires cooling during periods when there are low ambient wet bulb temperatures (less than about 65°F), and cooling needs can not be met with outside air alone (economizer). Direct coolers are not suitable for spaces requiring strict humidity control, unless some kind of humidity controller is installed as well. Since this strategy saves more energy during hours when the economizer can not meet the cooling load, more energy is saved in hotter areas, such as Fresno and Sacramento. This strategy is applicable to all commercial building types which require cooling.

ENERGY PERFORMANCE:

Equipment performance is based on the wet bulb depression ($T_{wb} - T_{db}$) of the entering air stream, and the resulting drop in dry bulb temperature in the supply air stream. For example: outside air conditions of 80°F DB, 60°F WB = 20° depression. If the temperature of supply air drops 15° after passing through the cooler, the efficiency of the cooler is 75%.

Equipment performance:

Direct:	Rated performance range:	single spray type	50-80%
		double spray type	80-90%
		wetted media type	85-95%
	Measured performance: (wetted media type, one case)		82-100%
Indirect:	Rated performance range:	cloth wick type	60-65%
	Measured performance: (based on two demonstration projects)		33-100%

Note: Measured efficiencies greater than rated can occur, if the city water temperatures are lower than the ambient air wet bulb. This can happen in systems that do not recirculate water within the system, but always bring in new water to prevent scale and algae build up. Recirculating systems will reach an equilibrium with the ambient wet bulb temperature.

Energy performance is determined by the sensible heat removed from the air stream, and the energy required to run the cooler fans (if any) and pumps. Since equipment auxiliaries run continuously during operating periods, cooler consumption is independent of the load met; the same amount of energy is consumed if the system lowers the dry bulb temperature 5° or 15°.

Sensible heat removed = Equip. Eff. x Wet Bulb Depr. x 1.08 x CFM

Passing air through an indirect or direct evaporative cooler increases the static pressure drop of the system; this increase requires greater fan power consumption whether or not the evaporative coolers are operating (when the system is drawing 100% OSA). Reductions in mechanical cooling consumption must be traded off against increases in consumption due to the operation of evaporative cooling auxiliaries.

Energy performance: See Table 2-13. These savings figures are based on DOE-2 building module simulations, with a direct cooler efficiency of 0.9, and an indirect cooler efficiency of 0.6.

The savings stated for the indirect and combination systems are based on 100% outside air during all evaporative cooling operating hours. Generally, it is prohibitively expensive to install the ductwork needed to send return air through an indirect cooler, due to the surface area of the cooler intake. However, if such control was possible, the savings would be considerably higher, especially in warmer areas.

COSTS: Installed costs vary according to building specific parameters, such as available space, plumbing requirements, type of water treatment required, as well as unit size selected. Indirect units generally come in modular form, and are selected on the basis of size vs. static pressure drop. (For the same capacity, units with less static pressure drop are larger, and are more expensive.)

Generally, installed costs range between $0.50 and $1.10 per cfm. At about 1 cfm/ft^2, this translates to $0.50-$1.10 per square foot.

Evaporative cooling systems may, in some cases, cost as much as conventional refrigeration cooling systems. Having both capabilities can nearly double the cost of central plant equipment.

RELIABILITY/LIFETIME: The wetted media (in both direct and indirect) is one of the most likely parts of the system to fail (wear out). However, it can be replaced without replacing other parts of the system as well. One manufacturer of a direct cooler recommends replacement every cooling season. Duct work and controls should last as long as standard equipment.

Decreased performance or failure may also occur due to water treatment problems and/or algae build up on wet surfaces. This build up can be prevented with chemical treatment and/or frequent flushing of the system with fresh water. Tradeoffs between water and chemical costs and energy savings must be made, and vary from case to case.

UTILITY SYSTEM IMPACTS: In general, evaporative cooling systems reduce energy consumption (kWh) during cooling periods but not peak power demands (kW). Mild climates (like San Francisco) are an exception to this; on the warmest days, wet bulb temperatures are low enough to provide a benificial evaporative cooling effect. In all climate zones, peak demands are reduced in cooler months (winter), but do not correspond to the utility system peak.

USER IMPACTS: Reductions in monthly peak during milder months. Reductions in energy consumption. Increases in water consumption due to evaporation and due to bleed-off (if used for water treatment). Requires operator attention to water treatment needs, and to scale and algae build up. Direct evaporative coolers add moisture to the air stream, and, under certain conditions, can cause uncomfortably high humidity levels.

PRODUCT AVAILABILITY: Several U.S. manufacturers today, including Vari-Cool, Tradewinds, and others.

EXPERIENCE: Many installations in California, especially in the San Joaquin Valley. One example (Wells Fargo Mortgage, Santa Rosa) has an indirect/direct system designed to meet cooling needs except on extremely warm days. In actual practice, the system has had some problems (now being repaired) with malfunctioning water treatment systems and algae buildup (especially on indirect units). It is estimated that the system saves $4,000/yr in chemical treatment costs by consuming an extra $400 in water bleed off.

COMMENTS + CAVEATS:

Data limitations: water treatment and water consumption costs; details on equipment lifetime and reliability.

Special requirements: protection from ultraviolet rays to prevent algae buildup.

Indoor air quality may be affected; bacteria in the air stream due to added moisture may carry diseases.

References:

1. ASHRAE *Systems*, Chapter 39, "Evaporative Air Cooling," 1980, pp 39.1-39.6.
2. Leon Dombroski and William I. Nelson, "Two-stage Evaporative Cooling," *Heating/Piping/Air Conditioning*, May 1984, pp 87-92.
3. Neil Eskra, "Indirect/Direct Evaporative Cooling Systems," *ASHRAE Journal*, May 1980, pp 21-25.
4. J.A. Nation, "Evaporative Cooling in Nontraditional Climates," ASHRAE *Transactions*, Vol. 90, Pt. 1, 1984.
5. Pacific Gas and Electric Company, "Effectiveness of Indirect/Direct Evaporative Cooling," May 1982, and "Indirect Evaporative Precooling in Constant Volume, Return Air HVAC System," no date. (Demonstration projects)
6. Richard G. Supple, "Evaporative Cooling for Comfort," *ASHRAE Journal*, August 1982, pp 36-42.
7. "Evaporative Cooling for Energy Conservation," *Heating/Piping/Air Conditioning*, September 1983, pp 111-118.

Table 2-13

Evaporative Cooling Performance and Energy Savings [1]

System		LA	SF	Sacto
Base [2]	Overall COP	3.1	2.8	3.8
	W/ft^2, peak	2.0	1.7	2.2
	Cooling EUI, kWh/ft^2	1.6	0.7	2.3
Direct [3]	Overall COP	4.3	7.3	4.9
	W/ft^2, peak	2.0	1.5	2.4
	Cooling EUI, kWh/ft^2	1.1	0.3	1.8
	Peak Savings: %	0%	10%	-10%
	Energy Savings: %	30%	55%	20%
Indirect [4]	Overall COP	3.0	3.4	4.0
	W/ft^2, peak	2.0	1.6	2.2
	Cooling EUI, kWh/ft^2	1.5	0.5	2.1
	Peak Savings: %	0%	5%	0%
	Energy Savings: %	5%	30%	10%
Indirect/ Direct [3,4]	Overall COP	3.6	4.8	4.8
	W/ft^2, peak	2.2	1.5	2.2
	Cooling EUI, kWh/ft^2	1.3	0.4	1.9
	Peak Savings: %	-10%	10%	0%
	Energy Savings: %	20%	40%	20%

NOTES

1. Savings results are based on DOE-2 building module simulations. Sacramento weather tape used for valley areas; Fresno weather tape not available for use with evaporative cooling simulation tool. All savings figures are savings from the base system. Overall COP includes chiller plant consumption (including cooling tower) as well as evaporative cooler energy usage. This also *includes* resulting increase in fan consumption. (Actual COPs with evaporative cooling will be somewhat higher than those stated, with a corresponding increase in fan consumption. The same is true for cooling EUIs and savings figures.) Peak kW/ft^2 is cooling peak.
2. Base system is a constant volume, variable temperature central system with reheat, with economizer control.
3. Direct system has a direct cooler performance of 0.9, and auxiliary input of 0.00025 kW/cfm. This input factor includes increased fan consumption due to increase in fan static pressure drop. Direct cooler locked out at 65° WB.
4. Indirect system is based on direct cooler performance of 0.6, and auxiliary input of 0.00049 kW/cfm. This input factor includes increased fan consumption due to increase in fan static pressure drop. Indirect cooler locked out at 65° WB.

Commercial Technology Summary Sheet

END-USE: Space Cooling

TECHNOLOGY: **Use of the cooling tower to chill water** (also called Strainer Cycle, Thermo Cycle, Injection Cooling).

GENERAL DESCRIPTION: During cooler months and/or nighttime operation, cooling towers can produce water cold enough to be used in the building chilled water loop. In general, cooling towers consume 80% less electricity than conventional chillers per ton of cooling effect.

PHYSICAL CHARACTERISTICS: Tower cooling systems require piping and automatic valves to connect the chilled water system to the cooling tower system. If the tower water is injected directly into the chilled water circuit, a filter can be installed to keep cooling tower water impurities from entering the chilled water loop (strainer cycle). Alternatively, a heat exchanger is installed between the tower water and the chilled water (thermo cycle).

APPLICABILITY: This technology is applicable only to buildings with cooling towers (medium to large size buildings : large offices, large retail, hotels, hospitals, etc.) Applicable for new construction or retrofit. This technology is not effective if the building already has or can install economizer controls.

ENERGY PERFORMANCE:

Table 2-14

Strainer cycle performance and energy savings

(Los Angeles)

System configuration	% Savings from base case
Strainer cycle only	2%
Economizer cycle only	55%

Note: Savings are based on DOE-2 building module simulations. Base case is constant volume, variable temperature system without economizer. Strainer cycle savings will be higher in buildings: 1) with high nighttime and winter cooling requirements, 2) in drier climates, such as the Central Valley.

UTILITY SYSTEM IMPACTS: Energy consumption savings only; no peak demand savings.

USER IMPACTS: Tower cooling system require frequent tower inspections, adjustments and cleaning. In some cases, cooling tower freeze protection is required (not a significant danger in California).

PRODUCT AVAILABILITY: Most major HVAC contractors can install this in new construction or as a retrofit. Some manufacturers specialize in tower cooling (e.g., Natkin Service Co.)

EXPERIENCE: Most successful installations are found in the Southwest, especially Colorado. One building in New Jersey (Park Plaza) planned to run an injection cooling system, estimating 0.5 kwh/ft^2 in savings. However, the system has *never been run* due to control problems (building engineers found manual controls difficult and inconvenient to operate).

COMMENTS + CAVEATS:

Tower cooling should not be considered if economizer control is feasible and supply air temperatures are reset during off-peak seasons. With reset, the economizer will be able to meet almost all of the cooling load during off-peak seasons. Problems may develop over time with filter or heat exchanger fouling due to water impurities.

Commercial Technology Summary Sheet

END-USE: Space Cooling

TECHNOLOGY: **Thermal Storage Strategies for Off-Peak Cooling**

GENERAL DESCRIPTION: Four different off-peak cooling strategies have been examined for this project:

1. Ice storage,
2. Water storage,
3. Storage in thermal mass,
4. Storage in other phase change materials.

This summary sheet covers the demand and energy shifts that can result from the use of any of the storage technologies. These shifts are determined by size of storage capacity, building load profile, and rate structure, and are independent of the storage media itself. Each of the technologies differ only in the method and materials used for storage. Characteristics and costs of each of these techniques are covered in individual summary sheets (following). Considerably more emphasis has been placed on ice and chilled water storage, since these are the most frequently installed and most cost-effective in commercial buildings today.

PHYSICAL CHARACTERISTICS: See the summary sheets for each storage method.

APPLICABILITY: Applicable to both new and retrofit (with some exceptions, as noted). In general, storage systems will be more suited to new construction, because of first cost reductions in cooling plant equipment, and the ability to design storage for the building at the outset.

ENERGY PERFORMANCE: The ability of a storage system to shift demand and energy consumption from peak to off peak periods depends a great deal on the load profile of the particular building.

Peak demand reductions (in absolute terms) are determined by the building cooling load profile, which depends on individual building configuration and climate characteristics. *Full* storage will shift close to 100% of cooling equipment demand (except for chilled water circulating pumps). *Partial* storage can shift 100% of demand during off-peak months, and 50-70% during the peak month (ice or chilled water system).

Table 2-15 summarizes results for two different storage strategies, based on DOE-2 simulations for the building module. See the cooling equipment documentation (section 2.3.4) for further discussion of these equipment alternatives. To summarize, the following ranges of peak and energy savings are possible:

Annual peak demand shifted off-peak: 40-100%

Energy consumption shifted off-peak: 50-100%

COMMENTS + CAVEATS: The use of an economizer significantly impacts year-round peak and energy shifting potential. Although annual peak demand and energy consumption for cooling will generally occur on days when the economizer is not in use, monthly cooling loads during cooler months may be met almost entirely by the economizer (see economizer summary sheet). The storage system can not shift any load that is not there to be shifted. System cost effectiveness must be based on cooling needs throughout the year, not just on cooling needs for the peak day.

Table 2-15

Shifts in Demand and Energy Consumption[1]
Full [2] and Partial [3] Thermal Storage

	LOS ANGELES [4]		SAN FRANCISCO [5]		FRESNO [6]	
	Full	Partial	Full	Partial	Full	Partial
Storage Capacity (ton-hrs/1000 ft^2)	23	11	18	10	27	13
Chiller Capacity (tons/1000 ft^2)	1.9	0.9	1.6	0.6	2.2	1.3
Potential Reduction in Chiller Capacity (tons/1000 ft^2)	0.6	1.6	0.6	1.6	0.6	1.5
Peak Shifted [7] (annual peak, W/ft^2)	2.0	1.1	1.8	1.2	2.8	1.6
Energy Shifted [8] (kWh/ft^2/yr)						
With Economizer	1.6	N/A	0.8	N/A	3.4	N/A
Without Economizer	4.2		3.7		5.8	

Notes

1. All figures in this table are based on results from DOE-2 simulations of the building module with a constant volume, variable temperature system. Reductions will change according to building operating schedule, internal loads, and HVAC system type. See the documentation (2.3.4) for details on how these variations will affect the savings. (See Appendix 2-A for more detail on the module.) All systems are sized to meet the peak cooling load.
2. Full storage assumes that all of the cooling load (except circulation pumps) is met off peak, and that cooling equipment can not run more than 12 hours per day.
3. Partial storage assumes that the peak load is met by running the equipment continuously (24 hrs/day) and that coincident cooling loads do not require storage capacity.
4. Los Angeles: Peak cooling load = 40 tons = 2.5 tons/1000 ft^2.
5. San Francisco: Peak cooling load = 35 tons = 2.2 tons/1000 ft^2.
6. Fresno: Peak cooling load = 45 tons = 2.8 tons/1000 ft^2.

7. "Peak Shifted" is based on the peak demand shifted off peak for the peak cooling day of the year. For the other months, shifted peak will be less, and may even be zero if the building has an economizer.

8. "Energy Shifted" includes both peak and partial peak consumption. For the module, about 60% of cooling occurs between 12 PM and 6 PM, on the peak day. The energy shifted off-peak for partial storage will be somewhat less than that for full storage. It was not possible to determine how much less from the building module runs that were done. (More data on variations in load profile by month are needed.)

Commercial Technology Summary Sheet

END-USE: Space Cooling

TECHNOLOGY: **Off-Peak Ice Storage**

GENERAL DESCRIPTION: Ice storage can be used to shift peak cooling loads to off-peak periods by running equipment at night, making and storing ice, and using it the next day to meet building cooling requirements. The major advantages of ice over other storage media include smaller tank size due to the high latent heat content of ice, low evaporator/chilled water temperatures which can allow for smaller fan size and lower air flows, and lower pumping and piping costs since ice storage utilizes direct expansion coils. Disadvantages include lower cooling plant efficiencies due to low evaporator temperatures, sizing limitations due to requirement for direct expansion refrigeration equipment, and typically higher installed costs per ton-hour of storage.

Costs and savings of storage are determined by system sizing (full or partial storage), building cooling load profile, and electric rate schedule. Tables 2-16 and 2-17 summarize the main differences between ice/water and full/partial storage. (See section 2.3.4 for a more detailed analysis of how these factors affect system operation and cost.)

PHYSICAL CHARACTERISTICS: Ice storage tanks (also called ice makers, banks, or builders) are available in several different configurations. Tank size is about 2-4 cubic feet per ton-hour of storage, and tank weight is about 15-30 pounds per ton-hour.

The most common type is a water tank with refrigerant coils running through it. The coils run at about 26-28°F; ice builds up around the coils. When needed, the chilled water is drawn out of the tank at about 32°F. [1]

A second type of ice builder freezes all the water in the tank, using a counter flow, spiral-wound heat exchanger. Water is then sent through the ice in order to chill water to meet daily building requirements. Manufacturers claim that this type of ice builder is more efficient than the standard builder (above), since the standard builder must overcome the insulating effect of the ice on the freon tubes in order to build more ice. (Additionally, ice thickness controls are not required.) These spiral builders are available in modular sizes (36, 54, 100 ton-hours) and can be located indoors or outdoors. [2]

A third type of ice storage system makes ice (crushed or in chunk form) and transfers it into bins. Water is circulated through the bins as needed in order to meet building cooling loads. [3]

APPLICABILITY: Ice storage systems are applicable to new construction and retrofit projects. Weight of the storage system may prevent rooftop installation. New construction installations benefit from decreased first costs for cooling equipment (chiller, cooling tower). Retrofit projects may have space constraints. Buildings that are expanding can use storage so that cooling capacity does not have to be added. Typically, ice storage systems are installed in larger buildings, since a chilled water system is required, and tanks are not available in smaller sizes. However, compressor sizes are limited. [4]

ENERGY PERFORMANCE: Due to the heat of fusion of water, ice at 32°F stores 144 Btu/lb. With a return chilled water temperature of 55°F, one pound of ice can store about 170 Btus. At 12,000 Btu/ton-hour,

$$1000 \text{ lb ice storage} = 14 \text{ ton-hours}$$

Generally, not all of the water in the tank will be frozen, so the storage capacity of the tank as a whole will be somewhat lower. See the summary sheet "Thermal Storage for Off-peak Cooling" for estimates of how this storage capacity can be used to shift energy and peak demand for cooling off-peak.

All ice storage systems must pay the penalty of operating at evaporating temperatures lower than those in conventional systems. This drop (usually 10-15°F) decreases cooling equipment performance (COP). Since equipment runs at night, condensing temperatures are lower as well, and tend to offset this penalty. Due to heat transfer losses in the tanks, ice storage systems can not be expected to use less energy than a conventional system (although the energy will be shifted off-peak).

COSTS: Ice storage system costs vary according to size, location of tank relative to refrigeration equipment, and site-specific constraints. For new construction and expansion projects, storage costs can be somewhat offset by decreased first costs for chilling equipment.

Costs per ton-hour of storage: $50 - $150/ton-hour [5]

RELIABILITY/LIFETIME: Ice storage systems present reliability problems if operation is dependent on an ice thickness sensor. Pipe coils within the tank should be coated or some form of water treatment used to prevent pipe corrosion. Under normal conditions, tanks will last 20-30 years. If pipe coils do develop leaks, they can be repaired without replacing the entire tank.

UTILITY SYSTEM IMPACTS: Energy consumption (kWh) and demand (kW) shifted off-peak.

USER IMPACTS: No known negative user impacts. Storage systems will require more maintenance and general attention than conventional systems. If the chilling system is down-sized due to storage capacity, a failure in storage operation (e.g. due to sensor malfunction) will result in lack of cooling capacity to meet building needs (on peak days).

PRODUCT AVAILABILITY: Several manufacturers market ice storage systems, including Caloskills, Baltimore Air Coil, Chester-Jensen Co., Process Products, National Integrated Systems, and CALMAC Co.

EXPERIENCE: See Table 2-18, "Overview of Off-peak Cold Storage Case Studies," for a summary of ice storage experience in California and other areas.

COMMENTS + CAVEATS: Control strategies are very important with ice storage systems; it is important not to overcharge the tanks with ice. This is especially true in tanks where ice is built up around refrigerant tubes; the more ice there is, the less efficient it is to produce more.

Notes

1. An example of this type of system is an ice storage installation at the Union Oil Co., in Brea, California. The installation has 11 100,000 pound ice storage tanks, each 50 ft by 10 ft by 10 ft. At a cost of $600,000 (mostly for the tanks themselves), the system serves 250,000 ft^2 of floor space. ($45/ton-hr, $2.40/$ft^2$). This case study is from "Night Cooling Melts Electric Costs," *Building Design and Construction,* February, 1983, pp 60-63.
2. Costs for this type of builder are about $60/ton-hour, installed. See "An Introduction to Ice Bank Stored Cooling Systems for Commercial Air Conditioning Applications," Calmac Manufacturing Corp., Englewood, New Jersey, no date.
3. Costs for this type of system range from $50/ton-hr (larger systems) to $150/ton-hr (smaller systems). See "Thermal Energy Storage Systems for Cooling," Potomac Electric Power Company, Washington, D.C., 1983.
4. Since ice storage refrigeration compressors are usually confined to the reciprocating type (or screw), the largest buildings must use multiple compressors. Centrifugal chillers would have to be customized to handle brine and would operate at low COPs.
5. See the two utility publications, "Thermal Energy Storage, Inducement Program for Commercial Space Cooling," San Diego Gas and Electric Company, April, 1984, and "A Guide for Off-Peak Cooling of Buildings," Southern California Edison Company," for cost information in addition to that cited above.

Commercial Technology Summary Sheet

END-USE: Space Cooling

TECHNOLOGY: **Off-Peak Chilled Water Storage**

GENERAL DESCRIPTION: As with other types of thermal storage, chilled water storage can shift peak cooling loads to off-peak periods by running equipment at night, storing chilled water, and using it the next day to meet building cooling requirements. The major advantages of chilled water over other storage media include operating temperatures similar to conventional chilled water systems (and therefore comparable efficiencies), a wide range of compressor size availability, and relatively low cost storage tanks (although total costs may not be less due to pump and piping costs). Disadvantages of chilled water systems include high space and weight requirements for tanks, and difficulties with keeping tanks stratified (chilled water supply separate from return water).

Costs and savings of chilled water storage are determined by system sizing (full or partial storage), building cooling load profile, and electric rate schedule. Tables 2-16 and 2-17 summarize the main differences between ice/water and full/partial storage. (See section 2.4.3 for a more detailed analysis of how these factors affect system operation and cost.)

PHYSICAL CHARACTERISTICS: Chilled water storage tanks are relatively simple in design, and differ primarily in how they keep stored chilled water from mixing with warmer return water during building cooling periods. A few stratification methods are summarized below. For a 15-20^{O}F temperature difference, tank size will be about 80-100 gallons/ton-hour, or about 10-13 cubic feet per ton-hour. Tank weight is about 650-850 lb/ton-hour. [1]

Multiple tanks keep return water from mixing with chilled water by filling an empty tank with return water while supplying the building with chilled water from the remaining tanks. Disadvantages of this method include increased tank volume (one tank must always be empty), complicated controls for proper valve operation, and increased maintenance due to the number of valves which must operate properly.

Diaphragms separate cool water from warm in one single tank. Flexible diaphragms move across the tank (either horizontally or vertically) as the volume of chilled water in the tank decreases or increases. Leaks can develop in these membranes; if warm water is above cool with a horizontal diaphragm, natural stratification will minimize leakage.

Nozzle matrix systems rely on the buoyancy effect of warm water over cold (warm water is less dense than cold) to keep water stratified in one tank with no physical barriers. Cold water is withdrawn through a series of nozzles in the bottom of the tank; warm water enters the top of the tank through another series of nozzles. The nozzles keep turbulence (and mixing) in the tank to a minimum. (25% blending with this system is possible, meaning that tanks would have to be oversized by 25%.)

APPLICABILITY: Chilled water systems may be better suited to retrofit applications since existing refrigeration equipment (chillers) can often be used. (Ice systems require direct expansion coils.) However, chilled water systems take up 2 to 4 times the space, which can be a constraint in retrofit applications. [2]

ENERGY PERFORMANCE: Chilled water storage tanks store 15 - 20 Btus per pound. At 12,000 Btu/ton-hour,

1000 lb chilled water storage = 1.3 - 1.7 ton-hours

See the summary sheet, Thermal Storage for Off-Peak Cooling," for estimates of how this capacity can be used to shift energy and power demand for cooling off-peak.

Chilled water storage systems do not have to pay the efficiency penalty that ice systems do for low evaporating temperatures. Energy consumption may, in fact, decrease due to lower condensing temperatures during nighttime equipment operation, and operation at high part-load ratios. Some energy penalty will be paid in tank and piping losses and in energy used to cool that portion of the tank that is oversized to compensate for stratification losses.

COSTS: Chilled water storage system cost varies according to size, location of tank relative to refrigeration equipment, and site-specific constraints. For new construction and expansion projects, storage costs can be somewhat offset by decreased first costs for chilling equipment. The greatest portion of system cost goes toward the tank itself, with large, concrete tanks being the least expensive per gallon, and smaller, steel tanks being the most expensive. [3]

Costs per gallon of storage (tank only):	$0.25 - $1.00/gallon
Costs per ton-hour of storage:	$25 - $125/ton-hour

RELIABILITY/LIFETIME: Water chilling systems may be subject to maintenance problems, depending on stratification technique. The additional piping, valves, and controls will require regular maintenance. Tank lifetime is approximately 20 years.

UTILITY SYSTEM IMPACTS: Energy consumption (kWh) and demand (kW) shifted off-peak.

USER IMPACTS: No known negative user impacts. Large volumes can be required for storage. Storage systems will require more maintenance and general attention than conventional systems. Some form of water treatment may be advisable. If the chilling system is down sized due to storage capacity, a failure in storage operation (due to poor stratification, etc.) will result in inability to meet building cooling needs (on peak days).

PRODUCT AVAILABILITY: Several manufacturers market chilled water storage systems, including Baltimore Air Coil.

EXPERIENCE: See Table 2-18, "Overview of Off-Peak Cold Storage Case Studies," for a summary of chilled water storage experience in California and other areas.

COMMENTS + CAVEATS: As with other storage strategies, project effectiveness will vary depending on control strategy and site-specific impacts.

Notes

1. The following reports have more detailed summaries of different stratification methods:

   San Diego Gas and Electric, "Thermal Energy Storage: Inducement Program for Commercial Space Cooling," April, 1984.

   Southern California Edison, "A Guide for Off-Peak Cooling of Commercial Buildings," September, 1980.

   Electric Power Research Institute, "Thermal Energy Storage: Cooling Commercial Buildings Using Off-Peak Energy," February, 1982.

2. For larger applications, storage tanks are too big to be built to ASME codes for pressure vessels, so tanks must be open to the atmosphere. Since the tanks are large, they must be located at ground level. Pumping energy may be substantial in comparison to normal closed loop pumping, especially in high rise buildings.

3. Cost information is from the sources cited above, as well as the following:

   Potomac Electric Power Company, "Thermal Energy Storage Systems for Cooling," Washington, D.C., no date.

   R.T. Tamblyn, "Thermal Storage Applications," *Heating/Piping/Air Conditioning*, January, 1982, pp 59-70.

Table 2-16

Ice vs. Chilled Water Storage [1]

(to meet identical cooling loads)

Factor	Ice	Chilled Water
Space Requirements	1/3-1/2 of CHW	Large
Power Requirements	higher kW/ton	lower kW/ton
Chilled Water Operating Temps.	32-60°F	45-60°F
Chilled Water Pumping Power	Low	High
Compressor Size Availability	Limited [3]	Various
Maintenance[2]	Medium	High

Notes:

1. See also *Thermal Energy Storage: Cooling Commercial Buildings Using Off-Peak Energy,,* EPRI EM-2244, February 1982. This report also includes several case studies (some with monitored data).
2. Maintenance requirements are site and installation specific. Since ice systems do not have the extra circulating pumps and heat exchangers that water systems do, maintenance costs may be lower for ice systems.
3. Ice storage systems require direct expansion units, which generally require reciprocating compressors. These are not available in very large sizes.

Table 2-17

Comparison of Full vs. Partial Storage

(to meet identical cooling loads)

Factor	Full Storage	Partial Storage
Cooling Plant Cost Avoided	Lower	Higher
Storage Capacity/Cost	Higher	Lower
Peak Power Shifted	Higher	Lower
Energy Consumption	Comparable	Comparable
Applicability	Retrofit	New Construction
Year-round Utilization (Load factor)	Lower	Higher

Table 2-18
Overview of Thermal Storage Case Studies

Building/Location	Storage Type/Size	Ton-hours per 1000 ft^2	Chiller plant avoided tons/1000 ft^2	Peak power avoided(annual) W/ft^2 (COP=3.5)	COSTS	COMMENTS
Union Oil Company Brea, California 420,000 ft^2	ICE STORAGE 1,100,000 lbs 14,000 ton-hrs (Full storage)	33	1.2	4.1	\$45/ton-hr \$1.50/ft^2	Peak load = 1700 tons. This is an unusually high peak load. Avoided chiller cost = \$250/ton, \$0.30/ft^2.
15 story office building Los Angeles, Calif. 300,000 ft^2 (simulation)	WATER STORAGE				\$50/ton-hr	Peak load = 725 tons. Avoided chiller cost = \$350/ton. Results based on simulations.
	Partial - 300,000 gal	13	1.4	1.4	\$0.15/ft^2	
	Full - 470,000 gal	19	1.0	2.4	\$0.21/ft^2	
Wells Fargo Mortgage Co. Santa Rosa, Calif. 110,000 ft^2 (new building)	ICE STORAGE 140,000 lbs	20	N/A	N/A	N/A	Detailed costs not available. Estimated payback - 10-15 yrs. During first year of operation, ice thickness sensors malfunctioning.
Department Store Baltimore, MD 127,000 ft^2 (retrofit)	WATER STORAGE 400,000 gal (Partial)	40	N/A	1.5	\$50/ton-hr \$1.90/ft^2	8 year payback estimated.
Gilbane Building Providence, RI 80,000 ft^2 (new building)	WATER STORAGE 60,000 gal (Partial)	9	0.9	N/A	N/A	Reports an excellent maintenance history.
PEPCO Building Washington, D.C. 48,000 ft^2 (new building)	WATER STORAGE 26,000 (Partial)	7	1.0	N/A	N/A	

Commercial Technology Summary Sheet

END-USE: Space Cooling

TECHNOLOGY: **Phase Change Materials for Cold Storage**

GENERAL DESCRIPTION: Due to the latent heat of fusion, a material in the solid state can store more thermal energy (cold) per unit volume than the same material in the liquid state at the same temperature. Phase change materials for cold storage are materials that freeze at temperatures in the range of conventional air conditioning evaporating temperatures (40-50°F). In theory, these materials can store more cold than the same volume of chilled water at the same temperature, and do not pay the penalty of low equipment efficiency which results from ice building at low evaporating temperatures. There are few commercial buildings using phase change materials for cold storage; most applications are for heat storage.

PHYSICAL CHARACTERISTICS: Some phase change materials are mixtures of water and some other compound; the freezing point of the solution will be higher than the freezing point of water (gas hydrates, for example, are a mixture of water and a refrigerant). One system uses a eutectic salt solution (freezing point = 47°F) encased in plastic bricks. Chilled water from a conventional chiller passes through a tank full of these bricks in order to freeze them. [1]

APPLICABILITY: These systems are applicable to any installation where chilled water or ice storage is applicable. These systems may be particularly well suited to retrofits, since less space is required than a chilled water system, and the conventional chiller can be used. These systems are most applicable to large buildings with chilled water systems.

ENERGY PERFORMANCE: Some phase change materials have heats of fusion of 400 Btu/lb or more, compared to 144 Btu/lb for water.

COSTS: Costs are higher than for the same capacity ice storage system.

RELIABILITY/LIFETIME: These materials may have long term stability problems.

UTILITY SYSTEM IMPACTS: Energy consumption (kWh) and demand (kW) shifted off-peak.

USER IMPACTS: No known negative user impacts. Phase change material should be non-toxic.

PRODUCT AVAILABILITY: There are very few manufacturers actively marketing low temperature phase change materials today.

Notes

1. San Diego Gas and Electric, "Thermal Energy Storage: Inducement Program for Commercial Space Cooling," April, 1984. This system is manufactured by Transphase Systems, Inc., Los Angeles, California.

   See also "Proceedings of the DOE Physical and Chemical Energy Storage Annual Contractors' Review Meeting," sponsored by the Department of Energy, various years (1981, 1982, 1983), for an overview of research and development activities in this area.

Commercial Technology Summary Sheet

END-USE: Space Cooling

TECHNOLOGY: **Mass Storage and Night Venting**

GENERAL DESCRIPTION: By exposing structural mass in a building, daytime heat gains (from lights, solar, and people) can be stored until they can be removed by flushing the building with cool nighttime air. Storing some portion of daytime gains will reduce mechanical cooling equipment operation during the day. Removal of the stored heat requires air transport energy consumption. Systems are controlled to vent the building at night when outside temperatures are below interior space temperatures.

PHYSICAL CHARACTERISTICS: Buildings need to be designed with exposed mass (or hollow core slabs). This affects the appearance of interior spaces. Covering mass with carpeting, etc. may affect its ability to store heat gains.

APPLICABILITY: Most applicable to new construction. In some rare instances, extra mass can be added to a building. This strategy will work best in areas with large day-night temperature swings. This technology is not suitable for buildings with nighttime occupancy.

ENERGY PERFORMANCE: Energy performance will depend upon building mass characteristics, and trade-offs with increased fan consumption during venting periods. There is little data available on the actual performance of these systems; most estimates are based on building computer simulations. Table 2-19 summaizes the results from one study [1] which estimated the *maximum* savings potential of night venting in a small and a large office building, based on BLAST simulations. This study assumed that no energy input was required for night venting. These numbers should be used with caution; they are estimates of maximum potential with a great deal of mass in the building. Night fan energy consumption can be quite large. Further, the base case cooling and air transport estimates appear to be low, in comparison with estimates from other sources (see section 2.2).

Table 2-19

Maximum Savings Potential - Night Venting

	Cooling and Air Transport Usage (kWh/ft^2-yr)					
	Seattle		Los Angeles		Fresno	
	Small Office	Large Office	Small Office	Large Office	Small Office	Large Office
Base Case	2.00	2.10	3.93	3.35	4.80	4.63
Night Venting	1.25	0.80	2.18	1.43	3.38	2.94
Reduction	0.75	1.30	1.75	1.92	1.42	1.69
% Change	35%	60%	45%	55%	30%	35%
Night Fan Energy	NOT ESTIMATED					

COSTS: Costs will vary with each application. Since these systems are designed for new buildings, incremental costs are difficult to determine.

RELIABILITY/LIFETIME: Reliability of these systems depend upon the reliability of system controls. There are no particular reliability problems with the equipment itself (mass and fans).

UTILITY SYSTEM IMPACTS: This technology will reduce energy consumption (kWh), and, to some extent, peak cooling demand (kW). Nighttime energy consumption will increase, due to fan power requirements.

USER IMPACTS: Comfort conditions may be affected by lower mean radiant temperatures. This is most likely to be a positive effect; thermostat settings may be able to be raised while maintaining comfort levels. These systems may not be effective if spaces are occupied at night.

PRODUCT AVAILABILITY: Several building designers are incorporating thermal mass and night venting strategies into commercial building designs. Any required equipment or controls are readily available on the market today.

EXPERIENCE: Several buildings in California have incorporated night venting strategies into building design. There is limited data available on the actual performance of these systems. In the Justice Building in Sacramento, a night venting system was installed, but has not been operated successfully. Part of the building is occupied 24 hours a day, and operation of the system was disruptive to building occupants.

COMMENTS + CAVEATS: Performance and savings estimates are based on the coupling of zone air to exposed mass, and this interaction is not well understood. Calculations have been based on ASHRAE convection coefficients; recent research shows that these may be off by as much as a factor of two [1].

Notes

1. See U.S. Department of Energy, "Passive Cooling Technology Assessment: Synthesis Report," LBL-14558 (Draft). June, 1982.

Commercial Technology Summary Sheet

END-USE: Space Cooling

TECHNOLOGY: **Ground and Ground-Water Source Heat Pumps**

GENERAL DESCRIPTION: Ground and ground water source heat pumps use the ground or ground water as a heat sink for rejecting heat from cooling equipment condensers. Since ground or ground water temperatures are often lower than ambient air dry bulb or wet bulb temperatures, cooling plant COPs will be higher than those of equipment using traditional condensing means (air cooled condensers or cooling towers). In general, ground source cooling will be suitable for few building sites.

PHYSICAL CHARACTERISTICS: For ground source heat pumps, heat exchanger pipes are installed about 100 feet below ground. For ground water source heat pumps, water is generally pumped out of one part of the aquifer, used in the building, and then pumped out into a separate well or another part of the aquifer.

APPLICABILITY: Ground source cooling is applicable in areas where 1) the ground is cool enough or there is an accessible aquifer that is cool enough (60-65°F), 2) local zoning ordinances permit digging into the ground to install piping or permit access to the aquifer, and 3) development is low enough so that ground loading of surrounding buildings does not result in subsidence. Large urban areas are not good candidates for ground source cooling.

Buildings which may be suitable for such a system, if they are located in rural areas, include airports, hospitals, schools, and shopping malls, since they often are on large parcels of land covering big enough heat sinks without encroaching on other property. [1]

ENERGY PERFORMANCE: Theoretical performance (based on 60-65°F ground temperatures) would be twice that of conventional systems, resulting in a 50% reduction in both demand and energy consumption. Limited actual performance is available. Extra pumping will be required.

COSTS: Little cost data available. Costs cited below are for units which provide both heating and cooling.

Small commercial (ground and ground water source): [2]

Heat pump equipment:	\$1000-1500/ton
Extra piping:	\$ 800-1000/ton
Total at 350/ft^2/ton:	\$6.00/ft^2
Ground area required:	2500 ft^2/ton

RELIABILITY/LIFETIME: Little long term reliability data available. If problems develop in underground piping, they will probably be very expensive to fix.

UTILITY SYSTEM IMPACTS: Assuming improved performance can be achieved, both energy consumption (kWh) and peak demand (kW) reductions will result.

USER IMPACTS: No known negative user impacts. It is not clear whether maintenance needs will increase or decrease.

PRODUCT AVAILABILITY: Few manufacturers are actively marketing ground cooling systems. Small systems are available as a package, and are manufactured by Megatech Corp., Freidrich Climate Air Conditioning Division, and Carrier Corp. Larger systems are generally custom built.

EXPERIENCE:

American United Life Tower, Indianapolis. 38 stories, 1.3 million ft^2. Using well water at 60-65°F, savings of 60% over conventional system are estimated. (The system is used for both heating and cooling.) Initial building plans required "dewatering" the site; instead, the below-grade aquifer is used as a heat sink during the summer and a heat source during the winter. No cost data available. [3]

Butler Rural Electric Cooperative, Hamilton, Ohio. 6,600 ft^2, 1 story. Four ground water source heat pumps installed for both heating and cooling. Cooling EER = 20 (COP = 5.9) (estimate). Savings estimates: peak demand reduced by 75%, energy reduced by 79%. System cost: \$48,000, \$7.30/ft^2. Estimated cost over and above conventional system: \$15,000, \$2.30/ft^2. [4]

COMMENTS + CAVEATS: Deposits and chemicals in the ground and in aquifers can cause corrosion on heat exchangers.

Notes

1. Greaves, Keith, "Ground Water Cooling System," *Proceedings, Sixth Annual Industrial Energy Conservation Technology Conference and Exhibition,* April 1984.
2. "Ground Source Heat Pumps Seen Cutting Operating Costs," *Energy User News,* May 9, 1983.
3. "Heat Exchangers Used in Energy Efficient Tower," *Heating/Piping/Air Conditioning,* November, 1983.
4. Entry in 1982 ASHRAE Energy Awards Competition, 1982. Figures based on competition entry form.

Commercial Technology Summary Sheet

END-USE: Space Cooling

TECHNOLOGY: **Desiccant Cooling Systems**

GENERAL DESCRIPTION: By passing an air stream through a desiccant material, water is absorbed by the desiccant, and the sensible temperature of the air stream goes up (latent heat exchanged for sensible heat). Under certain conditions, a warmer, *drier* air stream can be evaporatively cooled to a comfortable temperature while the cooler, moister air stream can not. Using the desiccant can eliminate mechanical cooling by allowing for evaporative cooling.

PHYSICAL CHARACTERISTICS: Desiccant system components include a rotary desiccant wheel (dehumidifier), an auxiliary heater and fan for desiccant regeneration. These components are connected in line with the conventional cooling system, so if space is limited, system installation will be difficult and/or expensive.

APPLICABILITY: Desiccant cooling systems are generally not cost effective in California. Desiccant cooling is only applicable in areas where ambient humidity levels rule out effective evaporative cooling (WB>70-75°F) or where extremely low levels of humidity are required inside the space.

Annual hours above 70°F wet bulb [1]:

San Francisco:	0
Los Angeles:	1
Fresno:	8
Sacramento:	34
San Bernardino:	55

Most areas can take better advantage of economizer cycles or direct/indirect evaporative cooling.

ENERGY PERFORMANCE: Desiccant cooling systems are relatively new, and many designs are still in the R&D phase. Performance depends on the tradeoff between energy for sensibly cooling the warmer air stream and the energy required to regenerate the moist desiccant. (The desiccant has to be heated by some source - fuel, recovered heat, solar energy - to drive off absorbed moisture.) The lower the cost of regeneration, the better the overall performance of the entire system.

Research estimates for solar/desiccant system COPs [2-5]:

Current prototypes (field tests):	0.5-0.6
Current design estimates:	1.1-1.2
Future research goal:	1.5
Second-law thermodynamic max:	3.5

COSTS: Since the product is not widely comercially available at this time, current costs are unknown. One GRI study (residential systems) predicts solar/gas systems to be 3.5 to 4 times the cost of a conventional system in 1990, and gas only systems to be roughly comparable to conventional systems. Should desiccant techniques improve in the future, costs will probably drop as well.

RELIABILITY/LIFETIME: Since these systems are not being widely used in commercial buildings at this time, there is no information available on system reliability or lifetime.

UTILITY SYSTEM IMPACTS: If a desiccant cooling system were to be installed and operated effectively, energy consumption (kWh) would be reduced during summer peak periods. In California, peak demand (kW) savings would probably result as well since peak wet bulb temperatures are well within the range of desiccant operation.

USER IMPACTS: Desiccant system users must provide some heat source to regenerate the desiccant, and the cost of this heat is traded off against avoided mechanical cooling costs. If there is a source of free or waste heat on site, such as solar or process heat, desiccant system operation will be more attractive. Similarily, an on-site need for recovered heat (domestic hot water) from the regeneration process could help to justify the system.

PRODUCT AVAILABILITY: Desiccant systems for commercial buildings are not widely available at this time. Industrial systems (primarily for dehumidification) are available. Ongoing research is being conducted by SERI, GRI, Argonne National Labs, Cargocaire Engineering Corp., and others.

EXPERIENCE: Aside from research field tests, little actual installation data available, particularily in California.

COMMENTS + CAVEATS: Climate conditions in California severely limit the potential for desiccant cooling systems, given the high performance and availability of other cooling options (specifically economizers and evaporative cooling). As stated above, desiccant cooling systems are suited to buildings subject to one or all of the following conditions: high ambient humidity, low space humidity requirements, free or waste heat availabilty, and a use for recovered heat.

References

1. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., *ASHRAE Handbook, 1980 Systems*, Atlanta, 1980, pp 39.3-39.5.
2. "SERI Dehumidifier Wheel Promises Cost-Effective Solar Desiccant Cooling," *In Review*, Solar Energy Research Institute, December, 1982.
3. William Anderson, "Desiccant Based Air Conditioning for Commercial Buildings," presented at the 11th Energy Technology Conference, Washington, D.C., April, 1984.
4. Robert A. Macriss, "High COP Rotating Wheel Solid Desiccant System," 9th Energy Technology Conference, Washington, D.C., 1982.
5. Gershon Meckler, "New Technology Achieves Savings Through Solar Cooling," 10th Energy Technology Conference, Washington, D.C., 1983.

Commercial Technology Summary Sheet

END-USE: Space Cooling

TECHNOLOGY: **HVAC System Modifications**

GENERAL DESCRIPTION: The type of HVAC system (e.g. variable-air-volume, dual-duct) and how it is controlled have a large impact on cooling energy use. Modifications to the HVAC system such as resetting supply-air temperature according to the warmest-zone or lowering the minimum stop on VAV terminals can save significant amounts of energy. However, the types of measures applicable to different systems and how much energy they save are strongly dependent on the configuration and control strategy of the initial system. Quantitative analysis is difficult beyond the level of an individual building, and even analysis of a individual building often requires the use of computer simulation tools. The "HVAC Systems" section of the cooling documentation attempts to describe some basic concepts that can be used to determine the energy use impacts of different system configurations. Specific technology summary sheets relating to this area of cooling have not been included.

Commercial Technology Summary Sheet

END-USE: Space Cooling

TECHNOLOGY: **Heat Gain Reductions from Equipment**

GENERAL DESCRIPTION: All energy-using equipment within a building produces heat, which contributes to cooling loads. Energy conservation measures that reduce the energy consumed by this equipment also reduce the heat produced by the equipment; the reduction in heat gain produces cooling savings in addition to the energy saved in the end use served by the equipment.

PHYSICAL CHARACTERISTICS: This summary sheet describes the *interactive* cooling effects of certain energy conservation technologies. The specific characteristics of those technologies are described in other summary sheets.

APPLICABILITY: The interactive cooling effects will occur in all buildings that are mechanically cooled.

ENERGY PERFORMANCE: The cooling savings resulting from equipment heat gain reductions depend on a number of factors. A few important ones are incorporated into Table 2-20. The table gives the amount of cooling savings in kWh for a 1 kWh reduction in equipment energy use. For example, in an Los Angeles office building with unvented lights and an efficient cooling system, a 1 kWh/ft^2-yr reduction in lighting energy use saves 0.10 kWh/ft^2-yr in cooling energy use.

COSTS: Not applicable.

RELIABILITY/LIFETIME: Not applicable.

UTILITY SYSTEM IMPACTS: Reducing heat gain from equipment also reduces peak cooling usage. The formula below calculates the approximate reduction in peak cooling power demand associated with an equipment heat gain reduction.

$$\text{Cooling Peak Reduction in } W/ft^2 = R \; x \; 0.8 \; x \; \frac{1}{COP} \; x \; V$$

where:

R = Reduction in the power usage during the peak demand period for the heat producing piece of equipment, expressed in W/ft^2 of floor area. For example, R would equal 0.5 W/ft^2 for a reduction in lighting power from 2.5 W/ft^2 to 2.0 W/ft^2.

COP = COP (coefficient of performance) of the chiller or air conditioning unit.

V = 1.00, for equipment not directly vented outside.
0.32, for equipment directly vented outside.

Table 2-20

Secondary Cooling Savings for Heat Producing Equipment [1]

(kWh of Cooling Electricity Reduction per
1 kWh of Equipment Electricity Reduction)

Equipment Type	San Francisco		Los Angeles		Fresno	
	Cooling Effic.		Cooling Effic.		Cooling Effic.	
	High	Low	High	Low	High	Low
Unvented Lights and Misc. Unvented Equip.	0.05	0.27	0.10	0.28	0.12	0.38
Lights w/ Heat-Removing Luminaires	0.03	0.26	0.08	0.27	0.09	0.36
Equipment Directly Vented Outside	0.02	0.09	0.03	0.09	0.04	0.12
Air Transport Fans	0.06	0.37	0.13	0.38	0.15	0.40

1. The results are from DOE-2 computer simulations of the office building module. "High" cooling efficiency refers to an air-conditioning system with a COP of 4.0 and an economizer cycle. "Low" cooling efficiency refers to a system with a COP of 2.0 and without an economizer. The heat-removing luminaires divert an amount of heat into the HVAC return air stream equal to 50% of the lighting power. For all equipment types, the 1 kWh electricity reduction is assumed to be spread evenly over the building's annual occupied hours.

Commercial Technology Summary Sheet

END-USE: Space Cooling

TECHNOLOGY: **Venting Heat Gains**

GENERAL DESCRIPTION: If heat gains from equipment can be vented outdoors, they will not add to the cooling load. In direct venting schemes, the air used to pick-up heat from the equipment is exhausted directly outside; exhaust hoods on kitchen appliances are an example of direct outdoor venting. Another venting scheme uses HVAC return air to vent equipment. Part or all of the return air is exhausted outside and carries the heat gain with it. This scheme is most often used with lights; heat-removing luminaires draw HVAC return air past the lamps to collect their heat.

PHYSICAL CHARACTERISTICS: Direct outdoor venting schemes require hoods and ducting to the outdoors. Heat-removal luminaires eliminate the need for return air grilles and do not require more space than a standard luminaire.

APPLICABILITY: Heat-removal luminaires are only practical for new construction or major renovation. They should only be used in clean environments, and the most common type are for fluorescent fixtures. In order to capture significant cooling savings, the cooling system used with heat-removing luminaires should have an ***economizer***. (A larger fraction of return air is exhausted with systems having economizers.) Direct venting systems are practical with concentrated sources of heat gain. (Air temperatures at the equipment greater than 95 °F.) Also, space for ductwork to the outside must be present.

ENERGY PERFORMANCE: The cooling savings from venting systems depend on the amount of heat gain diverted to the outside, the amount of cooling load that would have been created by the heat gain, and how efficiently the cooling load would have been met. Table 2-21 gives the cooling savings from using heat-removing luminaires or direct outside venting systems. The savings are expressed per annual kWh of equipment energy usage. If lights use 5 kWh/ft^2-yr, then using a heat-removing luminaire will save approximately 0.04 x 5 kWh/ft^2-yr = 0.2 kWh/ft^2-yr of ***cooling electricity***. (the 0.04 is from Table 2-21.)

To use the table to calculate savings from venting of natural gas equipment, annual gas usage in Btus first needs to be converted to kWh equivalents by dividing by 3413 Btu/kWh. (Also, the heat loss out the flue should be subtracted out.) This energy use expressed in kWh is then multiplied by the value in Table 2-21.

For direct venting systems, subtract the energy consumption of the fan from the cooling savings. For small ventilation units, fan and motor efficiencies are poor, and fan energy consumption can be as much as 0.03 kWh per kWh of energy used by the equipment being ventilated. (This number can be subtracted directly from the savings figures Table 2-21.) Larger ventilation systems can have fan energy consumption of .01 kWh per kWh of equipment energy use or less. Direct venting systems also induce infiltration of outside air, which has cooling impacts. Since the average temperature of outside air during cooling periods is reasonably close to indoor temperatures for most California climates, we have not quantified this effect. In climates where the introduction of outside air is undesirable, equipment can be ventilated with outside air instead of room air by providing a supply air duct from the outside.

Heat-removing luminaires can affect the energy consumption and performance of the associated lighting systems. The air flow reduces the operating temperature of both lamps and ballasts, which can effect the efficacy and light output of fluorescent lamps. These effects are often positive but depend on the specific situation. Heat-removing luminaires can also increase dirt build-up on lamps, which causes degradation in light output.

Both types of venting systems reduce peak space cooling loads, so allow for reductions in air trasport flow rates. These reductions can result in significant air transport savings.

Table 2-21
Cooling Savings from Venting Systems [1]

(kWh of Cooling Savings per 1 kWh of Annual Equipment Energy Use)

Venting System	San Francisco	Los Angeles	Fresno
Heat-Removing Luminaires	0.01 - 0.03	0.03 - 0.05	0.02 - 0.05
Direct Outside Venting	0.03 - 0.06	0.07 - 0.14	0.08 - 0.16

1. From DOE-2 simulations of the office module. A typical office schedule was used to model equipment usage. The range of savings within each entry is largely due to variation in cooling system efficiency. The heat-removing luminaires are assumed to divert an amount of heat into the HVAC return air stream equal to 50% of the lighting power. The direct venting system is assumed to vent two-thirds of the equipment heat gain; radiative heat transfer keeps one-third in the building space.

COSTS: For new construction, the additional cost of heat-removing luminaires above standard fixtures is about $0.10 - $0.20 per square foot of floor area.

For a direct outside venting scheme, 10 to 20 Watts of heat-producing equipment can be ventilated with one cfm of air. The materials costs for the ventilating system are approximately $0.30/cfm. (estimated from costs of exhaust hood units and ventilators listed in Grainger's catalog.) Total materials costs are $15 - $30 / kW of heat-producing equipment. For a retrofit installation, labor costs can equal equipment costs; labor costs would be less for new construction.

RELIABILITY/LIFETIME: Few reliability problems.

UTILITY SYSTEM IMPACTS: Heat-removing luminaires have only a small impact on peak cooling demands, since the economizer is not operating during this period, and therefore only a small fraction of the lighting gains are being exhausted outside. Direct venting systems do reduce peak cooling demand, since they are exhausting gain during peak periods. An approximate formula for calculating the reduction in the cooling peak is:

$$Cooling\ Peak\ Reduction\ in\ kW = \frac{P\ x\ 0.55}{COP},$$

where,

P = power consumption of the heat-producing equipment being ventilated. (kW)

COP = coefficient of performance of the cooling equipment.

USER IMPACTS: Direct venting systems are often needed for odor removal, so the cooling benefits are an additional positive benefit.

PRODUCT AVAILABILITY: Heat-removing luminaires and equipment for direct venting systems are readily available.

EXPERIENCE: Heat-removing luminaires have caused accelerated dirt deposition on lamps and fixtures in some situations.

Commercial Technology Summary Sheet

END-USE: Space Cooling

TECHNOLOGY: **Roof and Wall Insulation**

GENERAL DESCRIPTION: Insulation can be added to roofs or walls to increase the resistance to heat flow of these building elements. One effect of the insulation is to reduce the amount of heat conducted into the building during hot and sunny periods, so insulation can save cooling energy.

PHYSICAL CHARACTERISTICS: The thermal resistance value (R-value) of insulation is directly related to its thickness. The use of insulation will make walls and roofs thicker unless the insulation just fills empty cavities. Fiberglass and cellulose insulation have R-values of 3 to 4 per inch of thickness. Different types of rigid foam board insulation have R-values from 5 to 8 per inch thickness.

APPLICABILITY: Applicable to both new and retrofit situations. Retrofitting wall insulation can be difficult in many situations. If the wall cavity is uninsulated, holes can be drilled to blow in insulation. More alternatives are available for retrofitting roof insulation. At the time of reroofing, foam board can be installed beneath the roofing membrane. Batts and blow-in insulation can be used with roofs having suspending ceilings.

ENERGY PERFORMANCE: Added insulation can reduce cooling energy use because it reduces the temperature-induced flow of heat into the building during hot periods and reduces the amount of absorbed solar radiation conducted into the building. However, a relatively large amount of cooling occurs in California climate zones during periods when it is cooler outside than inside. If only a small amount of solar radiation is absorbed on a particular exterior building surface, there can be heat *loss* through the surface during these periods, and the surface provides a cooling effect to the building. Additional insulation for this building element will reduce its cooling effect during these periods and therefore cause increased cooling energy use. This implies that insulation is most effective at reducing cooling loads when applied to building elements that absorb large amounts of solar energy during cooling periods. A dark colored horizontal roof is a prime target, whereas a light colored north-facing wall is a poor candidate. However, insulation has heating and peak cooling load benefits that must be considered together in a comprehensive evaluation.

The following formula can be used to estimate cooling savings from insulation of roofs and walls:

$$Cooling\ Savings\ (kWh/yr) = \left(\frac{1}{R_i} - \frac{1}{R_f}\right)\ x\ \frac{A\ x\ D}{COP}$$

where:

R_i = The R-value of the roof or wall before it is insulated. (hr-ft^2-°F/Btu)
R_f = The R-value of the roof or wall after it is insulated. (hr-ft^2-°F/Btu)
A_r = The area of the insulated portion of the roof or wall. (ft^2)
D = Value from Table 2-22. (kWh-hr-°F/Btu-yr). Needed information includes the solar absorptivity of the exterior surface, and whether the building has an economizer or not. (See Table 2-24 in the "Light Colored Roofs and Walls" summary sheet for solar absorptances of various surfaces.)
COP = Coefficient of performance of air conditioning unit.

Table 2-22

D - Values for Determining Cooling Savings from Insulation [1]

(kWh-hr-°F/Btu-yr)

	San Francisco		Los Angeles		Fresno	
	Solar Abs. [2]		Solar Abs.		Solar Abs.	
	0.3	0.7	0.3	0.7	0.3	0.7
Buildings with Economizers:						
Roofs	-1.6	0.1	-4.0	1.4	1.6	13.2
Walls	-2.3	-1.7	-6.6	-4.5	-3.8	0.6
Buildings without Economizers:						
Roofs	-9.3	-1.1	-6.4	2.7	1.1	13.6
Walls	-12.7	-9.0	-10.1	-6.0	-5.3	-0.5

1. Figures derived from simulation of the office building module. Wall area is assumed to be distributed equally on N, S, E, and W faces of the building. The roof is assumed to be horizontal.
2. Typical solar absorptivities are given in Table 2-24.

COSTS: Costs for insulating can be expressed as dollars per unit R-value per square foot of insulated area. Multiplying this figure by the total R-value of the insulation and the total area insulated gives the total cost of the insulation job. For retrofit insulation jobs, blown-in insulation or insulating with rolled in batts costs about \$0.02 - \$0.04 / R-value-ft^2 for roofs. Blown-in insulation for walls costs significantly more because of costs to drill and then refinish walls. Retrofitting batts into walls is not practical except during extensive remodelling. Spray-on fiberglass costs about \$0.05 / R-value-ft^2, and rigid foam board costs \$0.06 - \$0.09 / R-value-ft^2 if applied at the time of reroofing or re-siding. Installed costs for new construction are slightly less. (SOURCE: Insulation contractors in the San Francisco area.)

RELIABILITY/LIFETIME: Most insulation materials have long lifetimes, although blown-in insulation can settle. The impact of settling is greater in walls because top portions of the wall are left uninsulated. For roofs, the R-value is decreased over the entire roof.

UTILITY SYSTEM IMPACTS: Insulating walls and roofs decreases the peak cooling demand. The following formulae estimate the impacts on the peak cooling demand:

Cooling Peak Reduction in kW:

$$For\ Walls = \left(\frac{1}{R_i} - \frac{1}{R_f} \right) x\ A\ x\ \frac{(14 + 19s)\ ^\circ F}{(3413\ Btu/hr\text{-}kW)\ x\ COP}$$

$$For\ Roofs = \left(\frac{1}{R_i} - \frac{1}{R_f} \right) x\ A\ x\ \frac{(14 + 79s)\ ^\circ F}{(3413\ Btu/hr\text{-}kW)\ x\ COP}$$

where variables are defined in the Energy Performance section, except:

s = Solar absorptivity of the exterior surface of the roof or wall.
$(0<s<1)$.

The formula is derived from the ASHRAE Cooling Load Temperature Difference Method presented in the *ASHRAE Handbook, 1981 Fundamentals,* p. 26.11.

USER IMPACTS: In buildings where roofs and walls are initially uninsulated, insulating will noticeably reduce the radiant heating effect from hot walls and roofs during the cooling season.

Commercial Technology Summary Sheet

END-USE: Space Cooling

TECHNOLOGY: **Light Colored Roofs and Walls**

GENERAL DESCRIPTION: Using light colors on the exterior surfaces of roofs and walls reduces the amount of solar radiation absorbed by those surfaces. Heat flow through the roof is reduced thereby decreasing cooling energy use.

PHYSICAL CHARACTERISTICS: For walls, a light-colored paint creates a low solar absorptance. For roofs, a white roof coating gives a low absorptance; some coatings have weatherproofing benefits also. White gravel can also be used as a low absorptance surface for a roof.

APPLICABILITY: This measure is better suited to roofs than walls. Since most commercial roofs are horizontal, their color has little aesthetic impact on the building. Also, roofs receive significantly more solar radiation than walls; a reduction in solar absorptance saves more cooling energy when applied to roofs than to walls.

ENERGY PERFORMANCE: The reduction in cooling energy use depends on the decrease in solar gains absorbed during cooling periods. The formula below estimates cooling savings from use of a light-colored exterior surface. Solar absorptance is defined as the fraction of incident solar radiation absorbed by a surface.

$$Cooling\ Savings\ (kWh/yr) = (s_i - s_f)\ x\ \frac{A\ x\ I}{R\ x\ COP}$$

where:

s_i = Solar absorptance of roof or wall *before* using light color. ($0<s<1$).
See Table 2-24.

s_f = Solar absorptance of roof or wall with light exterior color.
White gravel has a solar absorptance of appx. 0.3, and white elasto-plastic roof coating has an absorptance of appx. 0.2.

A = Area of the roof or wall. (ft^2)

R = R-value of the roof or wall. ($hr\text{-}ft^2\text{-}{}^\circ F/Btu$)

I = Value from Table 2-23. ($kWh\text{-}hr\text{-}{}^\circ F/Btu\text{-}yr$)

COP = Coefficient of performance of air conditioning unit.

Table 2-23

I - Values for Determining Cooling Savings from Light Colors [1]

(kWh-hr-°F/Btu-yr)

	San Francisco	Los Angeles	Fresno
Buildings with Economizers:			
Roofs	4.1	13.6	29.0
Walls	1.6	5.2	11.0
Buildings without Economizers:			
Roofs	20.5	22.7	32.2
Walls	9.3	10.3	12.1

1. Figures are derived from simulation of the office building module. Wall area is assumed to be distributed equally on N, S, E, and W sides of the building. A horizontal roof was assumed.

COSTS: If a roof is scheduled to be gravelled, using a white gravel will have little additional cost. If the roof would not normally be gravelled, the additional cost of covering with white gravel is approximately $0.20 per square foot of roof. (Cost from PG&E application note No. 32-32-83.) A white elasto-plastic roof coating which has sealing and weatherproofing benefits in addition to low solar absorptivity costs $1.25 - $2.00 per square foot of roof. Other white coatings that do not have the weatherproofing benefits cost $0.50 - $0.70 per square foot of roof.

RELIABILITY/LIFETIME: In some environments, dirt and soot will rapidly degrade the solar reflective properties of a light colored roof or wall surface. An increase in absorptivity of 0.1 or 0.2 is likely in dirty environments. During periods without rain, occasional washing may be necessary to maintain low absorptivity.

UTILITY SYSTEM IMPACTS: Peak cooling demand is reduced because of reduced solar absorptance during peak periods. The following formulae estimate the impacts on peak demand:

Cooling Peak Reduction in kW:

$$For\ Roofs = \frac{(s_i - s_f)\ x\ 79\,^{\circ}F\ x\ A}{(3413\ Btu/hr{-}kW)\ x\ R\ x\ COP}$$

$$For\ Walls = \frac{(s_i - s_f)\ x\ 19\,^{\circ}F\ x\ A}{(3413\ Btu/hr{-}kW)\ x\ R\ x\ COP}$$

where the variables are defined in the Energy Performance section.

The formula is derived from the ASHRAE Cooling Load Temperature Difference Method presented in the *ASHRAE Handbook, 1981 Fundamentals*, p. 26.8.

USER IMPACTS: For uninsulated roofs and walls, the reduction in solar absorptance will decrease roof and wall temperatures, and will reduce the radiant heating effect of these surfaces on building occupants.

COMMENTS + CAVEATS: Roof coverings have non-energy impacts that should be considered in a comprehensive analysis. The elasto-plastic coatings seal and weatherproof roofs and can sometimes eliminate the need to reroof. The use of a light colored roof surface also reduces roof temperatures significantly (30 - 40 °F in peak conditions) and can prolong roof life.

Table 2-24
Solar Absorptances

Material	Solar Absorptance	Material	Solar Absorptance
Absbestos Cement		Paints	
White to Red	0.42 - 0.70	Dark (red, brown, green)	0.65 - 0.80
Aged	0.61 - 0.83	Light (yellow,buff)	0.30 - 0.50
		White	0.23 - 0.49
Black, Non-Metallic Surfaces			
Asphalt, Carbon, Slate, Paint, Paper	0.82 - 0.98	Roofing	
		Aluminized	0.40
		Green, Bituminous Felt, Black	0.86 - 0.97
Bricks			
Purple, Blue	0.77 - 0.89	Tiles	
Light Buff, Red	0.50 - 0.77	Concrete, uncolored to black	0.65 - 0.91
White, Cream	0.26 - 0.50		
		Red to Dark Purple	0.43 - 0.81
Granite, Marble, Sand	0.41 - 0.68		
		Wood, smoothly planed	0.78
Gravel, Limestone, Sandstone	0.29 - 0.76		

1. Abstracted from ASHRAE, *Cooling and Heating Load Calculation Manual,* 1979, Table A3.5, p. A3.7.

Commercial Technology Summary Sheet

END-USE: Space Cooling

TECHNOLOGY: **Roof-Spray Cooling**

GENERAL DESCRIPTION: Water is sprayed onto the roof, and the evaporation of that water removes heat from the surface of the roof. Less heat is transferred into the building from the roof, so cooling energy use is reduced. The system usually sprays in an intermittent fashion. The frequency of spraying is controlled by temperature and humidity sensors at the roofs surface. During peak cooling periods, roof-spray cooling can reduce the surface temperature of the roof from 140 °F to 90 °F.

PHYSICAL CHARACTERISTICS: A series of pipes and sprayheads are laid on the roof surface to sprinkle the roof with water.

APPLICABILITY: The technique is most applicable to flat roofs because of aesthetic impacts of the system on a sloped roof, and the need for more sophisticated flow controls to avoid drainage water loss.

ENERGY PERFORMANCE: Roof-spray cooling can virtually eliminate all of the cooling load impact of a roof in California climate zones. However, this reduction is often small in absolute terms (kWh/yr) for buildings that utilize economizers and have well-insulated, low solar-absorbing roofs. The formula below estimates the cooling savings from roof-spray cooling:

$$Cooling\ Savings\ (kWh\ /yr\ ) = \frac{s\ x\ A\ x\ I}{R\ x\ COP}$$

where:

s = The solar absorptance of the roof. ($0<s<1$). See Table 2-24 in the "Light Colored Roofs and Walls" summary sheet for typical values.
R = The R-value of the roof. (hr-ft^2-°F/Btu)
A = The area of the roof. (ft^2)
I = The proper value from Table 2-25. (kWh-hr-°F/Btu-yr)
COP = The coefficient of performance of the air condtioning unit.

Table 2-25

I - Values for Determining Cooling Savings from Roof-Spray Cooling [1]

(kWh-hr-°F/Btu-yr)

	San Francisco	Los Angeles	Fresno
Buildings with Economizers:	4.1	13.6	29.0
Buildings without Economizers:	20.5	22.7	32.2

1. The procedure assumes that the roof-spray system removes all of the absorbed solar gain from the surface of the roof. This roughly implies that the roof-spray system reduces the roof exterior surface temperature to the outside air temperature during cooling periods.

COSTS: Capital costs for a roof-spray system are approximately $0.30 per square foot of roof area. (from "Roof Sprinkling System Sweats Down A/C Costs", *Energy Management Technology,* May/June 1984, p. 49.) However, water usage can be significant with these systems. For a 2000 ft^2 roof with a solar absorptivity of 0.7, water is used at the rate of approximately 0.9 gallons/minute during peak cooling periods. For a building in Los Angeles with an economizer (the roof-spray system should not operate if the economizer is supplying all of the cooling load), annual usage would be approximately 30,000 gallons for the same 2000 ft^2 roof.

Another way to view water requirements is in terms of water use per kWh of cooling electricity saved. If a system is installed and controlled so that there is little water waste, the following simple formula gives that relationship:

$$Water\ use \left(\frac{Gallons}{kWh} \right) = R\ x\ COP\ x\ 1.6\ \frac{Gallons - Btu}{kWh - hr - ft^2 - {}^\circ F}$$

The formula is derived for a 7.5 mph average wind speed and water use will be somewhat less for smaller wind speeds. For a building with an air conditioner of COP = 3.0 and a roof with R-10 insulation, water use is 50 gallons per kWh of cooling electricity saved.

Water pumping is required if the building is more than three stories high, but pumping energy use is small. Approximately 5×10^{-5} kWh/gallon/story is required for each story above the third.

RELIABILITY/LIFETIME: Reliability may be affected by drought-time sanctions on water usage. Equipment should have reliability similar to agricultural sprinkling systems.

UTILITY SYSTEM IMPACTS: If the system is operated during peak demand periods, the cooling peak demand will be reduced. However, there is some probability that the system will not be operated during critical peak periods because of equipment failure, or because of bans on water usage for roof spraying due to droughts. This probability should be accounted for when analyzing utility system impacts. If the system is operated, the following formula estimates the reduction in peak cooling demand:

Cooling Peak Reduction in kW:

$$= \frac{(6 + 79s)\ {}^\circ F\ x\ A}{(3413\ Btu/hr - kW)\ x\ R\ x\ COP}$$

where the variables are defined in the Energy Performance section.

USER IMPACTS: In buildings where the roof is poorly insulated, roof-spray cooling will reduce the radiant heating effect to the occupants from a hot roof.

COMMENTS + CAVEATS: See the discussion of water usage in the cost section. Roof-spray cooling can be controlled to provide additional fire protection for a building. Also, the reduction in roof surface temperature caused by the roof-spray can prolong roof life.

Commercial Technology Summary Sheet

END-USE: Space Cooling

TECHNOLOGY: **Reducing Outside Air Ventilation**

GENERAL DESCRIPTION: HVAC systems in commercial buildings exchange outside air for room air in order to remove odors and indoor pollutants. In actual systems, the minimum level of outside air intake may be *more* than that necessary to perform the ventilation function and meet code requirements. Reducing the amount of outside air intake during hot periods will reduce cooling energy use, because cooling is required to reduce the temperature and humidity of the outside air brought into the building.

PHYSICAL CHARACTERISTICS: Reducing the minimum outside air intake generally involves adjusting existing dampers or louvers.

APPLICABILITY: This measure is only applicable to buildings that take in more outside air than required to meet codes or ventilation needs. Also, this measure may *increase* cooling energy use if applied to HVAC systems that do not have economizers. (See Energy Performance section.)

ENERGY PERFORMANCE: In order for this measure to save cooling energy, outside air intake must be reduced only during periods when the outside air is warmer than the air within the building. If this measure is applied to HVAC systems with economizers, this control strategy is achieved. The minimum outside air setting is only in effect when outside air conditions are undesirable for conditioning the building. A reduction in the minimum setting only affects the amount of intake during those periods; the economizer admits *more* than the minimum amount of outside air during periods when the air is favorable for cooling the building. If the HVAC system does not have an economizer, minimum outside air intake occurs during *all* operating periods, and a reduction will affect the intake during all periods. For the three climate zones studied, a reduction will usually *increase* cooling use, since outside air conditions averaged over the annual cooling period are cooler than interior conditions.

The following formula estimates the cooling savings from reducing the minimum outside air intake setting:

$$Cooling\ \ Savings\ \ (kWh\ /yr\ ) = \frac{(F_i\ - F_f\ )\ x\ \ C}{COP}$$

where:

F_i = The minimum outside air flow rate before the reduction. (cfm)
F_f = The minimum outside air flow rate after the reduction. (cfm)
C = Proper value from Table 2-26. (kWh/yr-cfm)
COP = Coefficient of performance of the air conditioning unit.

Table 2-26

C - Values for Determining Cooling Savings from Reducing Outside Air [1]

(kWh/yr-cfm)

	San Francisco	Los Angeles	Fresno
Buildings with Economizers:	0.1	0.9	2.4
Buildings without Economizers:	-15.1	-11.0	-7.8

1. Derived from simulations of the office building module.

Reducing the minimum outside air intake will also save heating energy, and the heating savings may be more significant than the cooling savings.

COSTS: There are essentially no hardware costs for this measure. Labor involves measuring the existing flow rate, and adjusting the dampers or louvers. An approximate labor cost per fan is $30.

RELIABILITY/LIFETIME: Dampers need to be checked periodically as they can come loose or malfunction.

UTILITY SYSTEM IMPACTS: Cooling peak demand will be reduced by this measure (even for systems without economizers), since outside air intake presents a cooling load during peak demand periods. The following formula estimates the cooling peak demand reduction for a reduction in outside air intake:

$$\text{Cooling Peak Reduction in } kW = \frac{(F_i - F_f) \; x \; P}{COP}$$

where variables are as defined before, except

P = 0.004 kW/cfm, for San Francisco
= 0.006 kW/cfm, for Los Angeles
= 0.009 kW/cfm, for Fresno

(Derived from typical temperature and humidity conditions during peak
cooling period.)

USER IMPACTS: If this measure is applied to buildings that are *not* overventilated, indoor air quality will be adversely affected.

Commercial Technology Summary Sheet

END-USE: Space Cooling

TECHNOLOGY: **Air-to-Air Heat Exchangers**

GENERAL DESCRIPTION: Air-to-air heat exchangers are devices that transfer heat (and sometimes moisture) between two air streams that are at different temperatures and humidities. In commercial buildings they can be used to exchange heat between the intake ventilation air-stream and the HVAC exhaust air-stream. During periods when the outside air is warmer than the building air, the exchanger transfers heat from the incoming air to the exhaust air which lowers the temperature of the incoming air and reduces its impact on cooling requirements.

PHYSICAL CHARACTERISTICS: A number of types of units perform an air-to-air heat exchange, including heat wheels, heat pipes, run-around coils, and standard air-to-air exchangers, which do not have moving parts or exchange fluids. Duct and equipment configurations vary, but some units have large or cumbersome space requirements.

APPLICABILITY: Most easily used in a new construction situations because of size and ducting requirements. Also, heat exchangers tend to save only small amounts of cooling energy even in warm California locations. Their main application is for saving heating energy in buildings with large outside air ventilation needs.

ENERGY PERFORMANCE: The heat exchanger must be controlled to operate only during periods when it is warmer outside than inside. (Also, it should operate during heating periods.) Since there are relatively few hours where it is significantly warmer outside than inside in most California locations, heat exchangers tend to save small amounts of cooling energy. For a properly controlled heat exchanger with a 70% average effectiveness, the cooling energy saved can be estimated by the following formula:

$$Cooling\ Savings\ (kWh/yr) = \frac{F\ x\ X}{COP}$$

where:

F = The minimum outside air flow rate. (cfm)
X = 0.1 kWh/yr-cfm, for San Francisco.
= 0.6 kWh/yr-cfm, for Los Angeles.
= 1.7 kWh/yr-cfm, for Fresno.
COP = Coefficient of performance of the air conditioning unit.

(X values based on DOE-2 simulations of the office module.)

The reductions in heating use should be considered in a comprehensive analysis. Also, heat exchangers create an air pressure drop, which increases air transport energy use. This loss should also be accounted for in a more sophisticated analysis.

COSTS: Costs can vary from $0.50 to $1.50 per cfm of outside air, depending on the type of unit and the air-handling unit configuration.

UTILITY SYSTEM IMPACTS: Air-to-air heat exchangers reduce cooling peak demand, since they lower the temperature of the incoming ventilation air. The formula below estimates the cooling peak demand reduction for a heat exchanger that only exchanges sensible heat (no moisture exchange) and has an effectiveness of 70%:

$$Cooling\ Peak\ Reduction\ in\ kW = \frac{F\ x\ P}{COP}$$

where F and COP are as defined in the Energy Performance section, and

P = 0.004 kW/cfm, for San Francisco.
= 0.005 kW/cfm, for Los Angeles.
= 0.006 kW/cfm, for Fresno.

(Derived from typical temperature conditions during peak cooling period.)

Commercial Technology Summary Sheet

END-USE: Space Cooling

TECHNOLOGY: **Increasing Cooling Thermostat Settings**

GENERAL DESCRIPTION: Increasing the cooling thermostat setpoint reduces the cooling loads related to temperature, since the difference in temperature between the hot outdoors and the building interior is reduced.

PHYSICAL CHARACTERISTICS: Resetting the thermostat involves no additional equipment.

APPLICABILITY: Applicable to buildings where increased interior temperatures will not adversely affect comfort. Also, energy may not be saved for buildings with HVAC systems that are not load responsive unless adjustments in air flow rates or supply air temperatures are made.

ENERGY PERFORMANCE: Only some of the cooling loads in a building depend on the inside/outside temperature difference; internal loads and solar loads are independent of temperature and are not affected by raising thermostat settings. Raising the cooling setpoint also increases the cooling effect produced by the economizer, since the increased setpoint creates a larger temperature difference between the cool outside air and the inside air.

The amount of cooling savings from this measure depends on the amount that the thermostat setting is increased, whether the building has an economizer or not, and the thermal integrity of the building envelope. For very well insulated buildings, changing the thermostat setting has a small effect, since the amount of temperature-induced cooling load is small.

The formula below estimates cooling energy savings from increased cooling thermostat setpoints. The associated table is derived for a building with an envelope of poor to moderate thermal integrity. (UA per unit floor area = 0.2 Btu/hr-°F / ft^2 of floor area.) Scaling according to UA value can be used to adjust the figures for different envelope insulation amounts in the "no economizer" case. Because of the effect on the economizer, adjustment by scaling can *not* be used with the "building with economizer" figures.

$$Cooling\ Savings\ (kWh/yr) = \frac{T\ x\ M\ x\ A}{COP}$$

where:

T = Increase in thermostat setting. (°F)
M = Proper value from Table 2-27. (kWh/ft^2-yr-°F)
A = Floor area of the building. (ft^2)
COP = Coefficient of performance of the air conditioning unit.

Table 2-27

M for Determining Cooling Savings from Raising Cooling Setpoints [1]

(kWh/ft^2-yr-°F)

	San Francisco	Los Angeles	Fresno
Buildings with Economizers:	0.2	0.5	0.3
Buildings without Economizers:	0.5	0.5	0.5

1. Derived from simulation of the office building module. The (U x A) per square foot of floor area for the module is approximately 0.2 Btu/hr-°F / ft^2 of floor area. The thermostat-setting change that was tested was a change from 75°F to 78°F.

In addition, substantial *heating* savings can occur when the *cooling* thermostat setpoint is raised. A significant amount of heating for commercial buildings results from the need to warm up the building in the morning after cool nights. If the cooling setpoint is raised, the building begins the evening at a higher temperature and does not cool off to as low a temperature in the morning.

COSTS: The costs for this measure are essentially zero.

RELIABILITY/LIFETIME: In buildings where occupants have access to thermostats, thermostats settings may be altered by occupants.

UTILITY SYSTEM IMPACTS: Peak cooling demand is reduced by increased cooling thermostat settings. The peak demand reduction can be estimated by the formula below:

$$Cooling\ Peak\ Reduction\ in\ kW = \frac{T\ x\ P\ x\ A}{COP}$$

where variables are defined in the Energy Performance section, except

P = 3 x 10^{-5} kW/ft^2-°F, for Good thermal envelopes.
= 6 x 10^{-5} kW/ft^2-°F, for Mediocre thermal envelopes.
= 9 x 10^{-5} kW/ft^2-°F, for Poor thermal envelopes.

USER IMPACTS: Changing thermostat settings has comfort impacts. The value of the building occupants' services far outweigh energy costs, so these tradeoffs must be closely examined.

Commercial Technology Summary Sheet

END-USE: Air Transport

TECHNOLOGY: **Variable-Air-Volume (VAV) Systems**

GENERAL DESCRIPTION: VAV systems are air transport systems that respond to changes in heating or cooling load by reducing the amount of conditioned air flowing to the space; constant-volume air systems commonly respond to variations in load by varying the temperature of the supply air or reheating the supply air. VAV systems use significantly less air transport energy than constant-volume systems.

PHYSICAL CHARACTERISTICS: VAV systems require the use of VAV terminal boxes at each zone supplied, as well as hardware to control the main HVAC fan. The exterior physical characteristics of VAV terminals differ little from other terminals. Main fan control is done by variable-speed motor drives, variable-pitch fans, fan inlet vanes, or fan discharge dampers. Duct and fan housing configurations sometime make the retrofit of inlet vanes and discharge dampers difficult.

APPLICABILITY: Applicable to most new construction situations, except buildings requiring high ventilation rates such as hospitals. Applicable as a retrofit to HVAC systems with medium to high velocity ductwork, most typically dual-duct systems. Low velocity ductwork will often leak and bellow when operated at the higher static pressures present in a VAV system. As well as having ductwork that can withstand the higher static pressures of a VAV system, dual-duct terminals are easily converted to VAV terminals. A modified version of VAV can be used with low-velocity HVAC systems. For this type of system, VAV terminals are not installed, but the main fan flow rate is controlled by the warmest zone in the building. Reheat will be required in zones other than the warmest, but significant fan energy savings will be realized.

ENERGY PERFORMANCE: The use of VAV systems has impacts on air transport, cooling, and heating energy-use. Air transport energy savings depend on the cooling load profile and the type of main fan control used in the VAV system. Buildings that operate at part-load cooling conditions for significant periods of time (e.g. buildings that remain open during nighttime periods) will save more fan energy through VAV use. Different methods used to reduce the flow of the main fan also result in different energy savings. Table 2-28 is the result of DOE-2 simulations of the office module. We found variation over climate zone to be relatively small, so only one savings figure is presented per variable-volume method. Also, DOE-2 does not simulate variable-pitch fans, but efficiency curves for these fans are close to the curves for variable-speed drives; the results from the variable-speed drives are used for both. Note that the savings results are derived for *one* specific building; savings will vary across different buildings.

Table 2-28

VAV Air Transport Energy Savings

DOE-2 Simulation of a Typical Office Building

(Savings in % of Initial Energy Use)

Main Fan Control	Air Transport Savings
Discharge Dampers	28%
Inlet Vanes	53%
Variable-Speed Drives, and Variable-Pitch Fans	78%

This chart can also be used to determine savings from switching between different types of main fan control. Switching between inlet vanes and variable-speed drives results in approximately a 50% savings:

$$\frac{(initial\ \ use\ -final\ \ use)}{(initial\ \ use)}=\frac{[(1-.53)-(1-.78)]}{(1-.53)}=0.5$$

The heating and cooling impacts of a VAV system are often important. However, the control configuration of the system being replaced or compared against is very important for determining the effect. VAV systems use significantly less heating and cooling energy than systems that are not load-responsive, i.e. systems that employ large amounts of simultaneous heating and cooling, or systems that regularly overcool spaces. The savings are difficult to quantify in a general way; computer simulations of specific buildings are necessary for reliable results.

VAV systems often use *more* cooling energy than good constant-volume systems that have economizers. This is because VAV systems reduce air flow rates and therefore get less free cooling from their economizers. For the office building module we simulated, the following formula estimates the magnitude of this effect per square foot of floor area:

Increase in Cooling Energy Use $(kWh\,/\,ft^2\text{-}yr) = \frac{X}{COP}$

with use of VAV: Economizer Effect

where,

X = 1.6 kWh/ft^2-yr, for San Francisco.
= 2.5 kWh/ft^2-yr, for Los Angeles.
= 0.6 kWh/ft^2-yr, for Fresno.

COP = Coefficient of performance of the air conditioning unit.

COSTS: For retrofit situations, the cost of VAV system include changing the supply terminals to VAV terminals, and adding a main-fan variable-flow device. Retrofitting dual-duct systems is less expensive because the supply terminals can be easily modified to VAV terminals. Retrofitting main-fan control devices can be difficult for some buildings. For new construction, differences between VAV systems and other systems are less. The table below summarizes cost information. We assumed that for new construction, the only difference in cost was due to the variable fan control device. The costs are expressed in \$/cfm of air flow. Converting this to \$/ft^2 of floor area involves estimating cfm/ft^2 of floor area. Typical values are 0.7 - 2.0 cfm/ft^2.

Table 2-29
VAV Costs
($/cfm)

VAV Fan Control	Retrofit System Replaced: Dual-Duct	Retrofit System Replaced: Other	New Construction
Discharge Dampers	0.20 - 0.50	0.60 - 1.10	0.08 - 0.10
Inlet Vanes	0.24 - 0.56	0.65 - 1.15	0.10 - 0.20
Variable-Speed Drives	0.40 - 0.90	0.83 - 1.47	0.20 - 0.60
Variable-Pitch Fans	0.48 - 1.28	0.93 - 1.83	0.10 - 0.40

RELIABILITY/LIFETIME: Reliability of VAV systems is generally worse than constant-volume systems because of more complex hardware, but the decrease in reliability is not a major concern. The additional complexities are controllable dampers in the VAV terminals (although, dual-duct and multi-zone systems have controllable dampers too), and equipment to vary the main fan air flow.

UTILITY SYSTEM IMPACTS: Most savings occur during part-load cooling conditions, so savings during utility peak periods are small since building air conditioning peaks then also. However, there is a 5 - 20% savings in peak fan power due to the diversity of zone peaks captured by the VAV system. (Not all the building zones peak at the same time. The coincident peak is less than the sum of individual zone peaks.) A typical value for this peak savings is 0.1 W/ft^2. Also, energy savings from VAV systems are greater during winter months since part-load conditions are more prevalent then.

USER IMPACTS: VAV systems produce less air movement in building spaces than constant-volume systems. This can lead to comfort complaints, but air temperature seems to be the more critical comfort parameter. VAV systems tend to maintain lower space humidities than constant-volume variable-temperature systems, because supply air temperatures are lower with VAV systems. The extra moisture removal may not be necessary in many situations because of the low outdoor humidities found in most California locations. Also, noise can sometimes be a problem with poorly isolated vane-axial, variable-pitch fans.

Commercial Technology Summary Sheet

END-USE: Air Transport

TECHNOLOGY: **Reducing Fan Flow Rate**

GENERAL DESCRIPTION: The flow rate of an HVAC fan should be chosen so that the peak cooling load can be met using the design supply air temperature. Fan flow rates are often larger than needed because of oversizing in the original design process or because energy conservation measures have reduced the peak cooling load in the building. By reducing the flow rate to more closely match the peak cooling load, savings in air transport energy can be achieved. This measure also has impacts on cooling and heating energy use; the impacts are positive or negative depending on the type of HVAC system being retrofitted. Reducing the fan flow rate involves changing the motor sheave for belt-driven fans, using a lower-speed motor for direct-driven fans, or duty-cycling the fan at its original flow rate. An engineering analysis is required to determine the amount of reduction possible, and a rebalancing of the air transport system is sometimes required after the flow reduction has been implemented.

PHYSICAL CHARACTERISTICS: The measure generally involves replacing a component so does not consume extra space or add extra weight.

APPLICABILITY: This measure is applicable as a retrofit to constant-volume HVAC systems with oversized air flows. It is also applicable to variable-air-volume systems using low-efficiency flow-reduction methods such as discharge dampers or inlet vanes, but the savings will not be as great. The measure should not be applied to induction systems. The analog measure for new construction is a more careful fan-flow sizing procedure. The measure may be impossible for some direct-driven fans because standard motor speeds are limited in number.

ENERGY PERFORMANCE: Air transport energy use is proportional to the flow of air in the system and the pressure drop overcome by the air; both of these variables are affected by this energy conservation measure. A 5% reduction in flow rate will result in approximately a 5 - 10% reduction in pressure drop, depending on the zonal distribution of the flow rate reduction (see section 2.6.4 for more detail). Energy savings will be 10 - 20%, since energy use is proportional to the product of pressure and flow. The exception to this is duty-cycling; duty-cycling causes no reduction in pressure, so a 5% reduction in flow results in a 5% reduction in energy use. Table 2-30 gives air transport energy savings for reduced flow.

Table 2-30

Air Transport Savings from Fan Flow Reduction

	Energy Savings	
Flow Reduction	Changing Fan Speed	Duty-Cycling
5%	10 - 15%	5%
10%	19 - 28%	10%
15%	28 - 40%	15%
20%	36 - 50%	20%
25%	44 - 59%	25%
30%	51 - 67%	30%

The cooling and heating impacts can be negative or positive depending on HVAC system type. Both cooling and heating energy use will decrease for systems that are not load responsive, since simultaneous heating and cooling will be reduced. Cooling may increase for systems with economizers, since reducing air flow reduces the amount of free cooling the economizer can provide.

COSTS: A peak sizing audit for the building costs approximately $0.10 per square foot of floor area. Changing a motor sheave or installing a duty-cycler costs $50 - $150 per fan.

RELIABILITY/LIFETIME: Replacing motor sheaves or motors improves system reliability, since new parts are substituted for old ones. Duty-cycle timers occasionally have problems with loose tripper pins or worn out motors. Also, duty-cycling can shorten the life of motors, especially if shut-off intervals are short.

UTILITY SYSTEM IMPACTS: Air transport energy savings are evenly distributed across the HVAC operation hours. If air transport energy savings are 10%, peak savings will be 10% of the air transport power. Therefore, Table 2-30 can be used to determine peak savings also. Air transport power is typically 0.7 - 2.0 W/ft^2, so the percentage savings should be applied to this base.

USER IMPACTS: If used, fan duty-cycling subjects building occupants to intermittent HVAC noise, which may be annoying.

Commercial Technology Summary Sheet

END-USE: Air Transport

TECHNOLOGY: **Fixing Duct Leaks**

GENERAL DESCRIPTION: Low-pressure duct systems often have substantial amounts of leakage because of poor sealing during construction. By fixing these leaks with tape or sealant, main-fan air-flow can be reduced providing energy savings while still maintaining the same amount of air flow to building spaces.

PHYSICAL CHARACTERISTICS: Sealing requires accessibility to the ductwork.

APPLICABILITY: This measure is applicable to duct systems that have substantial amounts of leakage and are reasonably accessible for sealing purposes. This retrofit is most often undertaken to eliminate noise problems. High pressure duct systems are generally sealed during construction, so this measure is not applicable to those systems.

ENERGY PERFORMANCE: This measure saves air transport energy by reducing the main-fan flow-rate and decreasing the system pressure drop because of the flow reduction. (see the "Reducing Fan Flow Rate" summary sheet for more explanation.) Fixing leaks will typically allow a 10% reduction in fan flow rate, and the associated air transport energy savings are 19 - 28%. Since flow rates to the building spaces are the same, the impact on cooling and heating energy use is small.

COSTS: The major cost component for this retrofit is fixing the leaks in the ducts, but downsizing the main-fan flow-rate also contributes to the cost. The cost range per unit floor area for this measure is 0.15 - 0.40 $\$/ft^2$.

RELIABILITY/LIFETIME: Duct tape has a short lifetime when used on ducts that carry hot air. Special sealing tapes are available that need to be moistened before installing. They dry hard and provide a more permanent seal. Also, aluminum tape designed for high temperature applications can be used.

UTILITY SYSTEM IMPACTS: Energy savings are distributed evenly over the HVAC operation period. Peak savings will be 19 - 28% of air transport power, or approximately 0.2 - 0.5 W/ft^2.

USER IMPACTS: A positive user impact from this measure is reduced noise caused by leaky ducts.

Commercial Technology Summary Sheet

END-USE: Air Transport

TECHNOLOGY: **Miscellaneous Pressure Reduction Measures**

GENERAL DESCRIPTION: In many existing air transport systems an engineering analysis will reveal various opportunities for reducing system pressure drop. These opportunities are often site-specific, and savings and costs are not easy to characterize. A sample of these measures includes reducing resistance in the index duct run (the duct run with the most friction), utilizing one coil for both heating and cooling, modifying fan fittings to reduce air-flow resistance, installing energy-efficient filters, and installing turning vanes to round corners in square duct bends.

PHYSICAL CHARACTERISTICS: Dependent on measures implemented.

APPLICABILITY: This description applies to retrofit measures. See the summary sheet on "Air Transport Designs: New Construction" for information on new design approaches.

ENERGY PERFORMANCE: Savings can range from 0.5 - 7.0 kWh/ft^2 depending on the characteristics of the air transport system (large potential in systems with high pressure drops) and the measures employed.

COSTS: The costs of the measures are highly variable, ranging from $ 0.20 to $ 1.20/ft^2.

RELIABILITY/LIFETIME: Dependent on measures implemented.

UTILITY SYSTEM IMPACTS: Dependent on measures implemented.

USER IMPACTS: Dependent on measures implemented. Often, reducing pressure drop also reduces the amount of noise generated by the air transport system.

Commercial Technology Summary Sheet

END-USE: Air Transport

TECHNOLOGY: **Air Transport Designs: New Construction**

GENERAL DESCRIPTION: When designing air transport systems there is a trade-off between cost and size of components and energy use. Systems with large ducts and large central air-handling components operate at low air velocities and therefore have low frictional energy losses. For central air-handling components (cooling coils, filters, etc.), a commonly used rule-of-thumb has been to size components so that air velocities are approximately 500 feet per minute. With escalation of energy prices, this design approach produces systems that are not optimal from a life-cycle cost perspective. Recent studies have shown that sizing so that velocities are in the 300 to 400 feet per minute range result in minimum life-cycle cost. (This is not true for VAV systems; see the applicability section.) Using this design criteria for central air-handling components, and increasing duct size in order to lower duct pressure losses can produce systems with about one-half the total system pressure drop of more standard system. This pressure reduction in combination with reduced air flow rates from conserving cooling designs presents the possibility of reducing air transport energy use in new designs to about one-third of that found in typical existing buildings.

PHYSICAL CHARACTERISTICS: To achieve reductions in system pressure for a given flow rate, larger ducts and air-system components need to be used. However, the tendency of new energy conserving building designs to require smaller flow rates may cancel the increased need for space caused by smaller system pressures. (Standard sized components when used with smaller flow rates will give low pressure drops.)

APPLICABILITY: This description refers to design issues pertaining to new building construction. Component and duct sizing for VAV systems will be different than sizing for constant-volume systems. Since VAV systems operate at part-flow often, optimally sized components will be smaller than those for a constant-volume system serving a similar building.

ENERGY PERFORMANCE: Static pressures in multiple zone systems can be reduced to approximately 2.5 or 3 inches, and energy-conserving building designs can require 1 cfm/ft^2 or less of air flow. If a 70% combined motor and fan efficiency is assumed, this design uses 1.4 kWh/ft^2-yr when operated 3000 hrs/year and 2.3 kWh/ft^2-yr when operated 5000 hrs/year. A typical existing building consumes about 5 kWh/ft^2-yr in air transport energy at 3000 hours of operation per year and 9 kWh/ft^2-yr for 5000 hours/year operation. The use of a VAV system could reduce the energy-use of the efficient system further.

COSTS: An energy-efficient air-handling unit (fan, filters, coils, and outside-air intake damper) may cost an additional \$0.20 - \$0.40/ft^2 when compared to a standard system. To reduce the pressure drop in ducts and supply grilles by 50%, approximately \$0.10 - \$0.80/ft^2 must be spent to increase the size of these components, giving a total incremental cost of \$0.40 - \$1.10/ft^2 for the efficient air transport system.

RELIABILITY/LIFETIME: Same as standard systems.

UTILITY SYSTEM IMPACTS: Efficient new design tends to proportionally reduce the air transport energy use profile. For constant-volume systems, this profile is flat across the operational hours of the system. For VAV systems, the air transport energy use profile tends to track the cooling profile, peaking during hot periods.

USER IMPACTS: Air-systems operating at lower air velocities generally create less noise than standard systems.

Commercial Technology Summary Sheet

END-USE: Air Transport

TECHNOLOGY: **Fan Shut-Off during Unoccupied Hours**

GENERAL DESCRIPTION: The operation of air transport fans during building unoccupied hours often serves no useful purpose. By using a timeclock the fans can be turned off during unoccupied hours thus saving a significant amount of energy.

PHYSICAL CHARACTERISTICS: The measure only requires installation of a timeclock(s) which occupies an insignificant amount of space.

APPLICABILITY: This measure is applicable to buildings that run air transport fans continuously even though the building is not occupied continuously.

ENERGY PERFORMANCE: Air transport energy savings are proportional to the number of hours that the fans are shut down by the timeclock. If a cycling scheme is *not* used to maintain comfortable space temperatures during unoccupied periods, this measure will also save heating and cooling energy, although the air transport savings should be dominant. The table below gives air transport savings for various shut-down durations.

Table 2-31
Fan Shut-Off Energy Savings

Unoccupied Hours (Hours/Week)	Air Transport Savings (%)
60	36%
90	54%
120	71%

COSTS: For control of one fan, a 7-day timeclock costs from $50-$250, and installation adds about $150. Simple mechanical timeclocks are at the low end of the cost range, and more sophisticated timeclocks with power-failure backup features and more programming flexibility are at the high end. The cost per square foot of floor area can be determined by dividing by the square footage served per fan.

RELIABILITY/LIFETIME: The trip pins sometimes loosen and fall off simple mechanical time clocks. Occasional inspection of the timeclock or use of an electronic timeclock remedies this problem. Timeclocks without power-failure backup require resetting each time there is a power failure. Motors can also wear out on inexpensive mechanical time clocks.

UTILITY SYSTEM IMPACTS: This conservation measure generally saves energy during the night so does not reduce the utility peak load. Also, the savings have little seasonal variation.

USER IMPACTS: One concern when applying this measure is the comfort of service personnel who are in the building during unoccupied hours. A cycling scheme during the unoccupied period for the HVAC system and fans can be used to solve this problem and can still be accomplished with relatively simple timeclocks. Another problem can be lingering odors and smoke from the previous day. An extra hour of flushing after the building is vacated can solve this problem.

Commercial Technology Summary Sheet

END-USE: Air Transport

TECHNOLOGY: **Motion-Sensor Control of Intermittently Used Spaces**

GENERAL DESCRIPTION: Bathrooms, classrooms, conference rooms, storage spaces, and some office spaces are intermittently used during a building's occupied period and therefore do not need to be ventilated or lit continuously. By utilizing motion sensors to shut-off ventilating and lighting systems, energy can be saved in these spaces when they are not occupied.

PHYSICAL CHARACTERISTICS: The control circuitry requires little space.

APPLICABILITY: The ventilation and/or lights for the space must be controllable independent of other building spaces. This is usually true for lighting, but bathrooms and kitchens are often the only spaces with their own ventilation system. Motion-sensor control cannot be used in spaces where intermittent operation of the ventilating system will cause uncomfortable temperature, humidity, or odor conditions.

ENERGY PERFORMANCE: The energy savings provided by this measure depend on the amount of time that the control circuitry keeps the ventilating and lighting equipment off when otherwise it would have been left on. Bathrooms where occupants usually remember to shut-off lights and fans will benefit little from this measure. Savings are generally less per square foot in larger rooms, since there is a larger fraction of time when the room has one occupant or more; this reduces the amount of time that the lights and fans can be shut-off. (exception: classrooms and conference rooms). The table below gives estimated air-transport and lighting savings from use of a motion-sensor. The savings are expressed per square foot of ***controlled*** floor area, not total building floor area.

Table 2-32

Savings from Motion-Sensor Control of Ventilation and Lighting

Additional Hours Shut-off per Day (average, including weekends)	Lighting Savings [1] per Controlled ft^2 (kWh/ft^2-yr)	Air Transport Savings [2] per Controlled ft^2 (kWh/ft^2-yr)
1	0.7 - 1.5	0.5 - 0.8
2	1.5 - 2.9	0.9 - 1.5
5	3.7 - 7.3	2.4 - 3.8
10	7.3 - 14.6	4.7 - 7.7
15	11.0 - 21.9	7.1 - 11.5
20	14.6 - 29.2	9.5 - 15.3

1. Assumes 2.0 - 4.0 W/ft^2 lighting power density.
2. Assumes 1.3 - 2.1 W/ft^2 air transport power density.

COSTS: The installed cost of motion sensors is approximately $0.70 per square foot of controlled area.

UTILITY SYSTEM IMPACTS: The time-distribution of energy savings depends on the distribution of the hours for which the motion sensor has turned off fans and lights. Many of these hours will be at night, but some will occur during the utility peak demand period. Multiplying the expected shut-off fraction for the peak demand period (off time/total time) by the lighting and fan power density (approximately 3 to 6 W/ft^2 of bathroom floor area) will estimate the peak demand savings for the utility. The building will not see reductions in the peak unless many spaces are controlled independently.

USER IMPACTS: Sensors must be adjusted to stay on long enough after vacancy to remove odors and pollutants.

Commercial Technology Summary Sheet

END-USE: Air Transport

TECHNOLOGY: **Energy-Efficient Motors**

GENERAL DESCRIPTION: Energy-efficient motors can be used to drive the air transport fan. The improvement in efficiency over standard motors reduces energy consumption.

PHYSICAL CHARACTERISTICS: Energy-efficient motors have physical characteristics similar to the standard motors they replace.

APPLICABILITY: The measure is most economical in new construction or when replacing a damaged motor; early replacement of motors with poor full-load efficiencies or motors that are significantly oversized can also be economical.

ENERGY PERFORMANCE: For small motors ($<$ 5 hp), efficiencies of energy-efficient motors are as much as 8% more than standard motors. The efficiency improvements possible for larger motors ($>$ 50 hp) are less, approximately 3 - 5%. See Chapter 4 on motor efficiency for more detail.

COSTS: For a motor application of a given horsepower, use of an energy-efficient motor reduces the input motor power required to serve the application. A convenient way of expressing the cost of an energy efficient motor is in additional dollars (above a standard motor) per kW of reduced input power. For most energy-efficient motors, this cost is $100 - $300 per reduced kW. See Chapter 4 on motor efficiency for more detail.

RELIABILITY/LIFETIME: Comparable to standard motors.

UTILITY SYSTEM IMPACTS: The percentage savings in peak air transport power consumption will be roughly the same as the percentage savings in annual energy use.

Chapter 2

Cooling and Air Transport

2.1 INTRODUCTION

2.1.1 Summary

This chapter discusses cooling and air-transport energy conservation technologies for commercial buildings in the Southern California Edison and Pacific Gas and Electric service territories. The cooling end-use refers to the energy consumption of cooling equipment: chillers, air conditioners, cooling towers, and chilled water pumps. The air transport end-use covers the energy consumption of fans associated with the HVAC system.* There are linkages between these end-uses because both are part of the space conditioning process; therefore, they are discussed together in this chapter.

A number of key findings resulted from our work, and they are listed in summary form below. Our research also indicated several topics in need of additional work, and they are compiled in a list of data gaps.

Key Findings:

- In the California climate, air transport energy consumption is often as great or greater than cooling consumption, especially for buildings with economizer controls. Recent simulations suggest that stock wide cooling EUIs may be lower than presently believed, and air transport EUIs may be higher.
- Often, careful designs, control strategies, and regular maintenance yield the largest energy savings. The hardware itself does not guarantee reductions in energy consumption.
- Economizer controls have a large impact on cooling usage throughout California, with savings ranging between 15 and 80%. Further, the presence of an economizer significantly reduces both the applicability and savings potential of other conservation measures.
- Energy savings and costs (especially retrofit) for energy conservation technologies are often uncertain. Energy savings vary across buildings, and the traditional building type categories (e.g., office, retail) are not as useful as HVAC system parameters and building thermal characteristics for categorizing the variation.
- Air transport energy consumption can be reduced dramatically through the use of variable-air-volume systems (30 - 80% savings) and low-friction air-distribution designs (20 - 60% savings). Energy-efficient motors and fans will provide smaller savings (5 - 20%).
- Mechanical cooling equipment with full load COPs significantly higher (15 - 40%) than required by Title 24 and ASHRAE 90 standards is widely available today.

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* This end-use is sometimes called ventilation.

- The heat gain from lighting often is the largest contributor to both annual and peak cooling loads. Saving lighting energy will save significant amounts of cooling and air transport energy in addition.
- Peak cooling loads are important not only because of demand charges and utility system impacts. A large cooling peak demand requires large investments in cooling and air transport equipment and will force operation at poor part-load ratios for many hours of the year. Heat from lights and heat transmission through windows are the largest contributors to peak cooling demand.
- HVAC systems that employ large amounts of simultaneous heating and cooling for control purposes will have very high cooling and heating energy consumption. The new Title-24 office standards (effective in 1987) prohibit systems of this type, but existing buildings may still use these wasteful systems.
- While evaporative cooling can result in large percentage reductions in cooling usage in systems already equipped with economizers, the absolute savings are small compared to the savings due to the economizer alone. Further, evaporative coolers require frequent maintenance.
- After installing an economizer and high performance mechanical cooling equipment to reduce cooling energy consumption, peak shaving and load levelling measures become an attractive alternative for reducing peak cooling demand. Thermal storage systems using ice or chilled water are the most widely used, and have had the best reliability and performance records to date. Installation of these systems will be limited by space constraints, and will be cost effective only for buildings on time-of-use rates with large on and off peak differences in energy and demand charges.
- Many of the recently developed cooling equipment technologies (Strainer cycle, ground source cooling, etc.) are, in actual practice, prone to operation and maintenance problems. The savings are small considering the high first costs and continuing operation costs.

Data Gaps:

- Little measured data is available for assessing the performance of individual technologies in actual installations. More submetering and careful documentation of actual performance is necessary in order to verify manufacturers' claims and equipment characteristics.
- Further simulation work, benchmarked to the energy performance of actual buildings, is needed. The non-ideal conditions that exist in actual buildings are rarely incorporated into current simulation studies.
- In general, there is little data available on the performance of technologies over time, especially for newly introduced technologies. As a result, reliabilty of technologies over time is uncertain, especially for economizer controls, evaporative cooling systems, and variable-air-volume fan control equipment.
- Costs of equipment, controls, design, and installation are uncertain, especially for retrofit projects. Incorrect cost data can substantially alter the perceived cost-effectiveness of

energy conservation measures.

- The characterictics of the building stock necessary for estimating savings potential are not known in great detail. More information regarding a building's cooling and air transport systems and equipment operating characteristics needs to be acquired.

2.1.2 Structure of the Chapter

These discussions complement the technology summary sheets. Much of the technology specific information is included in the summary sheets, whereas this documentation provides the conceptual framework necessary for understanding the end-uses and associated technologies. Facts and figures are not sufficient when making decisions concerning complex cooling and air-transport energy conservation technologies. Also, the documentation provides a more comprehensive analysis of certain important technologies found in the summary sheets.

Section 2.2 discusses baseline energy consumption for the cooling and air transport end-uses. In addition, we identify important building and climate characteristics that influence energy use in these end-uses.

The next three sections address cooling. The examination of this end-use is patterned after the DOE-2 building energy simulation program. Section 2.3 addresses *cooling equipment*. This is the equipment that removes heat from the cooling medium, generally chilled water or air. The section considers ways to improve full and part-load equipment efficiencies and considers strategies for reducing the equipment's peak electricity demand. *HVAC systems* are discussed in section 2.4. The HVAC system includes equipment and controls that transfer cooling from the primary cooling equipment to the different building spaces in order to supply their time-varying cooling needs. Examples of HVAC systems are dual-duct and constant-volume reheat systems. The section identifies characteristics that determine the magnitudes of the cooling and air transport energy demands imposed by different HVAC system types. Section 2.5 covers *cooling loads*. These are the heat and moisture additions to a building that need to be removed to maintain comfortable temperature and humidity conditions. Cooling loads can be internal--people, lights, etc.--or external--solar gains through windows, conduction through roofs, etc. The section indicates the relative magnitudes of the various load components and explains possible ways to reduce these components.

The air transport end-use is discussed in section 2.6. Air flow, system pressure drop (a measure of air friction), hours of operation, and motor/fan efficiencies are identified as the key variables affecting air transport energy consumption. These variables are analyzed individually, and possible energy conservation measures are presented.

2.1.3 Energy Savings Estimation

A significant amount of our effort involved the estimation of energy savings from various energy conservation technologies. Typically, we relied on manufacturers' specifications and field measurements to provide us with the characteristics of the energy conservation hardware. We used different approaches to translate those characteristics into energy savings estimates for different types of commercial buildings. In some cases, the relationship between equipment characteristics and energy savings is simple, so hand calculations can produce reasonable results. An example of this is the use of high-efficiency chillers. The percentage savings in energy use is determined by the ratio of the COP (a measure of efficiency) of a standard chiller to the COP of the high-efficiency chiller. In other cases, the interaction between the energy conservation technology, building, and HVAC system is quite complex; computer simulation with the DOE-2 building energy analysis program was used as an estimation tool for many of these technologies. Appendix 2-A describes our simulation method and the building module we used in our computer analysis.

2.2 BASELINE COOLING AND AIR TRANSPORT CONSUMPTION

This section summarizes and compares baseline cooling and air transport energy consumption in commercial buildings in the PG&E and SCE territories. We examine cooling and air transport EUIs, briefly discuss some drawbacks to using building *type* to distinguish variations in performance, and the role of climate in determining consumption.

2.2.1 Comparison of EUIs

Since many of our savings estimates are presented in terms of a percentage reduction, it is important to have an accurate estimate of base line consumption. This baseline is also needed for targeting energy conservation measures and programs to the largest end uses. We have found that present utility model estimates of cooling EUIs may be high, while estimates of air transport EUIs may be low. Here, we present several estimates of EUIs in these two end uses. In tables 2-1 and 2-2 below, we present cooling and air transport EUIs from various sources (for selected building types).

Table 2-33

Comparison of Cooling End-Use EUIs (kWh/ft^2/yr)

Building Type	PG&E [1]	SCE [2]	CEC [3]	ASHRAE [4]		Title 24 [5]	LBL Module [6]
				LA	Seattle		
Sm. Office	7.4	7.7	7.1	5.9	3.3	3.0	
Lg. Office	7.4	7.6	7.4	3.7	2.0	3.1	1.4-3.1
Restaurant	6.6	6.2	12.8				
Retail	6.7	6.5	5.8	4.2	1.6		

Table 2-34

Comparison of Air Transport End-Use EUIs (kWh/ft^2/yr)

Building Type	PG&E [1]	SCE [2]	CEC [3]	ASHRAE [4] LA	ASHRAE [4] Seattle	Title 24 [5]	LBL Module [6]
Sm. Office	1.6	1.4	1.9	2.2	2.1	2.8	
Lg. Office	1.6	1.4	2.3	2.6	2.6	2.0	1.6-3.7
Restaurant	3.4	3.4	3.5				
Retail	1.3	0.6	1.2	2.8	2.8		

ASHRAE, Title 24 simulations, and our building module predict lower cooling EUIs and higher air transport EUIs. The building envelopes and cooling equipment modeled may be more efficient than the stock as a whole, so the cooling EUIs derived from these simulations may be low. However, the same is true of the air transport EUIs, which are already significantly higher than the utility and CEC estimates. In other words, a bias, if it existed, would appear in both estimates. It may be that more comprehensive site surveys, coupled with actual consumption data, are needed to determine the best estimate of stock consumption in these two end uses. Since the savings resulting from a particular conservation measure are often best represented by a percentage reduction from base line consumption, this EUI estimate is needed to calculate the total energy savings for a given measure. If the estimate is incorrect, the resulting energy consumption for the technology will also be incorrect, even if the percentage reduction is a good estimate. Inaccuracies in total savings will also affect project cost effectiveness.

2.2.2 Building configuration vs. building type

In this section, we discuss the elements of building configuration which have the greatest impact on cooling and air transport EUIs. Is it more important to know that a building is located in Fresno, or that it has a variable-air-volume air handling system? Which has more impact on a building's cooling usage, the fact that the building is a retail store, or that the chiller COP is 4.0? Pinpointing the important parameters not only highlights variations in baseline usage, it also determines the variations in savings potential of different conservation measures. This assessment identifies the most important parameters for determining variations in conservation potential over the stock of commercial buildings in the PG&E and SCE service territories.

It is important to distinguish between building configuration and building type. Typically, commercial buildings are disaggregated by type (e.g. office, retail, restaurant). This classification is a good indicator of the activities within the facility, and affords some indication of occupancy levels, operating schedules, and internal loads. However, there are wide variations in other parameters within each building "type," specifically, variations in envelope (especially glass area), system, and equipment characteristics. For example, a large multi-story retail store in a downtown area may have cooling and air transport requirements more like those of an office building and less like those of a "typical" retail building. Analyzing conservation potential using only the conventional building type categories may, likewise, lead to considerable variance around the "typical" values for each category. Assessing the conservation potential in a store in a suburban shopping mall is quite different from analyzing the same store in a downtown setting, surrounded on all sides (including overhead) by other structures. Table 2-35 presents variations in cooling and air transport usage for the same building type and climate zone (Seattle). The numbers are based on simulations done to test the ASHRAE-90/84 standards. For each building type and climate zone, different HVAC system types and envelope characteristics were simulated for the same architectural configuration. (The system types simulated were not the same between types, however. A more revealing comparison would compare the variation over different building types with the same system, and the variation over different systems in the same building type.) Changes in occupancy levels and operating hours will cause even larger variations than those presented. The table shows that, in several cases, the variation within a building type is greater than the variation in the averages of each building type. For example, the spread in cooling consumption among large office buildings is 0.9-3.0 kWh/ft^2/yr, while the spread among "average" buildings of the four types in the table is only 1.3-2.5 kWh/ft^2/yr.

Table 2-35

Comparison of EUIs Within Building Type.

(Seattle, kWh/ft^2/yr) [7]

Building	Cooling EUI			Air Transport EUI		
Type	Low	High	Avg	Low	High	Avg
Sm. Office	1.7	4.6	2.5	1.2	3.3	1.9
Lg. Office	0.9	3.0	1.6	1.4	2.9	2.3
Lg. Retail	1.0	2.1	1.3	2.5	3.1	2.8
Strip Store	1.9	3.3	2.5	2.0	3.0	2.6

Additional categories of buildings need to be developed, based on key physical and operating parameters other than the conventional "building types," in order to narrow the within-group variance in energy consumption and conservation potential. Of course, the value of an increased number of building categories must be weighed against the additional complexity of analysis and the added cost of data aquisition.

2.2.3 Climate zones

In contrast to other end-uses, cooling and air transport energy intensities are affected by climate variations. (Air transport use varies by climate zone since fans are often sized to meet peak cooling loads.) For this analysis, we selected three California climate zones (San Francisco, Los

Angeles, and Fresno) to represent the range of climates in the SCE and PG&E's service areas, and to cover the major population centers (and therefore the largest concentrations of commercial buildings). The variation across climate zones within California is not large enough to warrant further disaggregation. This section briefly reviews the climate zone parameters that should be considered when analyzing cooling system performance.

The word "climate" includes seasonal variations in air temperature, humidity, wind speed, cloud cover, and precipitation. Of these, the following parameters are of primary importance for assessing a building's cooling and air transport needs as well as system performance:

- Air temperature (as measured by dry-bulb temperature).
- Humidity (as measured by wet-bulb temperature).
- Solar gains.

To determine cooling consumption on a daily or annual basis, both the extremes (for cooling capacity) and the distribution between extremes are required. For example, a building designed for a dry-bulb temperature of 95°F may operate for the majority of the time at temperatures around 60-70°F. Further, an inland zone with high daytime and low nighttime temperatures is very different from a coastal area with little day-to-night temperature variation.

These variations become critical when assessing conservation potentials, especially for cooling strategies whose effectiveness is limited to a relatively narrow range of climate conditions. Consider the economizer cycle, which eliminates some or all mechanical cooling when ambient dry-bulb temperatures are below about 75°F. Every area of California experiences sub-75°F temperatures at some time during the year. However, coastal areas like San Francisco have a higher percentage of temperatures in this band than do inland areas like Fresno. Perhaps even more important than annual frequency is daily frequency and time-of-day, as these temperatures must occur during the hours that building requires cooling.

Of the three climate zones selected, Los Angeles and San Francisco are both coastal zones (LA is somewhat hotter) while Fresno is an inland zone. In general, California's inland zones tend to have higher daytime and lower nighttime temperatures, and to be warmer in summer and cooler in winter than the coastal areas. Coastal zones are more humid than inland areas (i.e., less difference between wet- and dry-bulb temperatures) although no California zones have "high" humidity compared to other parts of the nation.

The variations discussed above determine the conservation potential of certain cooling technologies. For example, a high frequency of warm, dry temperatures will make an economizer much less cost-effective; evaporative cooling, on the other hand, becomes an appealing alternative. Further, if a technology appears to be cost-effective in both Fresno and LA, for example, it will also be cost-effective in zones with intermediate climates. If a technology looks good for San Francisco and bad for Fresno, interpolating for areas with intermediate climates is difficult. Extrapolating to more extreme climates may sometimes be a problem; fortunately, within California, there is relatively little commercial floor stock in these areas.

Notes

1. Pacific Gas and Electric Company, "Technology Options Documentation: Commercial Sector," December, 1982, p. 13. Prepared by Arthur D. Little, Inc. Data are 1979 estimates.
2. Southern California Edison Company, results from Dec. 19, 1983 commercial model run. Data are 1982 estimates.
3. Donald K. Schultz, "End-Use Consumption Patterns and Energy Conservation Savings in Commercial Buildings," presented at the ACEEE 1984 Summer Study on Energy Efficiency in Buildings, August, 1984. These numbers are based on PG&E auditor estimates. Cooling numbers may be high since auditors inconsistently assign some or all of fan energy to cooling. Ventilation EUIs may be low for the same reason.
4. These EUIs are based on DOE-2 simulations performed in support of the ASHRAE-90/84 Standard recommendations. EUIs are for ASHRAE-90/75 building shell, averaged over the three system types tested for each building type. Although the shell can be considered "efficient," the system types considered were not necessarily so. See "Recommendations for Energy Conservation Standards and Guidelines for New Commercial Buildings, Vol III: Description of the Testing Process," October, 1983, Battelle Pacific Northwest Laboratory. DOE/NBB-0051/6.
5. Title 24 results based on DOE-2 simulations. Small office based on Title 24 building shell with packaged multizone system, no economizer, warm zone reset. See "HVAC System Energy Bounding: Packaged System," Ayres Associates, July 29, 1982. Large office based on Title 24 building shell, central VAV system with economizer, 50% min. stop, inlet vane control, no reset. See "HVAC System Energy Bounding, High Rise Office," Vol. I, Ayres Associates, November 29, 1982. Both were simulated with Fresno weather tapes.
6. Based on results from the building module in LA with various system types. Cooling numbers may be low since cooling equipment modeled has a relatively high COP.
7. Battelle Pacific Northwest Laboratory, op. cit. EUIs are all for Seattle climate. "Average" EUIs are averages over all the system types and building shells modeled for that building type.

2.3 COOLING EQUIPMENT

2.3.1 Introduction

Most cooling equipment technologies have been covered in some detail in the summary sheets. This section discusses measures of equipment performance (efficiency), climate and systems impacts on savings potential of economizers, and sizing options and their impact on off-peak cold storage potential.

2.3.2 Measures of equipment performance

Each cooling equipment technology varies in its performance and applicability to particular climate zones and building configurations. Although instantaneous cooling equipment performance is reasonably easy to characterize for a given strategy, load, and ambient conditions, analysis of annual electricity consumption is difficult.

Coefficient of performance. Cooling performance is generally expressed in terms of equipment COP (Coefficient of Performance).* However, energy savings (kWh saved) depends on the difference in COP as well as equipment operating hours. Both COP and hours of operation will vary over the range of part load cooling requirements. If baseline conditions are known (system operating hours, part load requirements, part and full load COPs) the calculation is

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* EER or SEER are often used, instead of COP.

straightforward. However, it is difficult to assess savings potential from a change in COP without these parameters. For example, two buildings with identical equipment COPs may be have very different cooling requirements, due to differences in operating hours and part load cooling requirements.

Part-load performance. Part load performance of cooling equipment complicates efficiency evaluation. Equipment operating at a particular COP at full load may operate at a significantly different COP at part load. In most commercial buildings today, equipment is sized to meet the peak load of the building (plus an additional safety factor, in many cases). The total equipment capacity will only be required a few hours every year. Some equipment operates at about the same efficiency at part load as it does at full load, but equipment seldom performs better at part load. For example, centrifugal chillers perform slightly better than rated between 60 and 80% of full load, and poorer than rated at less than 50% of full load. Many of the conservation strategies we have discussed are aimed specifically at operating equipment at as close to maximum efficiency operating conditions as possible. It is imperative to understand the variations (daily and seasonal) in a building's cooling load profile. The impact of these variations on equipment performance is discussed as each technology is considered.

Systems tradeoffs. Some equipment strategies eliminate mechanical cooling at the expense of increasing air transport equipment energy consumption. The net result should be a savings, but can be affected by interactive effects between end uses, as well as conservation measures implemented for air transport equipment. (See section 2.6)

Once cooling loads are established, operation of an economizer (if one is present) and system type determine building mechanical cooling needs, and will determine the savings potential and cost-effectiveness of cooling equipment strategies (see HVAC Systems, section 2.4.3). In our estimates of savings potential, we have attempted to isolate these effects, with the help of DOE-2 simulations on an office building module. (See Appendix 2-A)

Compression Refrigeration Cycles

Most cooling in commercial buildings is done by a compression refrigeration cycle. The components are compressors, condensers, evaporators and expansion devices. In addition to their relatively low first cost, compression refrigeration cycles are available over a wide range of sizes, and provide different coil temperatures over a wide range of ambient conditions. The major differences in the types of refrigeration machines are the method of compression, and the method of condenser cooling.

Compression Techniques

There are three types of commercial cooling compressors: reciprocating, centrifugal, and screw. Reciprocating compressors are most common in small and mid-size, all-air systems. Centrifugal compressors are most common in large, chilled water systems. Screw compressors, although less common, are used in both air and water systems, in mid-range sizes.

Compression systems remove heat from an air stream by either 1) sending cold refrigerant to the cooling coils (direct expansion (DX) system), or 2) sending cold refrigerant through a heat exchanger to cool water which is then sent to the cooling coils. Larger systems (above 60 tons) typically use chilled water systems, while smaller systems use all air systems. Since the methods for improving efficiency are different, each will be considered separately below.

Reciprocating Compressors

Improvements in reciprocating compressor performance can be made by replacing the existing unit with a more efficient model, or retrofitting the existing unit to improve either full or part load performance. Generally, it is not cost effective to remove a working unit and replace it with a new one, due to high first costs. However, it nearly always pays to select a high efficiency compressor for new systems or replacement of failed units.

Improvements in rated performance. As energy conservation has become a higher priority in specification of cooling equipment, manufacturers have been designing compressors with increasingly higher efficiencies. Industry standards, and, in California, state mandates, have been set to ensure improvements in the stock of equipment in new and existing buildings. See the summary sheet, High Efficiency Mechanical Cooling Equipment, for details on equipment performance by type.

Improvements in part load efficiency. Even though two pieces of cooling equipment may be the same size and have the same performance rating, they may operate quite differently over their range of output. These variations depend on two factors: how the compression system is designed to respond to changes in cooling loads, and how the compressor is unloaded to produce only a part of its full load output.

Many systems cycle to meet a given load. If that load is cut in half, the compressor operates for half as much time. However, start up inefficiencies and potential short cycling problems will reduce COP at reduced loads. This is typical of package units and single zone systems. [1] There are other methods to modulate capacity. Cylinder unloading shuts off the intake supply to one or more cylinders, eliminating unnecessary cylinder pumping. Hot gas bypass reroutes part of the output of the compressor to the inlet. This control method is inexpensive, but is also very inefficient at part load. Two speed (or variable speed) motors, or multiple, smaller compressors can also improve part load operation.

Centrifugal Water Chillers

As of 1981, approximately 16% of all new comfort cooling capacity nationwide (residential included) used chilled water systems. Water chillers made up 44% of the large commercial building market. Table 2-5 summarizes U.S. chiller installations by type. Due to the dominance of centrifugal chillers in the stock, they have been emphasized in this report.

Table 2-36

Installed Chiller Tonnage, by type, U.S., 1981 [2]

Type	Annual Tons	% of total
Reciprocating	364,000	21
Centrifugal	1,215,000	70
Absorption	69,000	4
All other	87,000	5

Improving full load performance. As with other types of refrigeration equipment, significant improvements in water chiller performance have been made in the last few years. See the summary sheet, High Efficiency Mechanical Cooling Equipment, for a comparison of available chiller COPs and past and proposed equipment standards. There are three ways to improve efficiency: increased heat transfer surfaces, variable entering water temperatures, and increased compressor efficiencies. [3]

Chiller optimization. In centrifugal chillers, inlet guide vanes regulate the flow of refrigerant into the compressor and control the amount of cooling produced. Depending on the type of compressor, inlet vane control can be in 5-25% increments. Most centrifugal chillers are supposed to operate at COPs higher than their full load COP between 40 and 90% of full load. There are limited data available on actual chiller performance at part load conditions. One study measured chiller input kW at various part load ratios. Actual performance was within 5% of manufacturer's data between 90 and 110% of full load output, within 15% between 60 and 90% of full load, and just over 15% at about 40% of full load. It should be noted that actual performance was poorer than predicted by the manufacturer's data. [4]

Cooling equipment auxiliaries (cooling tower pumps and fans, chilled water pumps) can become a significant part of energy consumption at part load, since the compressors may be off or unloaded 50-90% of the time while auxiliaries may run continuously.

Standards. At this time, there has been little activity towards developing part load efficiency standards for water chillers. [5]

2.3.3 Economizer cycles

Concept. Commercial building cooling requirements are primarily due to internal gains and solar gains. Outside air can, at certain times, be used to remove heat from internal spaces directly. An economizer cycle exhausts return air from a building, brings in outside air whenever conditions are favorable. More specifically, whenever the heat content (enthalpy) of the outside air is below that of the return air, less energy is needed to cool the outside air than is needed to recool the return air.

Equipment. Economizer equipment consists of temperature sensors, dampers, and damper controls. Temperature sensors in the return and outdoor air supply streams determine when the return and outdoor air dampers should be opened to bring in outside air and exhaust return air. When the outdoor air is colder than the return air, return air is exhausted. When the outdoor air temperature is higher than the return air, outdoor air intake is kept to a minimum. If the outside air intake satisfies all cooling needs, the control system turns off the mechanical cooling equipment. At warmer outdoor air temperatures, some mechanical cooling will be required to bring the air down to the desired temperature. Some ecoomizers are controlled by outside temperature only. Savings with this type of control will be lower.

Under certain ambient air conditions, the humidity of the outside air will be too high to meet space requirements, even if the dry bulb temperature is below the inside temperature. In these cases, it is preferable to sense enthalpy (latent and sensible heat content) differences between return air and outside air, as removing humidity from outside air can be more energy intensive than sensibly cooling return air. In most areas of California, this is not the case. Further, enthalpy sensors are more expensive and are difficult to maintain. The increased savings potential of enthalpy control has not been analyzed in this report.

Savings Analysis. The cooling loads which can be avoided with economizer operation are affected by three variables: outside air conditions (as given by climate zone), internal and external loads (as given by climate zone and building configuration), and HVAC system parameters (supply air temperatures and space temperatures). If all these conditions are known, along with either the baseline consumption or the system COP without the economizer, savings estimates can be made.

We chose to run DOE-2 simulations on an office building module (see Appendix 2-A) to evaluate the savings potential of economizer installation, given these different parameters. We found that:

1. Economizers significantly reduce cooling consumption in the climate zones examined (Fresno, LA, SF), which span the conditions found in the PG&E and SCE service territories.

2. Within a climate zone, economizer savings potential is most sensitive to HVAC system type (VAV vs. constant volume).

3. Outside air lock-out temperatures, building internal loads, and building operating hours are less important in determining savings.

Figures 2-1 through 2-4 summarize the results of our analysis of the impact of climate zone and system type on economizer performance. These graphs of monthly cooling energy show that buildings in San Francisco can run an economizer almost all the time. In this mild, coastal climate, temperatures are above 70°F for about 600 hours per year, and are above 75°F for about 200 hours per year. Fresno, on the other hand, gains almost nothing from an economizer during the summer months. However, Fresno buildings can eliminate almost all mechanical cooling during the winter and transitional months. Between November and April, Fresno has 100 hours above 75°F, and 250 above 70°F. Los Angeles falls somewhere in between San Francisco and Fresno. [6]

As explained in section 2.5, economizers in VAV systems result in lower percentage reductions in cooling energy consumption than economizers in constant volume, variable temperature systems. VAV systems can not take full advantage of economizer operation during low load periods, due to low air flow rates (and correspondingly low supply air temperatures).

Table 2-37 shows the effects of some of the secondary parameters that have an impact on economizer savings. Savings will also vary with building schedule. Buildings with 24 hour schedules typically include hotels, hospitals, light industry and restaurants. Retail and office operation may vary between 10 and 18 hours per day. Since outdoor air conditions vary greatly over a 24 hour period, buildings that operate more during cooler hours will be able to offset more mechanical cooling.

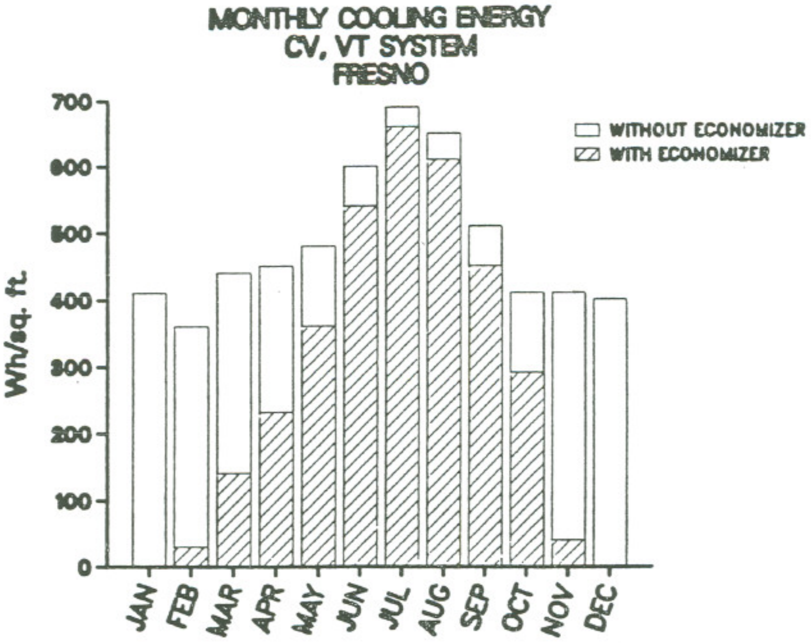


Figure 2-1. Monthly cooling energy usage, with and without economizer cycle: Constant volume, variable temperature system, Fresno. Based on building module simulations.

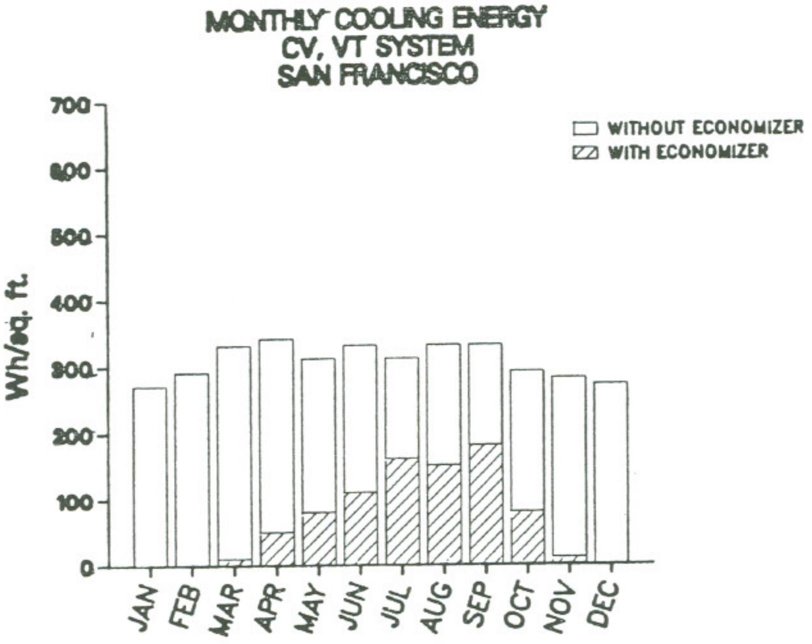


Figure 2-2. Monthly cooling energy usage, with and without economizer cycle: Constant volume, variable temperature system, San Francisco. Based on building module simulations.

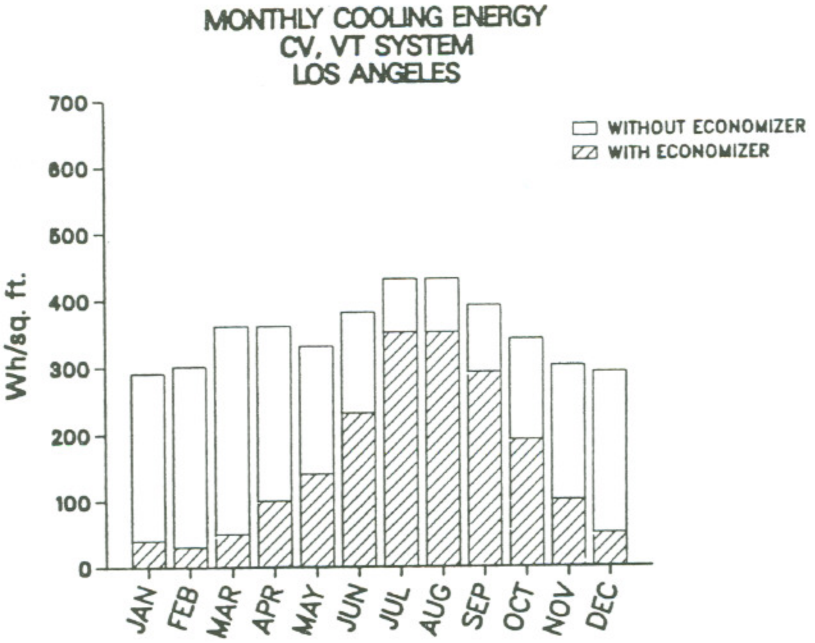


Figure 2-3. Monthly cooling energy usage, with and without economizer cycle: Constant volume, variable temperature system, Los Angeles. Based on building module simulations.

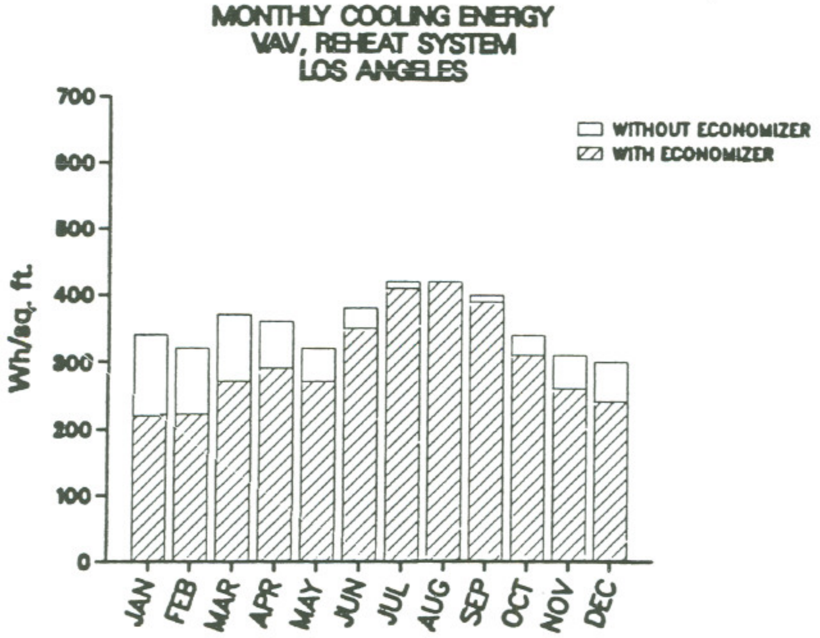


Figure 2-4. Monthly cooling energy usage, with and without economizer cycle: Variable-air-volume, reheat system, Los Angeles. Based on building module simulations.

Table 2-37
System Configuration and Climate Variations - Dry Bulb Economizer

BUILDING/SYSTEM CONFIGURATION [1]	PERCENT SAVINGS WITH ECONOMIZER [2]		
	Los Angeles	San Francisco	Fresno
2.7 w/ft^2 lighting			
Supply air min = 55° Economizer lockout = 72°	55%	77%	42%
Supply air min = 55° Economizer lockout = 68°	50%	74%	39%
Supply air min = 60° Economizer lockout = 72°	61%	77%	44%
1.7 w/ft^2 lighting			
Supply air min = 55° Economizer lockout = 72°	60%	-	-

Notes

1. All systems are constant volume, variable temperature systems.
2. Percent savings are based on a base case which is same configuration without an economizer. Blank spaces indicate no simulation run. Savings include reductions in chiller, cooling tower pump and fan, and chilled water circulation pump consumption. See Appendix 2-A for simulation details.

Economizer performance is typically stated in terms of mechanical cooling avoided, and, as such, an economizer is a cooling load reduction, not a piece of equipment actually producing a cooling effect. Therefore, it is not correct to express performance of the contribution of the economizer in terms of a COP. One could, however, impute a COP to performance of "economizer aided" cooling equipment:

$$COP_e = \frac{\text{(load met by economizer + load met by cooling equipment)}}{\text{energy input to cooling equipment}}$$

Table 2-38 presents this COP for two system types, with and without an economizer, for Los Angeles.

Table 2-38

Overall COP, with and without economizer

(Los Angeles)

	COP without economizer	COP with economizer
Const Vol, Var Temp	2.7	6.1
Variable Vol, Reheat	2.6	3.1

When an economizer is able to meet only part of the cooling load, cooling equipment must run at lower part load ratios. The COP of the cooling equipment depends on the equipment part load curve. [7]

Standards. California's Title 24 Standards for new non-residential buildings require systems of greater than 134,000 Btuh cooling capacity or 5000 cfm air flow to include economizer controls to allow for 100% outside air intake (with certain exemptions). [8] The proposed ASHRAE 90 standards require economizers for systems providing more than 3000 cfm air flow. [9]

2.3.4 Off peak cooling

As the differences between utility charges for peak and off peak energy and power increase, strategies for eliminating or offsetting cooling equipment operation during peak periods look attractive. Most traditional cooling systems are designed to meet the cooling load as it appears, and the highest cooling loads generally coincide with the utility's peak hours. This section considers sizing options for ice and chilled water storage systems specifically aimed at reducing peak period electricity usage for cooling.

Thermal Energy Storage (TES)

Thermal energy storage systems level out or eliminate peak cooling by storing cold, generated during off peak hours, and then used as it is needed during peak periods. Thermal storage also shifts energy consumption (kWh) off peak, which benefits customers who are on time-of-use rates. Generating and storing cold before it is needed allows equipment to operate at close to its full load efficiency at all times, and, in some cases, allows for equipment to be downsized.

The method of storage can be water, ice, other mass (concrete, gravel or rock) or phase change materials. Descriptions of each type of storage media are given in the summary sheets. Below, we present some examples of different storage sizing options, and comparisons of their impact on monthly peak cooling demands and energy consumption.

Partial vs. full storage capability

The amount of storage installed determines how much cooling demand and energy consumption will be shifted off-peak, as well as how much mechanical cooling equipment can be downsized, compared to a conventional system. The size of the storage tank (or tanks) dominate the total installed cost of the storage system. Partial storage generally means that storage is sized so that chillers will run continuously on the peak cooling day. During non-cooling periods, chillers run to charge the cold storage supply. During cooling periods, cold (usually as chilled water) is drawn out of storage, and chillers run as a supplement. Since the chillers operating alone meet part of the daily cooling load, the size of the storage system is less than the daily cooling load on the building's peak day. At the same time, part of the peak cooling load remains on peak. Full storage systems are sized to meet all of the building's cooling needs on the peak day; chillers never run to cool the building directly.

Clearly, storage systems could be sized anywhere between these two extremes. For example, it may be most economic to size a system to eliminate chiller operation during utility peak periods only. [10] These tradeoffs between storage system first cost and operating costs depend primarily on the building rate structure (specifically, cost differentials between off-peak, mid-peak, and on-peak energy and demand charges), and are outside the scope of this report.

Demand impacts. Once a storage system has been sized, the monthly peak demand shifted off-peak is determined by mechanical cooling equipment type, and the use of an economizer cycle (as well as other building configuration parameters). There may only be a small variation in monthly peak cooling demands, since the cooling equipment only needs to come on once at full load in order to record a high demand for that month. This may not be the case if chilling equipment operates at less than full load throughout the month, due to consistently low cooling loads. (This may be the case with centrifugal chilling equipment.) If an economizer cycle eliminates mechanical cooling completely during the coolest months, the cold storage system will not shift any demand.

A full storage system will shift all conventional equipment demand, except for chilled water pumps, which still run while cooling loads are being met by storage. (In our DOE-2 building module runs, chilled water pumping power was between 5 and 20% of total cooling equipment power.) A partial storage system will shift between 40 and 70% of cooling equipment power during the peak month, and will be able to shift all but chilled water pump power in cooler months, when the storage capacity will be able to meet all of the building's cooling needs.

Energy impacts. As shown in Figures 2-1 through 2-4, variations in climate zone and HVAC system type result in variations in monthly cooling energy consumption. There are similar variations in daily cooling energy profiles: on some days, cooling loads occur during on-peak periods only; on other days, cooling loads occur during all periods. Shifts in energy consumption result in cost savings to customers on time-of-use rates only.

Improvements in mechanical equipment performance. Often, ice and chilled water storage systems are promoted for improving mechanical equipment COPs, since equipment can run at close to full load, and at lower condensing temperatures (nighttime operation). However, it is unlikely that this improvement will justify the cost of the storage system. For storage to be justified on performance improvement alone, conventional equipment must have been operating at very poor part load conditions. (Centrifugal chillers, for example, operate at highest efficiency at about 60% of full load, not at 100% load.) Second, even though storage COPs may be slightly higher, equipment will run longer in order to make up for thermal losses. It is true that condensing temperatures at night are lower than those during the day. Ice storage systems also pay a penalty for operating at much lower evaporating temperatures.

Mechanical equipment sizing. One attraction of ice or chilled water systems in new construction is the opportunity to reduce mechanical cooling equipment first costs, which helps to defray the cost of the storage tanks. Cooling plant downsizing is not generally an option on retrofits, since cooling equipment is already in place. This can make full storage strategies more attractive on retrofit projects. Renovations or expansions are often good opportunities for cold storage system installation; increased cooling loads can be met with existing equipment.

2.3.5 Emerging technologies: prospects for the future

Even with the wide range of cooling equipment available, there is a great deal of research and development going on to improve on existing equipment and to develop new technologies. This section reviews this research, and briefly describes two on-site power generation technologies. (These are not cooling technologies, but are often dependent upon building cooling needs and equipment for successful implementation.)

Active solar cooling. [11] Current active solar cooling research and development centers on 1) absorption cycle systems, 2) vapor jet systems, 3) rankine cycle systems, and 4) zeolites. All of these technologies have to overcome cost or technological barriers before they will be cost-effective at electricity prices less than 10 cents per kilowatt-hour.

Absorption cycles utilize conventional absorption equipment (see summary sheet on gas absorption chillers) in conjunction with some type of solar heat collection. Present COPs range from 0.6 to 0.7, 20% of common COPs of vapor compression equipment. Further, costs are high, at about $8,000 to $8,500 per ton.

Vapor jet systems produce a cooling effect through the continuous vaporization of the working fluid in the evaporator at low pressures. Used with flat plate collectors, COPs are between 0.1 and 0.2. With focussing collectors, COPs may be as high as 0.6. Costs are estimated at $3000 per ton.

Rankine cycle systems use solar-powered turbines to generate electricity to run a conventional vapor compression cycle. Solar rankine engine conversion efficiencies are about 10%. If seasonal collector efficiencies are 40%, the overall performance will only be 4%. Focussing collectors could provide 300°F heat to drive engine efficiencies to 20%, but collector efficiency will drop.

Zeolite collectors exploit diurnal temperature swings, and using an adsorbent and daily solar heat inputs, store cold at night. Installed cost is estimated at $1000 per ton. [12]

Passive solar cooling. The most promising passive cooling strategy is probably daylighting (see Chapter 6). Beyond daylighting, night venting, evaporative cooling, desiccant dehumidification, and ground cooling are considered by some to be passive cooling strategies, even though they require mechanical devices, such as fans and pumps. These have been covered to some extent in the summary sheets, and research in these areas is continuing. [13]

Cogeneration systems for commercial buildings. Any building with both thermal and electrical needs is a candidate for cogeneration. If a commercial building has a fairly constant thermal load, it may be able to benefit from installing a gas turbine or diesel engine to generate electricity, and use the waste heat to meet thermal needs. Using waste heat to run an absorption chiller makes cogeneration an interesting option. However, a recent LBL study [14] shows that it is unlikely to be profitable, given utility purchase prices, building load profiles, and the poor performance of absorption chillers compared to electric vapor compression machines. Noise, vibration, and air pollution problems with standard cogeneration equipment may delay or prevent their wide spread use in commercial buildings.

Fuel Cells. On site fuel cells, used to provide both electricity and heat from one fuel source, are now being developed, tested and installed in commercial buildings. In theory, fuel cells can provide very high conversion efficiencies by converting chemical energy into electricity and heat without an intermediate combustion step. Like standard cogeneration equipment, fuel cells also produce fairly high grade heat ($160\text{-}275^{\circ}$F), which could be used to run a heat-operated absorption chiller. Major advantages to fuel cells over standard cogeneration equipment include quiet operation and virtually no air pollution.

Test units being installed now are rated at 80% overall efficiency at full load (40% electrical and 40% thermal). Predicted costs are in the range of $850-$1250/kW, once the units reach full commercial development. The Gas Research Institute (GRI) and the Department of Energy are sponsoring several field installations, in cooperation with several utilities. Both PG&E and SCE will have test installations in their service territories. Present research aims for full market availability by the 1990's. [15]

Notes

1. Science Applications, Inc., "The Development of Minimum Efficiency Standards for Large Capacity Air Conditioners, and Commercial Water Heaters, Refrigerators and Freezers." Final Report, prepared for the California Energy Resources Conservation and Development Commission (CEC), May 8, 1979, pp 7-6 - 7-8.

2. W.J. Coad, "Water Chillers: Changing Technology," *Heating, Piping, Air Conditioning,* July 1981.

3. We have not covered the engineering complexities involved in improving chiller performance. Several papers have been written on this subject, however, and we direct the interested reader to some of these for more detail:

    a. William J. Landman, "The Search for Chiller Efficiency," *Heating/Piping/Air Conditioning,* July, 1983, pp 77-62.

    b. William J. Coad, "Water Chillers: Changing Technology," *Heating/Piping/Air Conditioning,* July, 1981, pp 35-41.

4. R.J. Hackner, et al., "HVAC System Dynamics and Energy Use in Existing Buildings," ASHRAE *Transactions,* Vol. 90, Pt. 2, 1984. This report also includes monitored data on condenser water temperatures with changes in fan speed, and methods of simulating cooling equipment performance.

5. "Recommendations for Energy Conservation Standards and Guidelines for New Commercial Buildings," Vol. 2. Battelle Pacific Northwest Lab, October 1983, pp 7-21.

6. U.S. Departments of the Air Force, Army, and Navy, *Engineering Weather Data,* July, 1978. This weather data is from binned hourly temperatures. The weather station at Castle Air Force Base, Merced, was used for Fresno, Alameda Naval Air Station for San Francisco, and Los Angeles International Airport for Los Angeles.

7. For the economizer runs done for the building module, the COP of the cooling *equipment* decreased between 5 and 15%.

8. California Energy Commission, "Express Terms of Committee Proposed Energy Efficiency Standards," Building Conservation Committee, Report P400-83-032, August 2, 1983.

9. Battelle, op cit.

10. Commercial buildings in the SCE and PG&E service territories have significant cooling needs during partial or mid peak periods. (On-peak periods: 12:30-6:30 PM (summer) and 4:30-8:30 PM (winter) for PG&E; 1:00-7:00 PM (summer) and 5:00-10:00 PM (winter) for SCE.)

11. Further information is available in the report, "Assessment of Electric Power Conservation and Supply Resources in the Pacific Northwest," Vol. II: Supplement C, Solar Energy in Commercial Buildings, Battelle Pacific Northwest Laboratories, March, 1983. (Draft)

12. See also Charles Redman, "Testing of Zeolite Augmented Ice Storage and Utilization," *Proceedings of the DOE Physical and Chemical Energy Storage Annual Contractors' Review Meeting,* September, 1983.

13. U.S. DOE, "Passive Cooling Technology Assessment: Synthesis Report," June, 1982. LBL-14558 (Draft).

14. Joseph H. Eto, "Commercial Building Cogeneration Opportunities," presented at the ACEEE Summer Study, Santa Cruz, CA, August, 1984.

15. Richard R. Woods, Jr., "Onsite Fuel Cells - A Business Opportunity for Utilities," *Gas Research Institute Digest,* (GRID), March/April 1984.

2.4 HVAC SYSTEMS

2.4.1 Introduction

A building's HVAC system transfers the output from the primary cooling and heating equipment to the building zones in order to satisfy heating and cooling loads. These loads vary across zones and through time, and different systems and control strategies are used to respond to these variations. Common HVAC system types are variable-air-volume, dual-duct, and constant-volume reheat. In addition, a given system type can often be controlled in several different ways. This section explains how different systems and control strategies affect energy consumption.

We have chosen to discuss HVAC systems in the cooling section of this documentation. In fact, the type of HVAC system used has a large impact on the air transport and heating end-uses also. Our discussion will address the effects on these end-uses to the extent possible.

Table 2-39 illustrates the variation in energy use for seven different HVAC system configurations. The results are from DOE-2 computer building simulations of the office building module described in Appendix 2-A. The building, chiller, presence of an economizer, and boiler were not changed while the system configuration was varied. There is greater than a factor of two difference in the low and high energy use values for both the cooling and air transport end-uses. The low and high values for heating are a factor of ten different; the high values are associated with systems that use a large amount of reheat, heating for the purpose of controlling the amount of cooling delivered. Further information on the system types we simulated is presented in section 2.4.4.

TABLE 2-39

Energy-Use Variation due to HVAC System Type [1]
Los Angeles, Office Building Module

End-Use	Range of Energy Use Across HVAC System Types	Energy Unit
Cooling	1.9 - 5.0 kWh/ft^2-yr	Site
Air Transport	1.6 - 3.7 kWh/ft^2-yr	Site
Heating	4 - 40 kBtu/ft^2-yr	Site
Total HVAC	44 - 110 kBtu/ft^2-yr	Source

1. From DOE-2 simulations of seven different HVAC systems. Heating is assumed to be supplied directly from fossil fuels, so energy use is expressed in kBtus, not kWh. Source energy accounting was used to combine end-uses into a total; electric energy is multiplied by three before being added to fuel energy. A number of the systems simulated did not comply with the new 1987 Title-24 office building standards.

The specific simulation results have relatively limited applicability because of the fixed configuration of our test building module; however, the simulation results identified two key factors that explain much of the variation in energy use across system type:

1) Systems that are not "load-responsive" have high cooling and heating energy use. These systems wastefully utilize large amounts of simultaneous heating and cooling (SHC), or they overcool spaces.

2) For load responsive systems, two methods are available to vary the amount of cooling supplied to a space: vary the supply air temperature, or vary the supply air flow rate. The choice of method affects energy performance.

Sections 2.4.2 and 2.4.3 discuss these factors. Section 2.4.5 shows how the concepts presented can be used to explain the variation in energy use of the seven system configurations.

2.4.2 Load Responsiveness

For some systems, the amount of cooling produced at the central air conditioning unit does not vary significantly with variations in the total building cooling load. An extreme example of this is a constant-volume constant-temperature reheat system. With such a system, a constant flow of cool air at a fixed temperature is produced by the central unit, and reheat is utilized at individual zones to control the temperature of the air so that overcooling does not occur. (Or, reheat is *not* used and the spaces are overcooled.) Simultaneous heating and cooling (SHC) or overcooling is the main characteristic of systems that are *not* load responsive, and this is wasteful of cooling energy and heating energy. (It is not wasteful of heating energy if reheat is not used and overcooling is allowed to occur.) These systems do provide better humidity control, but, because of low outdoor humidities, this feature is generally not necessary in California commercial buildings.

HVAC systems can be made more load responsive and, therefore, less wasteful of cooling and heating energy by either varying the volume or the temperature of the air supplied in response to a load change. Variable-air-volume (VAV) systems use the first method. The supply air temperature is fixed, but supply terminals at each zone have controllable dampers that vary the volume of cool air supplied to the zone according to the magnitude of the cooling load. The air flow at the main fan varies according to the sum of the individual zone loads. This method does not make the HVAC system totally load responsive, because the VAV terminal boxes will not reduce air flow below some minimum level, a level sufficient to meet outside-air requirements and maintain reasonable air velocities in the space. If the minimum level is reached in a zone, reheat is used upon further reductions in cooling load, or the zone is allowed to be overcooled. Consequently, the amount of cooling supplied at the main air conditioning unit is unaffected by these reductions in space loads.

The second method for making HVAC systems more load responsive is to vary the temperature of the air supplied to the zones instead of supplying constant temperature air and reheating it to the proper temperature. Systems using this method are classified as constant-volume variable-temperature systems. There are several different ways of controlling the temperature of the supply air. The most efficient way is to cool it to a temperature that is just sufficient to meet the cooling load of the warmest zone. The other zones will also be supplied air at this temperature, and overcooling will occur unless reheat is used. Thus, this systems is totally responsive to the cooling load in the warmest zone, but unresponsive to loads in the other zones. (However, the location of the warmest zone changes throughout the day. The control circuitry monitors a variety of zones to determine which one is currently the warmest.) The new Title-24 office standards (mandatory for new construction in 1987) require that all new office buildings with constant-volume HVAC systems use warmest-zone reset of supply air temperature.

Another method for controlling the supply air temperature is to reset it according to the outside air temperature. This control method assumes that the magnitude of the building cooling load is related to the outdoor temperature. As the outdoor temperature increases, the supply air temperature is decreased on the supposition that the building cooling load has increased. This method does not track the actual load in the building, so it is not as efficient or reliable (there is a chance for undercooling) as warmest-zone reset.

Warmest-zone supply air reset can also be used to improve the load responsiveness of VAV systems. If the VAV terminal in the warmest zone reaches its minimum stop, the supply air temperature is reset upwards to avoid overcooling or the use of reheat. This system is the most load responsive of the systems disussed so far. The new Title-24 office standards require that new office buildings with VAV systems use the warmest-zone reset technique.

The previous discussion suggests that controlling an HVAC system to be load responsive is difficult if that system serves multiple zones. One way to circumvent this problem is to use separate systems for each zone. The systems can respond to their zones independently, and simultaneous heating and cooling can be avoided. This approach can have high capital costs but is optimal for some situations.

2.4.3 Variable-Volume vs. Variable-Temperature: Other Issues

The previous section showed that HVAC systems can respond to cooling load changes by varying the supply air flow rate or by varying the supply air temperature. Both techniques work well for improving the load responsiveness of a system, but there are other characteristics of these techniques that have important energy use implications. This section discusses a few of those characteristics.

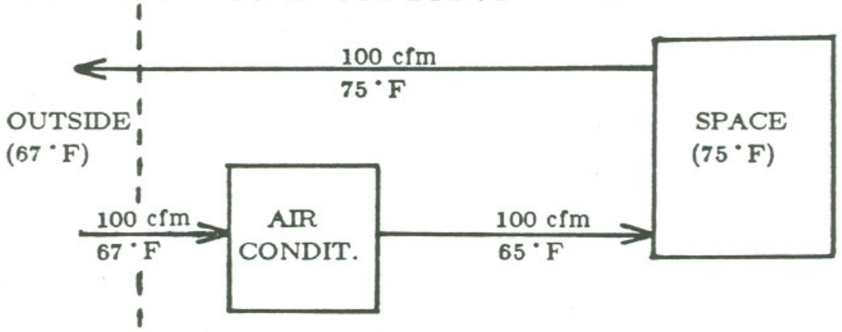
The major advantage of variable-air-volume systems is very low air transport energy use. The energy consumption from HVAC air transport fans is often the largest HVAC energy end-use, larger than cooling or heating. Since variable-air-volume systems reduce air flow rate during part-load conditions, these systems reduce air transport energy consumption. (See the air transport section, section 2.6, for more discussion.) In addition, the energy used by the air transport fans appears as heat in the building, which often needs to be removed by the cooling system. The fans for variable-air-volume systems contribute less cooling load because of their low energy use. Because of these advantages, variable-air-volume systems generally have lower total HVAC energy use than constant-volume variable-temperature systems.

Another important difference between variable-air-volume systems and variable-temperature systems is the magnitude of the cooling effect produced by an economizer. During part-load cooling conditions, a VAV system operates at lower air flow than a comparable constant-volume system. If the outside conditions permit operation of the economizer, the constant-volume system will realize a larger cooling effect from the outside air because its air flow rate is larger. This effect can have a significant impact on the relative cooling energy use of these two system types when used in California climates.

Figure 2-5
Economizer Performance: Variable-Temperature vs. VAV

75 °F Space Temperature
67 °F Outdoor Temperature
Cooling Load = 50% of Peak
Peak Supply Air Conditions = 55 °F, 100 cfm

CONSTANT-VOLUME VARIABLE-TEMPERATURE SYSTEM

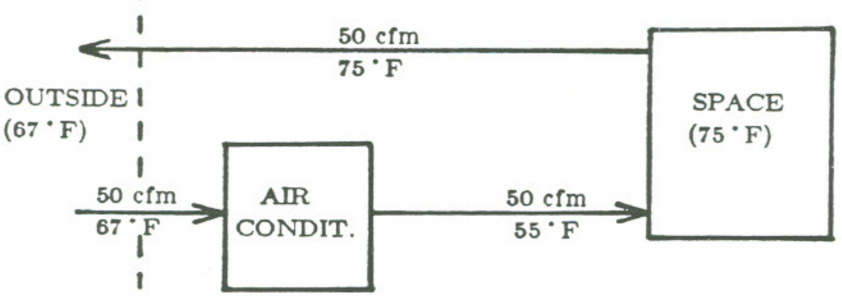


Total Space Cooling = (75 °F - 65 °F) x 100 cfm x 1.08.Btu/hr- °F-cfm
= 1080 Btu/hr (100%)

Mechanical Cooling = (67 °F - 65 °F) x 100 cfm x 1.08 Btu/hr- °F-cfm
= 216 Btu/hr (20%)

Economizer Effect = 1080 Btu/hr - 216 Btu/hr
= 864 Btu/hr (80%)

VAV SYSTEM



Total Space Cooling = (75 °F - 55 °F) x 50 cfm x 1.08 Btu/hr- °F-cfm
= 1080 Btu/hr (100%)

Mechanical Cooling = (67 °F - 55 °F) x 50 cfm x 1.08 Btu/hr- °F-cfm
= 648 Btu/hr (60%)

Economizer Effect = 1080 Btu/hr - 648 Btu/hr
= 432 Btu/hr (40%)

Figure 2-5 illustrates this effect. The figure shows how a VAV system and a constant-volume variable-temperature system, both with economizers, respond to a zone with a cooling load equal to 50% of the zone's peak cooling load. The outside air is at 67 °F, so the economizer is admitting 100% outside air and exhausting all of the return air. The constant-volume system uses less mechanical cooling because the economizer meets 80% of the total cooling load; the economizer meets only 40% of the cooling load when using the VAV system.

Another difference in cooling energy use between VAV systems and variable-temperature systems is due to differences in latent cooling. VAV systems have the same supply air temperature at part-load and full-load, but variable-temperature systems increase supply air temperature at part-load. Thus VAV systems have lower supply air temperatures on average, so moisture removal and therefore cooling energy consumption are greater. In many California commercial buildings, the extra moisture removal is not necessary because of low outdoor humidities, so the increased cooling energy consumption produces little benefit.

In summary, VAV systems usually have lower *overall* HVAC energy use than variable-temperature systems because of very low air transport energy consumption. However, when comparing a VAV system against a variable-temperature system, both of which are load responsive, the variable-temperature system will generally have lower *cooling* energy use because of two factors:

1) An economizer produces a larger cooling effect when used with a variable-temperature system.

2) VAV systems remove more moisture and therefore consume more energy to do the latent cooling. The extra moisture removal may or may not have significant comfort benefits.

2.4.4 Performance Summary of Seven Systems

This section summarizes the results of our DOE-2 simulations of seven different HVAC systems and shows how the concepts previously presented can explain the variations in energy use. The simulations were done for the Los Angeles climate, and the building configuration modeled was the standard office module used throughout our simulation studies. (See Appendix 2-A.)

Table 2-40 indicates the energy consumption across end-uses for each system type. The consumption is expressed as low, medium, high, or very high; our analysis was not comprehensive enough to justify giving numeric energy consumption results for the specific system types. Detailed descriptions of the system types are given in Table 2-41.

The cooling energy use results can be explained as follows. Systems 1 and 3 are not load responsive and utilize large amounts of simultaneous heating and cooling; these systems have the highest cooling energy consumption. Systems 2 and 4 vary the cooling supply air temperature according to the warmest zone; these systems are load responsive and have the lowest cooling energy use. The VAV systems, systems 5 through 7, have moderate cooling energy use; the systems *are* load responsive, but the two factors mentioned in the previous section (especially the economizer effect) cause these systems to have higher cooling consumption than systems 2 and 4.

Table 2-40 also shows a large difference in air transport energy use between constant-volume and variable-volume systems. Air transport energy use for VAV systems is about half that of constant-volume systems when using inlet vanes to control the VAV fan.

Heating energy use is a strong function of the amount of simultaneous heating and cooling used by the different system types. Once again, systems 1 and 3 have high heating energy use because they are not load responsive and use large amounts of heating energy to control the amount of cooling delivered. All the systems that employ warmest-zone supply air reset (systems 2, 4, and 7) have low heating energy use. Systems 5 and 6, the VAV systems without warmest-zone reset, have moderate heating energy use; much simultaneous heating and cooling is eliminated by use of VAV, but a moderate amount of reheat occurs when the VAV terminals are at their minimum stops.

The VAV systems have the lowest *total* energy use because of their low air transport energy use. The systems that are not load responsive are the highest users, and the others lie in the middle, although they are much closer in energy consumption to the VAV systems than the systems that are not load responsive.

TABLE 2-40

End-Use Energy Consumption for Seven HVAC Systems

System Type	Cooling	Air Transport	Heating	Total HVAC
1) Constant-Volume, Constant Temperature w/ Reheat.*	H	H	VH	VH
2) Constant-Volume, Warmest Zone Supply-Air Reset.	L	H	L	M
3) Dual-Duct, Constant Hot and Cold Decks.*	H	H	H	H
4) Dual-Duct, Hot and Cold Deck Reset According to Worst Zones.	L	H	L	M
5) VAV Dual-Duct, Constant Hot and Cold Decks, 30% Minimum Stop.*	M	L	M	L
6) VAV Constant Temperature, 30% Minimum Stop.*	M	L	M	M
7) VAV, Warmest Zone Supply Air Reset, 30% Minimum Stop.	M	L	L	L

NOTE: All Systems have Economizers. All VAV Systems use Inlet-Vane Fan Control.

L = Low
M = Medium
H = High
VH = Very High

* - Denotes a system prohibited by the 1987 Title-24 office building energy-standards for new construction.

TABLE 2-41
HVAC System Type Descriptions

System Type	Description
1	This system always supplies a constant volume of air at 55 °F to each zone, and the air is reheated at the zone to the temperature necessary to meet the zone's cooling or heating load. (Prohibited by 1987 Title-24 office building standards for new construction.)
2	Same as system 1 except that the supply-air temperature is continuously reset so that the cooling load of the warmest zone in the building is just met by the air. No reheat is used in the warmest zone, but reheat is used in the other zones to prevent overcooling.
3	This is a dual-duct system with a 55 °F cold-deck and a 95 °F hot-deck. (The "cold-deck" is the duct supplying cold air to the zones.) (Prohibited by 1987 Title-24.)
4	Same as system 3, except that the cold deck temperature is continuously reset so that the cooling load in the warmest zone of the building is just met by the air. Likewise, the hot deck temperature is reset so that the heating load in the coldest zone of the building is just met by the air. This minimizes the amount of simultaneous heating and cooling that occurs while still supplying all space loads.
5	This is a dual-duct variable-air-volume system with the cold deck temperature constant at 55 °F and the hot deck temperature constant at 95 °F. To meet cooling loads less than design conditions, this system first reduces the amount of air delivered from the cold deck. If the cooling load drops below 30% of peak, total air flow is maintained at 30%, but part is delivered from the hot deck in order to prevent overcooling. (Prohibited by 1987 Title-24.)
6	This is a single-duct variable-air-volume system that delivers air at a constant 55 °F temperature. Cooling loads less than design conditions are met by reducing air flow. At loads less than 30% of peak, air flow is maintained at 30% and reheat is added at the zone to prevent overcooling. (Prohibited by 1987 Title-24.)
7	Same as system 6, except that if the VAV terminal for the warmest zone in the building reaches its 30% minimum stop, reheat is not employed to respond to a further reduction in cooling load. Instead, the supply-air temperature is reset so that cooling load in this zone is just met without reheat. (The other zones in the building will use reheat.)

2.5 COOLING LOADS

2.5.1 Introduction

Cooling loads refer to the heat and moisture additions to a building that need to be removed in order to maintain comfortable temperature and humidity conditions. This section discusses the different sources of cooling loads and considers different ways that the loads can be reduced. The treatment of energy conservation technologies is brief and conceptual; much more information concerning the technologies is contained in the cooling loads technology summary sheets.

Four major sections follow. Section 2.5.2 discusses the magnitudes of different cooling load components. Section 2.5.3 discusses a few general concepts that are important when considering ways to reduce cooling loads. The final two sections, 2.5.4 and 2.5.5, examine load components individually. The former covers internal loads (e.g., lights, equipment), and the latter discusses external loads (e.g., solar gains through windows, heat conduction through roofs).

2.5.2 Magnitude of Cooling Load Components

Table 2-42 gives annual and peak cooling loads per square foot of floor area for a typical office building in San Francisco, Los Angeles, and FresnO. Figure 2-6 presents the Los Angeles results in graphical form. The results are from DOE-2 simulations of the office building module used throughout this project. (See Appendix 2-A for more detail on the module.) The cooling loads in the table are *not* expressed in terms of cooling site energy consumption. These are the loads that are on the *output* side of the cooling equipment; the loads must be met by an air conditioning unit or the use of outside air (economizer cycle).

The cooling loads are separated into components in the table. The internal loads are heat gains that originate inside the building, including heat generated from office equipment, lights, or people. External loads are caused by gains from the outside environment such as conduction through roofs or solar gain through windows. It is important to note that the figures in the table are derived from a very specific building and operating situation. Key assumptions are stated for each component, and simple scaling of the loads can be used to estimate loads for buildings with other characteristics.

Some important conclusions can be drawn from the table and figure. The variation in annual and peak cooling load across the three climates studied is not great. This is partially due to the large contribution from internal loads, loads that do not vary with climate. There *is* significant variation across climates in the *site* cooling electricity consumption, because a much larger fraction of the cooling load can be met by outside air (economizer cycle) in San Francisco than in Fresno.

TABLE 2-42

Typical Cooling Loads, Office Building

LOAD COMPONENT	SAN FRANCISCO		LOS ANGELES		FRESNO	
	Annual Load kBtu/ft^2-yr	Peak Load Btu/hr-ft^2	Annual Load kBtu/ft^2-yr	Peak Load Btu/hr-ft^2	Annual Load kBtu/ft^2-yr	Peak Load Btu/hr-ft^2
INTERNAL LOADS:						
LIGHTS (2.7 Watts/ft^2, 2800 equiv. full-load operating hours per year)	18.5 (55%)	7.5 (35%)	19.6 (49%)	7.4 (28%)	19.6 (42%)	7.5 (29%)
PEOPLE (1 person/100 ft^2, 2200 equiv. full-load occupied hours per year)	7.2 (21%)	3.3 (15%)	7.4 (18%)	3.2 (12%)	7.4 (16%)	3.3 (13%)
AIR TRANSPORT SYSTEM (1.0 Watt/ft^2, 3000 operating hours per year)	6.5 (19%)	3.4 (16%)	6.9 (17%)	3.4 (13%)	6.9 (15%)	3.4 (13%)
MISC. EQUIP. (0.5 Watts/ft^2, 2200 equiv. full-load oper. hours/year)	3.0 (9%)	1.4 (7%)	3.1 (8%)	1.4 (5%)	3.1 (7%)	1.4 (5%)
EXTERNAL LOADS:						
WINDOWS (.105 ft^2 windows/ft^2 of total floor area, evenly distrib. on 4 bldg. sides, single pane, SC=0.6, U=0.9 Btu/hr-ft^2-°F)	4.3 (13%)	4.5 (21%)	6.6 (16%)	5.9 (23%)	9.5 (21%)	5.5 (21%)
ROOF (4 story building, solar abs. = 0.7, U=0.13 Btu/hr-ft^2-°F)	-0.3 (- 1%)	1.6 (8%)	0.5 (1%)	1.7 (7%)	1.9 (4%)	2.7 (10%)
WALLS (.195 ft^2 wall/ft^2 fl. area, solar abs.=0.88, U=0.13 Btu/hr-ft^2-°F)	-0.0 (- 0%)	0.6 (3%)	0.2 (0%)	0.8 (3%)	1.0 (2%)	0.7 (3%)
FLOOR (4 story building, edge insulation U=0.2 Btu/hr-ft^2-°F)	-0.4 (- 1%)	-0.2 (- 1%)	-0.4 (- 1%)	-0.2 (- 1%)	-0.4 (- 1%)	-0.2 (- 1%)
OUTSIDE AIR VENTILATION (0.1 cfm/ft^2)	-5.2 (-15%)	-0.8 (- 4%)	-3.8 (- 9%)	2.5 (10%)	-2.7 (- 6%)	1.5 (6%)
TOTAL	33.6 (100%)	21.3 (100%)	40.1 (100%)	26.1 (100%)	46.3 (100%)	25.8 (100%)

NOTES - Load numbers are from DOE-2 simulations of the base-case building module used for this project. (See Appendix 2-A of this chapter for more detail on the module.) Numbers in parentheses are the percent of total load. Loads from people and outside air include both sensible and latent components. The weather data used in the simulations resulted in a September cooling peak for San Francisco, October for Los Angeles, and July for Fresno.

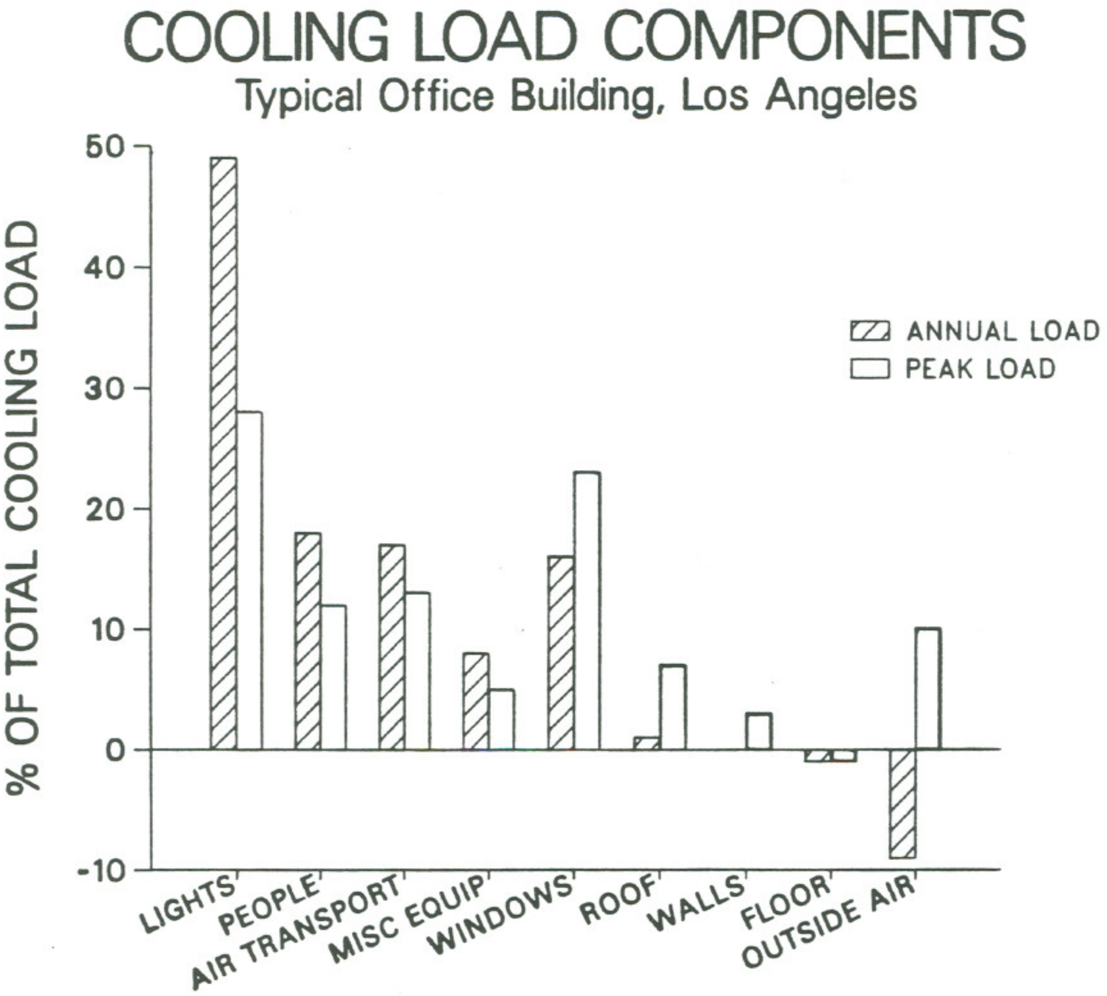


Figure 2-6. Cooling Load Components. Typical Office Building, Los Angeles.

Internal loads are a very large fraction of the annual cooling load in all climates. Heat from lights is the dominant internal load component, and the miscellaneous equipment load component is the smallest. However, extensive computerization of offices may make this component increasingly important, especially in light of the reductions in energy use from other components due to energy conservation. All of the internal load sources except people are pieces of equipment that serve other energy end-uses. This implies that an important way of reducing cooling load is to reduce energy consumption in other energy end-uses.

External loads make up a small fraction of the annual cooling load but a large fraction of the peak cooling load (although, not as large as the internal load contribution for this building). The variability of outside temperature and solar radiation explains the peaked nature of the external loads. As well as impacting the utility system peak, peak cooling loads have important HVAC design implications. The sizing of the air transport system is usually based on peak space cooling load. Therefore, the amount of air transport energy consumption (energy to run HVAC fans) is strongly affected by the peak cooling load, especially if the air transport system is a constant-volume system. Also, sizing of the primary cooling equipment is based on the peak cooling demand. As well as paying a capital cost penalty for larger cooling equipment, a large peak demand will cause operation at lower part-load ratios, thereby reducing the seasonal efficiency of the cooling equipment.

Windows admit a large amount of solar radiation into a building and are the dominant source of external load, both on an annual and peak basis. The rest of the external load components are a small or negative contribution to the *annual* cooling load for the three climate zones studied because, on average, outside air temperature and moisture content are less than temperature and moisture conditions within the building. Roofs and walls do make a minor positive contribution to the annual cooling load because they intercept solar radiation, which counteracts the temperature-induced heat loss.

2.5.3 Reducing Cooling Loads: General Concepts

When considering ways to reduce cooling electricity consumption by reducing cooling loads, a few general concepts are of primary importance. This section discusses issues of timing and cooling equipment efficiency as they relate to the effectiveness of cooling-load energy conservation measures.

Most load-related energy conservation measures attempt to reduce the amount of heat added to the building interior. The effectiveness of a measure depends not only on the amount of the heat gain reduction but also on *when* the heat gain reduction occurs. For example, if a conservation measure causes a heat gain reduction during a heating period, the effect will to be *increase* heating requirements. In order for a measure to reduce cooling load, a heat gain reduction must occur during a period when the building is requiring cooling.[1] In addition, the reductions need to occur during periods when the mechanical chiller or air conditioner is being used. If outside air from an economizer is meeting all of the cooling load, a heat reduction will not affect cooling electricity consumption, since the mechanical cooling equipment is not being operated. Thus, the presence or absence of an economizer in a building is an important determinant of cooling energy savings from cooling load reductions. For many California commercial buildings, the economizer eliminates many hours of mechanical cooling. Heat reductions from cooling load conservation measures have few hours to accrue cooling electricity savings in these buildings. (For the office building module we simulated, the chiller operated for 700 hours in San Francisco, 1300 in Los Angeles, and 1800 in Fresno, when the cooling system utilized an economizer.)

Another important factor when determining savings from cooling load measures is the efficiency of the cooling equipment. Equipment with higher COPs (efficiencies) require less electrical energy to meet a given cooling load. Consequently, a cooling load reduction produces less electricity savings in buildings having high efficiency cooling equipment.

2.5.4 Internal Loads

Internal loads are generated from lights, air transport fans, people, and equipment such as office equipment, cooking appliances, and refrigerators. The amount of internal loads generated in a building are a function of the type and amount of activity occurring in the building and the energy efficiency with which those activities are being performed.

Both the time-distribution and the location of the heat gain from internal sources are important for determining the impacts on cooling loads. Heat from office equipment radiates and convects directly to the building space. In contrast, light fixtures that have HVAC return-air drawn through them lose heat both to the space and to the return air. If all or a fraction of the return air is exhausted outside, that fraction of the lighting heat gain to the return air will not create a cooling load.

Energy Conservation Measures

The primary method for reducing the cooling load produced by internal sources is to reduce the amount of heat generated by those sources. All internal heat gains except those from people are generated as a by-product of equipment that provide other energy end-uses such as lighting or air transport. Therefore, reducing heat gain from this equipment is done by saving energy in these other end-uses. For example, using energy-efficient fluorescent lamps may save 1 kWh/ft^2-yr of lighting electricity use but, in addition, might save 0.2 kWh/ft^2-yr of cooling electricity use.

There are many factors that affect the additional cooling savings achieved by an energy conservation measure applied to a heat producing piece of equipment. Factors such as the time distribution of the heat gain reduction, where in the building the reduction occurs, and the radiative and convective characteristics of the gain reduction are all relevant to determining the cooling savings. In addition, the number of annual cooling hours for the building and the responses to the load change of the HVAC system and the primary cooling equipment affect the amount of cooling electricity savings. See the cooling-load technology summary sheets for quantitative savings estimates.

The other method for reducing the cooling load contribution of internal gain sources is to vent part of the heat gain to the outdoors. Heat-removing luminaires can be used for lights. These luminaires draw HVAC return air by the lamps thereby diverting some of the heat from the lights to the return air instead of the space. During periods when the economizer is admitting

100% outside air, all of the HVAC return air is exhausted outside so all of the heat in the return air is exhausted. Even during periods when the economizer is not operating, a fraction of the return air is exhausted to satisfy ventilation codes; the same fraction of the heat in the return air is carried away with the exhausted air.

The heat gain from other types of equipment can also be vented to the outdoors. The most favorable situation is one where the gain is relatively concentrated, so that simple ducting can exhaust a large amount of heat. Most types of cooking appliances fall into this category; for this equipment, the venting also has the benefit of removing odors as well as removing heat gain.

A venting system that diverts heat gain directly from a piece of equipment to the outdoors has a different energy impact than a system that uses HVAC return air to vent the equipment. A direct venting system always vents to the outside when the system is running, whereas a return air venting system is oftentimes recirculating the venting air. Thus, the direct system exhausts the heat gain more of the time. However, a direct system requires its own fan and consumes energy to run the fan; a return air system shares a fan and the fan energy consumption with the HVAC system.

A venting system will never collect all of the heat gain from a piece of equipment. The air flow removes most of the heat that convects from the surface of the equipment, but heat will still be added to the building space by radiation. Approximately one-third of the total heat gain from a vented kitchen appliance is still transmitted to the building space by radiation. [2]

Refrigeration appliances present a special case in terms of their cooling impact on a building. If the condenser for the refrigerator is located within the building space, the appliance produces a positive heat gain to the space. If the condenser is located outside the conditioned space (most common for large refrigeration units), the refrigerator cools the space. The relative merits of these two configurations depend on the cooling and heating requirements for the building. Food stores often employ a more optimal configuration that allows control over the location of the condenser heat gain. The condenser is interfaced with the HVAC system so that the heat can be recovered if needed or exhausted outside if not needed. Food stores usually have year-round demand for some heat because of the cooling effect from refrigerated cases.

Buildings with certain types of HVAC systems will not realize cooling savings from heat gain reductions unless adjustments are made to the system. Specifically, constant-volume HVAC systems that do not reset supply air temperature according to the current load need to have the fan flow-rate reduced to realize cooling savings from gain-reducing conservation measures. An air flow-rate reduction should accompany all such energy conservation measures.

2.5.5 External Loads

External loads refer to the transfer of heat energy (sensible and/or latent) between the building's exterior environment and the building interior. There are essentially three characteristics of the building's environment that produce this type of energy transfer--temperature, solar radiation, and humidity. A temperature difference between the air inside and outside of the building causes conduction of heat through walls, roofs, doors, and windows. Also, the exchange of outside air for inside air, either by natural infiltration through cracks in the building membrane or by forced mechanical ventilation, results in heat transfer, since the inside and outside air are at different temperatures. The second driving force involves the interception of solar radiation by the building. Some of the radiation is directly transmitted into the building through glass windows and doors, and some is absorbed at the outer surface of the building causing an increase in the amount of heat conduction into the building. Finally, a difference in water vapor concentration between the ambient air and the building interior air can cause latent heat transfer across the boundary of the building. The transfer results from air exchange due to natural infiltration and mechanical ventilation, and also from migration of moisture through building elements due to a vapor pressure differential.

Windows

Windows are usually the largest external load for commercial buildings both on an annual and peak basis. Windows interact with the lighting, cooling, air transport, and heating energy end-uses and are an important consideration in aesthetic aspects of building design. For this reason, a separate daylighting and fenestration chapter has been included in this report to address these impacts in a comprehensive way, and the discussion in this section will be relatively limited.

Both temperature and solar driving forces cause heat transfer through windows. The solar component is generally more important for determining cooling loads both on an annual and peak basis. For the California climates studied, the temperature contribution is small on an annual basis but becomes significant during the peak hour of the year.

The U-value of a window determines the window's response to a temperature difference between the inside and outside of the building. The U-value indicates how easily heat flows through the window when subjected to a temperature difference; windows with high U-values are poor insulators and conduct heat well. The U-value of the window is predominantly determined by the number of glass panes; double-pane windows are better insulators and have lower U-values than single-pane windows. The use of special insulating window-coatings, suspended insulating films, and interior shades also act to decrease the U-value of the window.

The shading coefficient (SC) describes the response of a window to impinging solar radiation. When solar radiation is intercepted by a window, some is reflected by the window, some is absorbed, and some is transmitted directly to the space. Of the absorbed portion, some is transferred into the building, and some is lost to the outdoors. When concerned with cooling loads, the important energy flows are those directly transmitted inside the building, and the portion of the absorbed radiation that is transferred inside; these heat gains can potentially add to cooling loads. The shading coefficient accounts for *both* these mechanisms of heat flow into the building. A window with a high shading coefficient allows a large fraction of the incident radiation into the building as heat, and a window with a low shading coefficient keeps out much of the heat. Clear windows have high shading coefficients, windows with heat-absorbing glass have intermediate shading coefficients, and windows with reflective glass or films generally have low shading coefficients. Blinds and other shading devices will also reduce shading coefficients.

Although low shading coefficients are desirable from a cooling perspective, there are usually aesthetic and daylighting tradeoffs to be considered when attempting to lower shading coefficients.

Conservation measures that reduce the cooling load imposed by windows usually attempt to reduce the window U-value or window shading coefficient. In California climates, the measures reducing the shading coefficient are generally more effective than those reducing the U-value, since solar is a larger driving force than temperature. In fact, reducing the U-value of a window will sometimes *increase* annual cooling requirements for buildings in cool climates. This is because the average outside temperature during periods when the chiller or air conditioner is operated may be less than the average indoor temperature. The windows ability to conduct heat actually cools the building. However, the cooling peak reductions and the heating savings from reducing the U-value can be important counteracting factors.

Roofs and Walls

The heat transfer mechanisms are quite similar for roofs and walls, so they are discussed together. The discussion will use the word "roof", but the reader should realize that the statements also apply to walls.

The rate of heat flow through a roof is proportional to the temperature difference between the inside of the building and the exterior surface of the roof, the area of the roof, and its U-value. [3] The primary unknown in this relationship is the exterior surface temperature of the roof. It is determined by the outside air temperature and wind speed, the radiant temperature of the surroundings, and the amount of solar radiation absorbed by the roof.

First consider the two temperature influences, air temperature and radiant temperature of the surroundings. Heat is exchanged between the roof surface and the outside air by *convection*, and the wind speed is the main determinant of how well this transfer occurs. This convective process attempts to hold the roof surface temperature at the outside air temperature. The roof also exchanges heat with the environment through *radiation;* roofs typically radiate to the sky which has an effective temperature lower than the air temperature, and walls radiate to objects they "see" such as other buildings or nearby trees. (These objects often have a temperature about equal to the air temperature.) The radiative process attempts to hold the roof surface temperature at the temperature of the radiative surroundings. Under totally still conditions, the radiative temperature of the surroundings and the air temperature have about equal influence in determining the roof surface temperature. [4] However, presence of a wind gives the air temperature a much stronger influence. With a 7.5 mph wind, the air temperature carries about an 80% weight in determining the roof surface temperature.

Absorbed solar radiation always increases the surface temperature of the roof above that determined by temperature. The amount of solar intercepted by the roof is determined by the location of the building, the presence of shading obstacles, and the orientation and tilt of the roof. Of the radiation impinging on the roof, a certain fraction is absorbed, which depends on the color of the outer surface of the roof. Dark colored roofs absorb more than light colored ones. A dark horizontal roof subject to peak solar gain and a 7.5 mph wind will be about 60 °F above the ambient temperature. For a dark horizontal roof with a wind speed of 7.5 mph, the amount of roof temperature increase due to absorbed solar is about 60 °F under peak solar conditions. [5] This temperature increase is highly dependent on wind speed; for stronger winds, the temperature increase will be less.

This example shows that solar radiation has a strong influence on the exterior temperature and therefore heat flow through roofs and walls. This factor causes a significant difference between the heat flow through roofs and the flow through walls. Roofs of commercial buildings are usually horizontal and receive much more solar radiation per square foot during the cooling season than vertical walls. For a building with comparable roof and wall areas, the roof will have significantly more impact on cooling loads.

The above discussion characterizes the total amount of heat energy that enters the building through the roof, but the time-distribution of the delivery of that energy is affected by the thermal massiveness of the roof. The thermal massiveness of the roof determines how well the roof can store heat energy and is dependent on the material that is used in its construction. Dense materials such as concrete are thermally massive and can store relatively large amounts of heat per unit volume of material. Light materials such as wood or insulation are poor thermal storage mediums. There are also material characteristics besides density that determine thermal massiveness. As an example, one pound of water has roughly five times the thermal massiveness of one pound of common brick.

Thermally massive materials in the roof delay the transfer of heat from the environment to the building interior. Instead of the maximum gain to the space occurring at a time of peak sunshine and peak temperature differential, the maximum will be delayed an amount determined by the amount and location of the thermal mass in the roof. This effect and its implications for conservation of cooling energy are discussed more in the energy conservation measures part of this section.

Energy Conservation Measures for Roofs and Walls

Energy conservation measures for roofs and walls modify the various elements of the heat transfer process in order to reduce the heat gain into the building during cooling periods. A very brief discussion of various measures follows, and more information can be found in the technology summary sheets.

Roof insulation can be added to increase the resistance to heat flow through the roof. When the outside surface temperature of the roof is greater than the indoor temperature, the heat *gain* into the building and, therefore, the cooling requirements are reduced by added insulation. When the surface temperature is less than the indoor temperature, heat *loss* from the building is reduced. This is a benefit during heating periods, but reduction in heat loss *increases* cooling requirements if it occurs during cooling periods. Because of this effect, insulation is most effective as a cooling energy conservation measure when applied to roofs instead of walls (roofs are warmer because of more absorbed insolation), and when used in warm climates.

The use of light colors on exterior surfaces of roofs and walls is often a more effective cooling measure than increased insulation. The light color decreases the amount of solar absorbed by the roof and, therefore, decreases the exterior surface temperature of the roof. The heating penalties are small because there is little solar radiation during commercial building heating periods.

Roof-spray cooling is applicable to roofs but not walls. Water is sprayed onto the outer surface of the roof, and the evaporation of the water reduces the temperature of the roof surface. The technique is very effective at eliminating roof heat gain, but water requirements are significant.

The amount of cooling saved by using light colors or roof-spray cooling is related to the amount of insulation in the roof. Both measures decrease the exterior surface temperature of the roof. If the roof is well insulated, its U-value is low, and the change in roof temperature only induces a small change in heat flow through the roof. The effectiveness of these measures is much greater on poorly insulated roofs.

Incorporating thermal mass, such as concrete or bricks, into roofs and walls during new construction is another cooling energy conservation measure. The thermal mass shifts the strong temperature and solar driven gain from the late afternoon to the evening. If the building is unoccupied during the evening, the gain does not need to be removed by the building cooling equipment. However, if the building is occupied during the evening (a restaurant, for example), the thermal mass will only change *when* cooling is required, but not significantly reduce the total amount of cooling. (It *will* reduce the peak cooling demand, however.)

Ground Floors

Heat transfer through floors is complicated but has a relatively small impact on cooling load. The heat transfer for on-grade floors is more responsive to ground temperature than air temperature. Since ground temperatures are usually less than interior building temperatures, the floor presents a continual heat loss to the environment. Better insulation of the floor will lead to *increased* cooling loads. However, the heating savings and improved comfort of an insulated floor are more important for determining optimal floor insulation levels.

Outside Air Ventilation

HVAC systems in commercial buildings exchange outside air for room air in order to remove odors, dust, and indoor pollutants. Since the temperature and humidity conditions of the outside air are different from the inside air, the exchange process has impacts on cooling and heating loads.

Natural infiltration through cracks in the building shell also causes exchange of outside air for inside air. However, many HVAC systems pressurize the building when the system is operating. Thus natural infiltration during operating periods is virtually eliminated, and mechanical ventilation is the only source of outside air exchange. This section focuses on mechanical ventilation as the dominant source of outside air exchange during building occupied periods.

Table 2-42 showed that the annual cooling load imposed by outside ventilation air is actually negative for all three climates studied. This is because the average enthalpy of the outside air is less than the enthalpy of the building air for periods when a cooling load is present. Enthalpy is a measure that accounts for both the temperature and moisture energy components of air. Since outside enthalpy is less than inside on average, the air exchange draws heat out of the building. During peak cooling conditions, the situation is reversed and the outside air exchange increases cooling load.

Outside-Air Energy Conservation Measures

When attempting to save cooling energy by minimizing the cooling impact of outside air, the periods of relevance are the periods when the outside air has greater enthalpy than the air inside the building. These are the *only* periods when the intake of outside air increases cooling requirements. During other periods, the economizer increases the outside air intake beyond ventilation requirements in order to help supply cooling loads.

One possible energy conservation measure for *over-ventilated* buildings is to reduce the minimum outside air intake setting on the intake dampers. This setting determines the amount of outside air brought into the building during periods when the air is not useful for cooling. Reducing the intake reduces the cooling load imposed by the air.

Air-to-air heat exchangers are devices that transfer heat between two air streams at different temperatures. They can be used in commercial buildings to exchange heat between the intake ventilation air-stream and the HVAC exhaust air-stream. During cooling periods when ventilation air is warmer than the building air being exhausted, the heat exchanger transfers heat from the warm incoming air to the cooler exhaust air. This lowers the temperature of the incoming air and reduces the load on the air conditioner.

The above two measures will have relatively small impacts on cooling requirements for most California locations, especially coastal locations. Surprisingly few hours occur where the outside air is substantially warmer than the air inside a building. The measures can have substantial impacts on individual buildings that have large ventilation requirements, such as hospitals and restaurants.

Thermostat Settings

Thermostat settings are not a source of heat gains or losses but are a primary determinant of temperature-induced external gains and losses. As the cooling thermostat setpoint is raised and the indoor/outdoor temperature difference declines, the temperature-related cooling loads are reduced. Also, as the indoor temperature increases, the cooling effect from an economizer cycle is increased, since the difference in temperature between the HVAC return air and the outside air is increased. Finally, an increased cooling thermostat setpoint increases the difference between the heating and cooling setpoints. If the building starts out cool in the morning, more heat gains can be absorbed by the mass of the building before cooling is required. This heat is released at night. The transfer of heat from day to night can decrease both cooling and heating requirements of the building.

Increasing the cooling thermostat setpoint costs little money. However, the costs are more in terms of comfort of the building occupants. Since the value of the occupants' services far outweighs energy costs, these comfort tradeoffs must be closely examined.

Notes

1. This simplied discussion neglects effects related to the thermal massiveness of the building. There are periods when a building is neither heating or cooling, and the effect of gain reductions during these periods is more complicated.
2. *ASHRAE Handbook, 1981 Fundamentals*, p. 26.25.
3. This simple relationship neglects effects of thermal mass.
4. This assumes that roof surface has an emittance of approximately 0.9, typical of most materials. The exception is bare metal, which has an emittance of about 0.3.
5. The air temperature plus the roof temperature increase caused by absorbed solar is called the sol-air temperature. For this example, the sol-air temperature would be 150 °F if the outside air temperature is 90 °F.

2.6 AIR TRANSPORT

2.6.1 Introduction

Air transport in commercial buildings serves a number of purposes. As a part of the space heating and cooling process, the air transport system distributes heating and cooling to the building spaces. Air transport systems also mix air within building spaces to even-out unequal distributions of temperature and odor. In addition, this mixing process creates air velocities in the occupied space. The air velocities improve comfort conditions by aiding the transfer of heat and moisture from occupants to the air. Finally, the air transport system is used to remove odors, dust, and indoor pollutants from the building space by diluting room air with outside air and by filtering room air.

Air transport energy consumption is the energy consumption of fans associated with the HVAC system. This end-use is often called "ventilation," but ventilation only describes one purpose of the air system. The name "air transport" was chosen because it is more generally descriptive of the purposes of the air system. This section explains how various characteristics of air transport systems determine air transport energy consumption. Working from this understanding, different types of energy conservation measures will be explained in general terms. Further specific information about these measures is presented in the air transport technology summary sheets.

2.6.2 Energy Consumption

The amount of air transport energy consumption in a building depends on a number of factors. The simple formula given below shows how the major factors combine to determine energy use.

$$E = \frac{F \ x \ P \ x \ H}{(8510 \ cfm\text{-}in. \ w./kW) \ x \ e_f \ x \ e_d \ x \ e_m}$$

E = Annual energy use per square foot of building floor area (kWh/ft^2-yr).

F = Flow rate of air per square foot of building floor area during HVAC operating hours (cfm/ft^2). Typical values = 0.5 - 2.0 cfm/ft^2.

P = Pressure drop across air distribution system (inches water). Typical values = 2 - 10 inches water (in. w.).

H = Number of hours that HVAC system operates per year (hours/yr). Typical values = 1500 - 8000 hours/yr.

e_f = Efficiency of fan ($0 < e_f < 1$). Typical values = 0.65 - 0.90. [1]

e_d = Efficiency of motor-to-fan drive mechanism ($0 < e_d < 1$). Typical values = 0.92 - 0.98. [2]

e_m = Efficiency of motor ($0 < e_m < 1$). Typical values = 0.72 - 0.93 (See Chapter 4).

The formula indicates a fairly intuitive energy consumption relationship. Energy consumption is proportional to the flow of air delivered by the system, the system pressure drop (a measure of the air friction occurring in the distribution system), and the number of hours that the system operates. Energy consumption is inversely proportional to the efficiency with which the motor and fan convert electricity to moving air. These variables, taken together, explain the variation in air-distribution energy use across different buildings. The ranges of typical values indicates that the variables tending to vary the most across buildings are the flow, pressure, and hours of operation; the fan, drive, and motor efficiencies vary within a smaller range. The following four sections discuss each one of these variables individually and explain how energy conservation measures affect them.

Air transport energy consumption also affects the heating and cooling end-uses. Nearly all of the energy consumed by the air transport system appears in the building as heat. Most of this heat adds to the building cooling load, although some offsets heating requirements. Therefore, savings in air transport energy consumption will also result in cooling savings. This is discussed further in the cooling loads section, section 2.5.

2.6.3 Air Flow Rate

The air flow variable, F, is closely linked to cooling parameters. Since the primary purpose of most air transport systems is transporting cooling to building spaces, air flow is related to cooling needs of a building. This relationship differs between constant-volume and variable-volume air systems, and these systems are discussed separately in the sections below.

There is a link between the flow variable, F, and the pressure variable, P. Reductions in air flow also cause reductions in the system pressure drop leading to increased air transport energy savings. The section on system pressure drop discusses this further.

Constant-Volume Systems

A constant-volume air transport system delivers a constant flow of air to building spaces during operating periods. Sizing of this air flow is generally determined by one of two methods. In a small minority of buildings, ventilation codes require a large amount of outside-air ventilation, and this constraint determines the flow rate of the air transport system. As an example, systems for hospitals are often designed in this way. For the majority of buildings, the amount of air flow is determined by the peak cooling load for the building space and the cooling supply air temperature.

The rate at which a space is cooled is proportional to the difference in temperature between the space and the cooling supply air, and proportional to the flow rate of cooling supply air into the space. Usually, a supply air temperature is chosen, and then the air flow is calculated so that the *peak* cooling load in the space can be met. Since the system is a constant-volume system, this air flow, which is determined for peak cooling conditions, is the flow for *all* operating hours.

Given this sizing procedure, there are two approaches to reducing the needed air flow rate--reducing cooling supply air temperatures and reducing the peak space cooling load. If the supply air temperature is reduced, the difference in temperature between the space and the supply air is increased, and air flow can be reduced. Air transport energy consumption will be reduced, but some important tradeoffs need to be considered. With low supply air temperatures, more latent cooling occurs, but this increased moisture removal may not be necessary because of relatively low humidities in most California locations. Using low supply air temperatures causes the air conditioning unit to operate at a lower COP and therefore increases cooling energy consumption. Also, comfort of occupants near supply grilles may be affected by extremely cool supply air.

There are other tradeoffs related to reducing air flows that are independent of the approach used for reducing the air flow. The amount of "free cooling" from an economizer is decreased by reduced air flows; this leads to increased mechanical cooling energy consumption. Heating requirements are increased slightly by reduced air flows, since there is less mixing of air from warm core zones with perimeter zones requiring heating. Finally, the comfort benefits from air velocities in spaces and good air mixture are decreased by reduced air flow. See section 2.4 on HVAC systems for more information of the cooling and heating impacts of using VAV systems.

A main determinant of the optimum combination of supply air temperature and air flow is the relative efficiency of the air transport system and the cooling system. If the air transport system is efficient (low energy consumption per cfm of air moved) and the cooling system is inefficient (low COP--high energy consumption per Btu of cooling provided), then the optimum combination will tend toward high air flow rates and high supply air temperatures in order to capture cooling savings. With an inefficient air transport system and an efficient cooling system, the optimum design will have lower air flow rates and lower supply air temperatures.

The other approach to reducing air flows is to reduce the peak space cooling load. Cooling energy conservation measures that reduce peak load will allow for a reduction in air flow rate and produce air transport energy savings. Note that these measures may not reduce *annual* cooling load (just peak), but they do lead to annual air transport energy savings, because a constant volume air transport system is forced to supply the air flow needed for peak conditions during *all* operating hours. A one percent reduction in peak space cooling load allows for a one percent reduction in air flow rate.

Variable-Air-Volume Systems

Variable-air-volume (VAV) systems differ from constant-volume systems because they vary the amount of air delivered in response to variations in cooling load. Air flow is low during periods when the cooling load is small. When relating the energy consumption equation to variable-air-volume systems, the flow variable, F, must be thought of as the annual average flow. [3] For a given building and supply air temperature, a VAV system will have a lower average flow than a constant-volume system, because the VAV system reduces flow under part-load cooling conditions. Therefore, VAV systems consume significantly less air transport energy than constant-volume systems.

Since air flow is responsive to cooling load, the air transport energy use for VAV systems is related to the annual cooling load, contrary to the situation for constant-volume systems. However, the peak cooling load is still important for VAV systems because it determines the design (peak) air flow. One penalty of a large cooling peak load is increased capital cost for the air transport system. Another penalty results from the many hours of operation at a small fraction of peak air flow; VAV systems become less efficient at fractional air flow, so low part-flow fractions cause increased energy use per unit of air supplied.

There are a few different ways to vary the volume of air delivered by the main fan in a VAV system. The relative efficiencies of the different methods are discussed in the motor/fan efficiency section, section 2.6.6.

2.6.4 System Pressure Drop

The system pressure drop is a measure of the air friction in the air transport system. Friction occurs in ducts, cooling coils, filters, and all surfaces subjected to moving air. The pressure drop is a function of the air flow through the system and the amount of restrictions occurring in the system. For air transport systems, the pressure is usually measured in inches of water; a pressure drop of 3 inches of water is equivalent to the amount of pressure (gauge, not absolute) that a 3 inch water column would exert.

As the flow through a given air transport system increases, air velocities increase because the flow cross-section remains unchanged. Larger velocities increase friction and therefore increase pressure drop. The pressure drop across most components in an air transport system is proportional to approximately the square of the air flow rate. For example, doubling the air flow causes the pressure drop to increase by a factor of four. The resultant energy use increases by a factor of eight, since energy use is proportional to the product of flow and pressure. This important cubic relationship (energy use proportional to the cube of air flow) indicates that energy use can be reduced substantially by reducing air flow rates, since the reduction in pressure associated with the flow reduction is large.

It is important to remember that this cubic relationship only applies if the restrictions in the air transport system remain unchanged. For some flow reducing measures, this is not the case. For example, if a cooling energy conservation measure allows air flow to be reduced to a particular zone in a building that is not the "critical" or "index" zone, the reduction is accomplished by partially closing the balancing damper to that zone. [4] Restriction has been increased in the system, so the pressure reduction is less than that indicated by the square relationship, and the energy reduction is less than that indicated by the cubic law. VAV systems also add restriction to the air transport system when they reduce flow (dampers in the VAV terminal boxes close), so these systems do not obey the cubic energy law.

The other factor determining the pressure drop in an air transport system is the amount of restrictions occurring in the system. Air restrictions are caused by all surfaces in contact with the moving air. Major restrictions in an air transport system are filters, cooling and heating coils, fan fittings, ducts, supply terminals, and outside air louvers.

Reduction of the amount of restriction in an air transport system can be accomplished in three different ways: better design layout, use of low friction components, and larger sizing of components. Better design layouts utilize distribution designs that minimize the length and the corners in the duct runs. Using multiple fans in a multi-story building is one way of reducing duct length.

Low pressure drop components are now being designed for use in air transport systems. Energy-efficient filters, outside air louvers, and supply terminals are available, and these components have lower pressure drops than standard units of the same size.

Altering sizing procedures probably has the greatest potential for reducing pressure drops in systems. By using filters, cooling coils, ducts, and other components with larger cross-sectional areas, the air velocities through these components decline causing a reduction in pressure drop. The costs for larger components are the cost of the components and the cost of the space that these components occupy. In the past, a rule-of-thumb used to determine the optimal size for central air-handling components (not ducts and terminals) for constant-volume systems was to size the components so that air velocities were approximately 500 feet per minute. One analysis showed that use of this rule-of-thumb produces systems that are not economically optimal because of today's increased energy costs. [5] The study showed that when equipment, space, and energy costs are considered in a life-cycle analysis, sizing based on 300 feet per minute air velocities produces systems closer to the economic optimum. The reduced energy costs associated with these low pressure systems more than outweigh the added equipment and space costs due to the larger components.

Sizing for variable-air-volume systems is different because these systems operate at part-flow much of the time. The components for a VAV system will be smaller than those for a constant-volume system serving a similar building; the *average* flow rate for a VAV system is less, even though the peak flow rates are similar.

2.6.5 Hours of Operation

The air transport system for a building needs to operate during occupied periods and during start-up periods prior to occupied periods. Energy conservation measures that affect the hours of operation are directed at turning the system off during unoccupied periods.

The most standard energy conservation measure is night shutdown of the air transport system. Odor and morning start-up problems sometimes occur, but these can be eliminated by methods other than continual night operation.

Another energy conservation measure that reduces operation hours is the use of motion sensors to shut-down fans and lights in intermittently occupied rooms. Typical applications are bathrooms, conference rooms, storage areas, and classrooms.

2.6.6 Fan/Motor Efficiencies

The fan/motor combination consumes electrical energy in order to force air through the air transport system. There are efficiencies associated with fans, drives, and motors, which indicate how well these components transform energy. The sections below discuss in more detail the efficiencies of these components. The final section examines the relative efficiencies of different variable-air-flow methods.

Fans

The types of fans most commonly used for air transport are airfoil, backward-inclined backward-curved, and forward-curved. Space and noise constraints, as well air transport performance, are important in the selection of fan type. Airfoil and backward-inclined backward-curved fans are usually used in large built-up systems. Airfoil fans have slightly better efficiencies, but both types fall into the 80 - 90% range. Forward-curved fans are less expensive and are typically used in smaller applications such as package air-conditioning units. These fans have efficiencies in the 65 - 75% range. Upgrading to a more efficient fan type from a forward-curved fan is usually difficult because of space and mounting constraints.

Operating efficiencies of fans are often less than rated efficiencies because of imperfections in the fan's environment. Inlet and outlet connections and close blade-housing tolerances are important for maintaining good efficiencies.

Drives

The motor is connected to the fan by a drive mechanism. The most efficient drives use gears and have efficiencies from 0.96 to 0.98. V-belt drives are the most common drive for air transport systems, and these drives have efficiencies of 0.92 - 0.95. V-belt drives can be upgraded to synchronous belt drives, which use cogged belts to eliminate slippage. The efficiency improvement with these drives has been disputed, but some sources claim a 3-4% improvement. [6]

Motors

The function of the motor is to convert electrical power into mechanical power to drive the fan. Efficiencies of motors are generally good, but some improvements are possible. The reader is encouraged to examine Chapter 4 on motor efficiency for a detailed discussion of this subject. A few key conclusions from that chapter will be presented here.

The efficiency of motors increases with size. Standard motors smaller than 5 horsepower have efficiencies in the 75 - 83% range, but motors larger than 50 horsepower usually have efficiencies near 90%. (To relate horsepower to air flow, a rough rule-of-thumb is that 1 horsepower can supply 1000 cfm in a typical air transport system.) However, the potential *improvement* in efficiency is greatest for smaller motors. For motors less than 5 horsepower (hp), the use of energy-efficient motors will result in efficiencies as much as 8% greater than standard motors. For larger motors, 3-5% improvements are possible. The use of energy-efficient motors is also cost-effective at the time of normal replacement, when using reasonable economic criteria. Early replacement becomes cost-effective for motors operating at very poor efficiencies.

Variable-Flow Methods

Variable-air-volume systems reduce energy use because they reduce flow and pressure drop, as discussed in previous sections. However, when the air flow is reduced at the main fan, the energy efficiency of the motor/fan combination is usually degraded. There are different methods for varying the air flow at the main fan, and they have different efficiencies. Some of the most common methods are:

1) *Discharge Dampers:* These are controllable dampers installed on the the outlet side of the fan. The dampers vary the amount of system resistance presented to the fan thereby varying the resultant air flow.

2) *Inlet Vanes:* These controllable vanes are installed on the inlet side of the fan. They alter the pre-spin of the air entering the fan, which reduces the pressure-producing capacity of the fan.

3) *Variable-Speed Motor Drives:* This approach varies the speed of the shaft driving the fan in order to vary the flow of air produced by the fan. There are a number of different ways to vary the fan speed. Electronic inverters can be used to supply a variable-frequency voltage to the motor causing its speed to vary. Eddy-current drives keep the motor shaft running at a constant speed and couple it magnetically to the fan shaft. By varying the amount of magnetic coupling between the shafts, the slip can be adjusted, thus varying the speed of the fan shaft. Other variable speed drives employ systems that mechanically vary the size of the motor sheave. Chapter 4 on motor efficiency has more detailed information.

4) *Variable-Pitch Fans:* These fans vary the pitch of their fan blades in response to a control signal; varying the pitch of the fan varies its air flow.

The energy efficiency of a variable-flow method can be characterized by plotting energy use against air flow, and this is shown in Figure 2-7 below. The graph assumes that the fan is feeding a typical VAV distribution system, and the energy use accounts for all air transport losses in the system.

The figure shows that discharge dampers are the least efficient variable-flow method, since they rely on introducing restriction into the system. Variable-speed drives and variable-pitch fans are the most efficient methods for reducing flow. Only one curve is shown for these methods, although the variety of devices available is large. Specifications do vary across manufacturers and different types of devices, but it is difficult to rank the methods according to relative efficiency without consistent testing procedures. Cost and non-energy features become important factors when choosing between these methods. More information on variable-speed drives is presented in the motor efficiency chapter, chapter 4.

The annual energy use of a VAV system employing one of the different variable-flow methods depends on the number of hours operated at different part-flow conditions. Computer simulations of an office building module were done to compare the different methods on an annual energy use basis, and the results are presented in the VAV technology summary sheet.

Notes

1. Typical values from American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., *ASHRAE Handbook, 1983 Equipment,* Atlanta, 1983, p. 3.3
2. Typical values from R. C. Monroe, "Energy Saving Fans", *Advances in Energy Cost Savings for Industry and Buildings,* Proceedings from the 6th World Energy Engineering Congress, November 29 - December 2, 1983, p. 379.
3. The equation does not give exact results even when F is entered as an average flow. The problem results from correlation between F and P, the pressure drop variable. The equation can be used as an intuitive aid, but a more sophisticated analysis must be done for exact numerical results.
4. The "index" zone is the zone that is separated from the fan by the largest amount of restrictions.
5. Arthur E. Wheeler, "Air Handling Unit Design for Energy Conservation", *ASHRAE Journal,* June 1977, pp. 47-52.
6. R. C. Monroe, "Energy Saving Fans", *Advances in Energy Cost Savings for Industry and Buildings,* Proceedings from the 6th World Energy Engineering Congress, November 29 - December 2, 1983, p. 379.

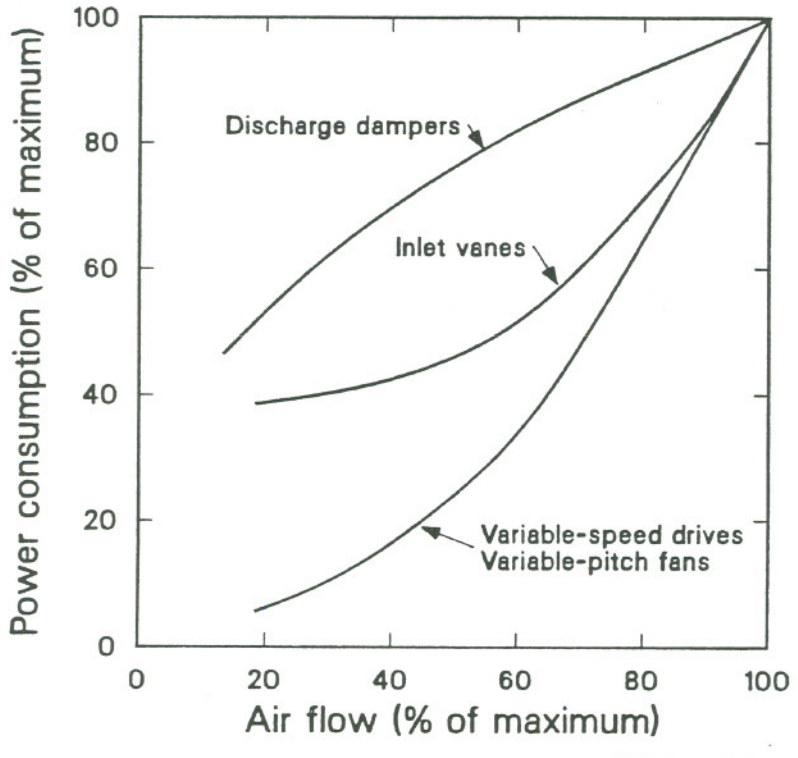


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Figure 2-7. Energy Efficiencies of Variable-Flow Methods.

Appendix 2-A

OFFICE BUILDING-MODULE SIMULATION

The DOE-2.1B building energy analysis program was used to estimate the energy savings from a number of energy conservation measures applicable to the cooling and air transport end-uses. This appendix describes the key assumptions that were used in our simulation studies.

A base-case building was established, and changes were made to investigate impacts on energy use. The architectural configuration of the base building is the same as the module used in the daylighting simulation studies (see Figure 6-1). The module is essentially a one floor slice from a medium to large office building. A 100 ft. by 100 ft. core zone is surrounded by four identical perimeter zones, each 100 ft. wide by 15 ft. deep. For the cooling and air transport studies, the floor was assumed to be adiabatic, but a roof transferring heat with the environment was simulated. The building was operated according to a standard 8 a.m. to 5 p.m. office schedule. TMY weather tapes were used for San Francisco and Fresno climates, and a WYEC weather tape was used for the Los Angeles climate.

Further information on the building module is presented below:

Thermal Building Characteristics

Lighting: 2.7 W/ft^2, 80% of heat enters space, 20% enters HVAC return air.

Miscellaneous Equipment: 0.5 W/ft^2.

Occupancy: 1 person / 100 ft^2, sensible gains = 230 Btu/hr, latent gains = 190 Btu/hr.

Walls: Total wall height is 12 feet; 4.2 feet is window, and the rest is opaque wall. Total length of non-adiabatic wall is 400 feet (perimeter of building). Wall U-value = 0.13 Btu/hr-ft^2-°F, solar absorptivity = 0.88. Wall assumed to be "quick", i.e. no thermal mass.

Windows: 4.2 foot high strip surrounding the building (length = 400 feet). Single pane glass, U-value = 0.9 Btu/hr-ft^2-°F, shading coefficient = 0.6, no external shading.

Floor: Adiabatic.

Roof: 16,000 ft^2 horizontal roof covering both the core zone and the perimeter zones. U-value = 0.134 Btu/hr-ft^2-°F, solar absorptivity = 0.7, low thermal mass.

Infiltration: No infiltration during occupied periods because of building pressurization. 0.8 air changes per hour in the perimeter zones only during periods when the HVAC system is off.

Thermostat Settings: Occupied period - 78 °F cooling, 72 °F heating. Unoccupied period - 90 °F cooling, 63 °F heating.

HVAC System Characteristics

System Type: Constant-volume reheat system with supply-air temperature reset according to the warmest zone. Design supply air temperature = 55 °F. Systems cycles on to meet loads during unoccupied periods.

Outside-Air Intake: 5 cfm/person minimum. Economizer cycle used with upper lockout = 72 °F.

Air Transport Characteristics: System pressure drop = 6 inches water. Combined motor and fan efficiency = 70%. Air flow approximately 1 cfm/ft^2 (dependent on peak space cooling load, and therefores varies some with climate).

Primary Cooling and Heating Plant: Cooling plant is a open centrifugal chiller with full-load COP = 4.8. (This COP is high, and results were sometimes adjusted-and noted to that effect--to reflect cooling plants with lower COPs.) A cooling tower was utilized. Heating plant is a hot-water boiler with an full-load efficiency = 80%.

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CHAPTER 3

REFRIGERATION

Table 3-1
SUMMARY TABLE - REFRIGERATION

Measure	Applicability (R = Retrofit; N = New)	Base Conditions(1)	Typical Savings(2) Energy	Typical Savings(2) Peak	Cost(3)	Lifetime	Comments
Glass Doors	Retail food cases R,N	Multi-deck case	40-50%	40-50%	$160 per lineal foot of case.	~15 years	Cost for retrofit only. New cases lower cost. Includes penalty for anti-sweat heaters.
Strip Curtains	Retail food cases R,N	Multi-deck case -low temperature -medium temperature	10-20% 40-50%	unknown unknown	$20-30 per lineal foot	~5 years	Savings are typical. Lifetime uncertain.
	Food service units R,N Warehouse doors R,N	Frequent door openings or doors left open	varies varies		$8 per ft^2 $7 per ft^2	~5 years	Lifetime uncertain. Large warehouse potential.
Parallel, Unequal Compressors with microprocessor temperature and pressure control	Retail food cases N	Parallel, equal compressors with mechanical pressure control	low temp. 13% med. temp. 27%	13% 27%	$50 per horsepower of peak capacity	~15 years (same as standard system)	Cost is dependent on competitive bidding. (4)
Variable-speed Compressor Control	Retail, Warehouse, Food Service N	Fixed-speed compressors with electro-mechanical cycling control (most common arrangement)	unknown		$1500 - $300 per horsepower (1hp - 50hp)	unknown	Experimental; possible substitute for multiple compressors. (4)
Evaporative Pre-coolers	Air-cooled condensers located outdoors: Retail, Warehouse, Food Service R, N	Condensers cooled by ambient air	S.F. and L.A. 8% Fresno 11%	8% 11%	$60 - $40 per square foot of condenser (5ft^2 - 30ft^2)	~10 years	Life and performance highly maintenance dependent; requires water supply. (4)
Floating Head Pressure Control	Retail R, N	Minimum pressure control	low temp. 2% med. temp. 15%	unknown unknown	~ $800 retrofit ~ $100 new	same as base equipment	Costs depend on cost of adding sensors and wiring to cases. (4)
Ultrahigh Temperature Sterilization and Aseptic Packaging	Retail dairy cases	Refrigerated dairy cases	100%	100%	not applicable		Widely used in Europe. No Summary Data Sheet.
Food Service Refrigeration Load Reductions	Food service walk-in and reach-in refrigerators and freezers N	Current industry practice	25%(5)	unknown	unknown	life of unit	Improvements in refrigeration unit shell. No Summary Data Sheet.

(1) 1982 Base Energy Utilization Indexes (EUI's):
Retail Grocery (Supermarket): 22 kWh/ft^2 for PG&E; 19 kWh/ft^2 for SCE.
Food Service: 0.12-1.4 kWh/ft^2 for PG&E; 0.08-1.7 kwh/ft^2 for SCE (variation mostly due to varying ratio of kitchen to other floorspace.)
Refrigerated Warehouses: 0.66 kWh/ft^2 for PG&E; 0.33 kWh/ft^2 for SCE.

(2) Combining measures will generally not result in a simple addition of savings.

(3) Costs do not include rebates or tax credits.

(4) The cost and savings of these technologies is highly dependent on system design.

(5) See Section 3.1.2.2.2.

Commercial Technology Summary Data Sheet

END-USE: *Refrigeration*

TECHNOLOGY: **Glass Doors and Strip Curtains**

GENERAL DESCRIPTION: Glass doors and strip curtains help reduce the heat gain in refrigerated enclosures.

PHYSICAL CHARACTERISTICS: Glass doors are typically made up of a multiple-glazed window assembly, mounted in a metal frame which usually includes an electric anti-sweat heater. Two to four panes of glass are typically used, sometimes including heat-reflecting glass. The doors generally contain magnetic gaskets to seal the door to the refrigerated display case. [1] Strip curtains are made of clear, flexible plastic strips which overlap to reduce the transfer of air to and from the enclosure while still allowing people and/or vehicles to reach, walk, and/or drive through the curtain. They typically attach to the rim of the opening in the enclosure by means of magnetic or "velcro" fasteners.

APPLICABILITY: Glass doors are suitable for retrofitting multi-deck display cases in retail food stores, and for equipping new display cases. The latter cases are known as "glass door merchandisers". Strip curtains are suitable for retrofits and new installations in food service units (reach-ins and walk-ins), warehouses (at the doors) and retail stores, for display cases.

ENERGY PERFORMANCE: The savings for glass doors range (in tests) from 30% to 60%; 50% is most often cited, for both low temperature (freezer) and medium temperature (meat and beverage, e.g.) cases. [2] [3] [4] Strip curtains save about 15% and 45% on low and medium temperature display cases, respectively. [5] [6] The energy performance of strip curtains in food service and warehouse applications is highly dependent on installation and operating conditions. In warehouse applications the potential is large, since up to 50% of the refrigeration load is due to infiltration, most of which is due to open door losses. [7]

COSTS: The installed cost of glass door retrofits is about $130 per lineal foot of multi-deck case, not including the case and refrigeration modifications to properly meet the reduced load. The equipment modifications may include new, smaller compressors; adjusted or new expansion valves; compressor pressure and defrost control resets; air curtain fans disconnections; and refrigerant piping changes. While highly variable, these costs typically amount to about $30 per foot of case. [8] The cost of strip curtains is about $20 per lineal foot of display case, about $8 per ft^2 for curtains suitable for food service, and $7/$\text{ft}^2$ for warehouse door units. [9] Some of the equipment modifications listed for the glass doors may be needed for the strip curtain applications.

RELIABILITY/LIFETIME: The lifetime of glass doors is long, on the order of the case lifetime. Fifteen years is assumed. Door gaskets need periodic replacement as they wear out. Strip curtain lifetime is more variable, as the entire curtain undergoes wear. A five-year lifetime is assumed.

UTILITY SYSTEM IMPACTS: Energy savings and peak load reductions.

USER IMPACTS: Reductions in electricity costs for both energy and power. In retail applications, often results in increased sales (due to warmer aisles) and an increase in food storage life (due to shorter defrosts). [10]

PRODUCT AVAILABILITY: Both glass doors and strip curtains are presently available from several manufacturers.

EXPERIENCE: Both technologies have been in use for several years. When properly installed and maintained, they result in significant savings, and make for a more pleasant shopping environment.

COMMENTS + CAVEATS: It is essential that refrigeration modifications be made at the same time glass doors are installed. It is less important, but still highly recommended, that the refrigeration equipment be inspected and adjusted when strip curtains are installed.

Energy savings from glass doors are reduced somewhat by the anti-sweat heaters. The amount of this reduction depends on how much the heaters operate. In California, the humidity is fairly low; this, combined with humidistat control of the heaters, results in a small reduction (typically ten percent) in savings. [11]

Strip curtains often have condensation problems when used on low-temperature cases, and are not generally recommended for this use.

Strip curtains can be objectionable to customers and staff when improperly installed or maintained. Particularly, they reduce the visual and physical accessibility of the product or space behind them. It is important to keep the curtains clean to prevent them from becoming a safety hazard, especially where people or equipment must pass through them. Due to concerns over aesthetics, visibility, or physical interference of shoppers or personnel, some stores and warehouses have removed strip curtains from their cases.

Commercial Technology Summary Data Sheet

END-USE: *Refrigeration*

TECHNOLOGY: **Parallel, Unequal Compressor Systems**

GENERAL DESCRIPTION: Parallel, unequal compressor systems (including suction controls) use a set of 3, 4, or 5 compressors to meet varying refrigeration loads in supermarket applications. The compressors are of unequal sizes and are connected in parallel.

PHYSICAL CHARACTERISTICS: The compressors used are conventional refrigeration units. In the most common arrangement, three compressors are selected to give a capacity distribution of approximately 1:2:4, which allows eight steps of capacity (zero to seven times the smallest compressor size). A microprocessor-based controller selects the compressor(s) to be operated based on the suction pressure, the refrigerated display case temperature, or both. The controller also manages compressor operation during defrost, and prevents short-cycling.

APPLICABILITY: The systems are applicable to retail food refrigeration systems. They are more likely to be used in new stores, and those undergoing renovation of their refrigeration systems, rather than as a retrofit. [12]

ENERGY PERFORMANCE: Computer simulations, backed up with laboratory tests, found the following energy savings for the parallel, unequal compressor system with microprocessor control compared to a parallel, equal system with mechanical pressure control. "Low temperature" refers to freezer display cases (typically 0° F); "medium temperature" to display cases for meat, dairy products, etc. (typically 40° F). [13]

Table 3-2

Microprocessor Control Savings

Control Type	Medium Case Temperature	Low Case Temperature
Pressure	13%	4.3%
Pressure and Temperature	27%	13%

Note that the savings are two to three times higher with the combined pressure and temperature control.

COSTS: The added cost of the parallel, unequal systems of 35 horsepower total compressor size is about $1000; the combined control may add several hundred dollars. The result is a cost of about $50 per horsepower of compressor. However, competitive bidding may result in lower added costs. [14]

RELIABILITY/LIFETIME: In tests, the system has proven to be as reliable as typical refrigeration systems; a 15-year life is assumed. [15]

UTILITY SYSTEM IMPACTS: Energy and peak load reductions.

USER IMPACTS: Reductions in electricity costs for both energy and power.

PRODUCT AVAILABILITY: The systems are presently available from the major suppliers of food store refrigeration equipment.

EXPERIENCE: Systems have been installed in about 500 food stores beginning in 1981. Reported savings are typically 15%. No major problems have been reported. [16]

COMMENTS + CAVEATS: The compressors must be carefully sized to ensure: 1) that the refrigeration load is always greater than the smallest unit's capacity, in order to minimize the amount of inefficient part-load compressor operation; 2) that the load is always less than the total capacity, in order to avoid exceeding acceptable maximum case temperatures.

Due to the greater complexity of such systems, the required level of installation, maintenance, and repair skills is higher, and may not be available in all areas, especially locations remote from metropolitan areas. However, as solid-state controls become standard, this situation should improve.

Commercial Technology Summary Data Sheet

END-USE: Refrigeration

TECHNOLOGY: **Variable-Speed Compressor Control**

GENERAL DESCRIPTION: In order to meet variable refrigeration loads, compressor speed can be varied by electronic variable speed drive.

PHYSICAL CHARACTERISTICS: A standard refrigeration compressor is coupled with an electronic variable-speed drive. The compressor may be of the open-drive, semi-hermetic, or hermetic design. To date, experiments have been run only on the first two types. The variable-speed drive responds to a pressure or temperature sensor by changing the compressor motor speed in response to refrigeration load. [17]

APPLICABILITY: All refrigeration systems driven by electric motors. Includes food service, warehouse, and retail food systems. In practice, retrofits would probably be limited to applications where the refrigeration system is being renovated.

ENERGY PERFORMANCE: Savings depend on the compressor performance at other than design speed. The research to date has been in the areas of control feasibility and the effect of variable speed operation on compressor reliability, and has not included energy performance. [18]

COSTS: The incremental cost depends on the type of system which is, or otherwise would be in use. If the control strategy is to cycle a single compressor in response to load, the electronic variable-speed drive is the cost. The cost per horsepower of these drives is about $1500 in the 1 hp size, $700 at 5 hp, $500 at 10 hp, $400 at 25 hp, and $300 at 50 hp. (See the Motor Efficiency chapter of this report for more information on variable speed drives.) If the strategy would otherwise be to use a set of compressors in parallel, the cost is the difference between the parallel compressor set (and control) and a single large compressor with variable speed drive.

RELIABILITY/LIFETIME: Unknown. Tests have indicated no lubrication problems with running compressors at approximately half their rated speed.

UTILITY SYSTEM IMPACTS: Unknown. Potential energy and peak power savings.

USER IMPACTS: Unknown. Potential reductions in electricity costs for both energy and power.

PRODUCT AVAILABILITY: While the components of variable-speed compressor systems are all presently available from a number of manufacturers, the systems are under study only.

COMMENTS + CAVEATS: Due to their relative mechanical simplicity, it is likely that variable-speed compressor systems will come into use as a substitute for multiple-compressor arrangements. However, considerable work must be done to determine the energy savings and reliability implications of this technology, as well as the appropriate control strategy and compressor type to use. This process could be carried out in a few years, making these systems available by about 1990.

Commercial Technology Summary Data Sheet

END-USE: Refrigeration

TECHNOLOGY: **Evaporative Pre-Coolers for Air-Cooled Condensers**

GENERAL DESCRIPTION: Evaporative pre-coolers reduce the temperature of the air supplied to air-cooled condensers by evaporating water into the air. The resulting drop in condenser temperature reduces compressor power requirements.

PHYSICAL CHARACTERISTICS: Evaporative pre-coolers use a wetted filter medium to evaporate water into the condenser air supply. The material is kept wetted either by a pumped water supply (from a sump kept full with a float valve), or through a direct flow from the building water supply.

Since the heat required to evaporate the water comes from the air, its temperature drops as it passes through the wetted material and becomes more humid. This cooler air causes the condenser coil to operate at a lower temperature, reducing the amount of work that the compressor must do to provide a given amount of refrigerating. The reduced compressor work results in a lower power requirement.

The wetted material is usually a few inches thick, and is sized to match the condenser coil dimension. [19]

APPLICABILITY: New and retrofit installations. Better suited to outside units with horizontal airflow, but can be adapted to vertical flow condensers through the use of sheet metal adaptors.

ENERGY PERFORMANCE: This depends on how much temperature reduction the pre-cooler can provide, and the effect of the temperature reduction on the specific refrigeration equipment involved. The temperature reduction depends on the humidity level of the air (the lower the humidity, the more reduction in temperature can be achieved). Since the humidity is generally low in California, significant savings are possible.

The estimated reductions in energy and power consumption are 8% for the San Francisco and Los Angeles areas and 11% for Fresno. [20]

COSTS: Prices per square foot of condenser coil face area: \$60 in the 5 ft^2 range, \$50 in the 20 ft^2, and \$40 in the 30 ft^2. Installed costs will be somewhat higher. [21]

RELIABILITY/LIFETIME: The basic unit, if well built from appropriate materials, has proven to be quite reliable. The wetted medium may need replacing every few years, depending on water conditions. Maintenance is critical to prevent degradation from mineral scale, biological growths, corrosion, and freezing.

UTILITY SYSTEM IMPACTS: Reductions in energy use and peak demand.

USER IMPACTS: Reductions in electricity costs for both energy and power. Increase in water use. May increase life of refrigeration equipment.

PRODUCT AVAILABILITY: The pre-cooler is available now. It should be noted, however, that it is designed for air conditioners, not refrigeration systems per se. The most significant adaptation needed is to override the temperature control that prevents the water from flowing when the air temperature is below 80 degrees F.

EXPERIENCE: Thousands of these units have been retrofitted onto air conditioning systems, especially in the Southwest. [22] Many have been in place for over 10 years without problems; others deteriorated into uselessness in a few years. [23] Proper installation, followed up by diligent maintenance, appears to be the difference.

COMMENTS + CAVEATS: The cooler must be properly sized to prevent liquid water carry-over onto the condenser coil, which might cause corrosion problems.

The pre-cooler acts as an air washer and filter, often serving to reduce the need for condenser coil cleaning.

Commercial Technology Summary Data Sheet

END-USE: Refrigeration

TECHNOLOGY: **Floating Head Pressure Control**

GENERAL DESCRIPTION: The floating head pressure control allows the compressor discharge pressure (and therefore temperature) to drop when the ambient air temperature drops, resulting in increased system efficiency.

PHYSICAL CHARACTERISTICS: The core of the floating head pressure control is a thermally-activated three-way valve located between the condenser outlet and the receiver inlet. It replaces the minimum pressure regulator that is most commonly used. The valve is activated by means of sensors in the display cases. This occurs when the refrigerant reaching the cases is at a pressure too low to prevent it from vaporizing before it reaches the expansion valve. When the valve is activated, it shuts off the condenser outlet and allows hot gas from the compressor discharge to flow directly into the receiver, thus raising the pressure. When the case pressure is adequate, the valve allows normal flow, which means the typical condenser pressure is below that allowed by the minimum pressure regulator. This results in lower condensing temperature and thus higher system efficiency. Refer to note [24] for more detail.

APPLICABILITY: The control applies to any refrigeration system that would otherwise use a fixed, minimum pressure regulator to control discharge pressure. In general, this includes retail store systems. It is more likely to be used in new systems due to its low marginal cost, but it should prove cost-effective in most retrofit applications as well.

ENERGY PERFORMANCE: In tests, the floating head pressure control resulted in energy savings of approximately 15% for R-12 systems and 2% for R-502 systems. Refer to note [25] for more detail. The savings are based on average improvements in EER for parallel, unequal compressor systems, using floating head control compared to a base system using minimum pressure control with ambient subcooling. Since floating head control was the only change contributing to the difference, and since the compressors used are standard refrigeration units, the results should be generally applicable.

The peak savings were not tested, so the effect is unknown. Due to the high ambient temperature during both utilities' annual peaks, it is likely that the condensing pressure of the minimum pressure system would be above the regulator setting. The peak savings would therefore be zero.

COSTS: The control system costs for new installations are about $100 (mostly for sensor wiring, since the mechanical parts are about equal in cost). For retrofits, the costs include the valve, wiring, and possible expansion valve changes. The retrofit cost is therefore variable; $800 is a typical figure. [26]

UTILITY SYSTEM IMPACTS: Energy savings. Peak load reductions unlikely.

USER IMPACTS: Reductions in electricity costs for energy; peak power charges are likely to drop only during cool months.

PRODUCT AVAILABILITY: The control is available from at least one manufacturer.

EXPERIENCE: No problems were encountered during laboratory and in-store tests. [27]

COMMENTS + CAVEATS: In retrofit applications, reducing the head pressure with a floating head control may result in compressor short-cycling due to the increase in compressor capacity. Another important possible difficulty with retrofits is that expansion valves may not be able to supply adequate refrigerant at low head pressures, requiring larger capacity valves to be installed. For these reasons, retrofitting these controls onto existing systems should only be done with the assistance of an experienced refrigeration designer.

Most of the savings will be during periods when ambient temperatures are low.

Chapter 3

Refrigeration

3.1 INTRODUCTION

Commercial sector refrigeration as an end-use falls predominantly into one of three building types: (1) Food Service (including restaurants, hospitals, schools, hotels, etc.), which uses 8 and 9% of the commercial refrigeration electricity in the SCE and PG&E areas, respectively; (2) Refrigerated Warehouses use 6% and 5%; (3) Retail Food (food markets) use the largest the share: about 85% for both utilities. See Tables 3-3 and 3-4 for detailed breakdowns of the use in each building type. Each of the three general refrigeration types may require either refrigerated space (35-50° F), freezing space (-20 to 32° F), or both. The equipment is used in three ways: to maintain food temperature, to cool food to storage temperatures from ambient temperature or above, and to display food.

Since refrigeration serves to retard food spoilage, there are two basic approaches to energy conservation. One is to reduce the need for refrigeration (i.e. heat removal) through improvements in food processing and handling, as well as improving the thermal integrity of refrigerated enclosures. The other is to supply the resultant need for cooling as efficiently as possible through improvements in refrigeration equipment, controls, and operation.

In spite of the wide variation in equipment size and type, refrigeration equipment is remarkably similar in basic operation, which yields the same basic types of efficiency-improving technology options for all applications (for examples, those which reduce heat gains, improved controls, and strategies for reducing condensing temperatures).

3.1.1 Usage in the Service Territories

Tables 3-3 and 3-4 detail the refrigeration end-use for 1982 and 2000, as currently contained in the SCE and PG&E commercial models.

3.1.2 Reducing the Need for Refrigeration

One approach to conserving energy in the refrigeration end-use is through efficiency improvements in mechanical systems (see section 3.1.3). This section addresses a more fundamental approach: reducing the need for mechanical heat removal in the first place. There are two basic approaches in this category: changing the way food is processed and handled, and reducing the heat gains into refrigerated enclosures.

Table 3-3

SCE REFRIGERATION BY BUILDING TYPE

BLDG TYPE	END USE	YEAR	ELEC USE (10E3 KWH)	ELEC FRAC	MARGINAL EUI (KWH/SQFT)	AVERAGE EUI (KWH/SQFT)	SQFT (1OOOS)	AVERAGE USAGE (10E3 KWH)	ADJ EUI (KWH/SQFT)
FOOD STO	REFRIGER	1982	1174931.	.962	17.018	20.133	58358	1130284	19.37
SMALL WA	REFRIGER	1982	76326.	.419	.784	.784	97355	31981	.33
RESTAURA	REFRIGER	1982	61474.	.913	1.846	1.846	33301	56126	1.69
SMALL ST	REFRIGER	1982	44858.	.380	.719	.719	62389	17046	.27
ELEMENTA	REFRIGER	1982	18520.	.827	.134	.134	138209	15316	.11
LARGE WA	REFRIGER	1982	18143.	.419	.784	.784	23142	7602	.33
DEPARTME	REFRIGER	1982	17794.	.380	.731	.731	24342	6762	.28
HOSPITAL	REFRIGER	1982	10871.	.650	.367	.367	29621	7066	.24
HOTELS/M	REFRIGER	1982	9712.	.857	.209	.209	46469	8323	.18
MISCELLA	REFRIGER	1982	8954.	.470	.079	.079	113342	4208	.04
LOW RISE	REFRIGER	1982	6636.	.465	.063	.063	105333	3086	.03
UNIVERSI	REFRIGER	1982	4327.	.569	.140	.140	30907	2462	.08
HIGH RISE	REFRIGER	1982	2628.	.465	.063	.063	41714	1222	.03
MEDICAL	REFRIGER	1982	924.	.651	.061	.061	15148	602	.04
			1456098	0.60	1.64	1.87	819630	92292	
FOOD STO	REFRIGER	2000	1284234.	.955	16.395	16.592	77401	1226443	15.85
SMALL WA	REFRIGER	2000	101856.	.415	.788	.788	129259	42270	.33
RESTAURA	REFRIGER	2000	71003.	.912	1.855	1.855	38277	64755	1.69
SMALL ST	REFRIGER	2000	58932.	.377	.712	.712	82770	22217	.27
LARGE WA	REFRIGER	2000	24226.	.415	.788	.788	30744	10054	.33
DEPARTME	REFRIGER	2000	23547.	.378	.729	.729	32300	8901	.28
ELEMENTA	REFRIGER	2000	17878.	.821	.130	.130	137523	14678	.11
HOSPITAL	REFRIGER	2000	14718.	.645	.369	.369	39886	9493	.24
LOW RISE	REFRIGER	2000	14459.	.465	.063	.063	229508	6723	.03
HOTELS/M	REFRIGER	2000	14152.	.850	.208	.208	68038	12029	.18
MISCELLA	REFRIGER	2000	11374.	.465	.079	.079	143975	5289	.04
HIGH RISE	REFRIGER	2000	5723.	.465	.063	.063	90841	2661	.03
UNIVERSI	REFRIGER	2000	5037.	.567	.141	.141	35723	2856	.08
MEDICAL	REFRIGER	2000	1227.	.646	.060	.060	20450	793	.04
			1648366	0.60	1.60	1.6	1156695	102083	

Source: SCE, Commercial-Sector Model Run, September 1983.

Table 3-4

PG&E REFRIGERATION ENERGY USE BY BUILDING TYPE

BLDG TYPE	END USE	YEAR	ELEC USE (10E3 KWH)	ELEC FRAC	AVERAGE EUI (KWH/SQFT)	SQFT (1000S)	AVERAGE USAGE (10E3 KWH)	ADJ EUI (KWH/SQFT)
GROCERY	REFRIGR	1982	1273240.	.940	23.884	53309	1196846	22.45
RETAIL	REFRIGR	1982	170022.	.570	.789	215490	96913	.45
WAREHSE	REFRIGR	1982	87818.	.510	1.294	67866	44787	.66
RESTRANT	REFRIGR	1982	73749.	.980	1.424	51790	72274	1.40
HEALTH	REFRIGR	1982	22639.	.980	.324	69873	22186	.32
E/S SCHL	REFRIGR	1982	20047.	.950	.134	149604	19045	.13
OFFICE	REFRIGR	1982	15615.	.740	.055	283909	11555	.04
MISCELL.	REFRIGR	1982	14021.	.780	.090	155789	10936	.07
COL/TRDE	REFRIGR	1982	10136.	.930	.129	78574	9426	.12
HOT/MOTL	REFRIGR	1982	9688.	.870	.217	44645	8429	.19
			1696975	0.83	2.83	1170850	149240	
GROCERY	REFRIGR	2000	1344060.	.940	19.079	70447	1263416	17.93
RETAIL	REFRIGR	2000	213563.	.570	.651	328054	121731	.37
WAREHSE	REFRIGR	2000	164314.	.500	1.197	137272	82157	.60
RESTRANT	REFRIGR	2000	67082.	.980	1.193	56230	65740	1.17
OFFICE	REFRIGR	2000	20398.	.740	.049	416286	15095	.04
E/S SCHL	REFRIGR	2000	18994.	.950	.119	159613	18044	.11
HOT/MOTL	REFRIGR	2000	18638.	.860	.195	95579	16029	.17
HEALTH	REFRIGR	2000	18577.	.950	.260	71450	17648	.25
MISCELL.	REFRIGR	2000	18541.	.770	.080	231763	14277	.06
COL/TRDE	REFRIGR	2000	8733.	.890	.114	76605	7772	.10
			1892900	.82	2.29	1643298	162191	

PG&E Commercial-Sector Model Run, October 5, 1983

3.1.2.1 Food processing technology

3.1.2.1.1 Ultrahigh Temperature Sterilization and Aseptic Packaging

This technology, which inhibits microbiological growth to a much greater extent than typical pasteurization, may significantly reduce the need to refrigerate dairy products. This technique is currently in use in Europe, with good results in room-temperature storage and sales of milk, even two or more weeks after packaging. [28] Any refrigerated dairy cases in food stores that are rendered unnecessary by this technology will result in 100% savings in both peak power and energy for those cases and their associated refrigeration equipment.

3.1.2.2. Load Reduction in Refrigerated Enclosures

Refrigerated spaces of all types (retail display cases, food service refrigerators, and warehouses) need mechanical cooling primarily to counteract heat gains from their surroundings (in the form of conduction, infiltration, and radiation), and from internal gains (anti-sweat heaters, defrosting systems, lighting, and fans). The following sections discuss how reducing these heat gains has the potential to reduce the need for refrigeration by as much as 50%.

3.1.2.2.1 Retail Food Display Cases

In order to preserve a wide variety of foods while making them easily accessible, a number of display cases of specialized design are in use. The most prevalent are the Multideck (also known as Multiple-shelf or Upright cases), Single-shelf (or Tub), Glass door merchandisers, and Delicatessen cases. See Figure 3-1 for illustrations.

MULTI DECK - AIR CURTAIN

OPEN TUB

GLASS DOOR REACH-IN

DELICATESSEN

Figure 3-1. Refrigerated Retail Food Display Cases.

- The Multideck case

The Multideck case, while it has the merchandising advantage of high product visibility (it has about twice the display space per lineal foot as the Tub case), relies on fan-forced air curtains to minimize heat gain from the surrounding store. The resulting air spill-over into the aisles makes for high energy consumption (more than four times that of the Tub case, per lineal foot, or twice that of the Tub, per amount of display area) [29] as well as reducing shopper comfort by making the aisles cold.

One approach to reducing the heat gain to these cases is to install flexible plastic strip curtains or multi-layered glass doors, thus converting them into the equivalent of Glass-door merchandisers. Approximately 75% of the fan load (for the air curtains) is disconnected, and less infiltration results in less frost build-up on the evaporator coil, reducing the need for defrosting. The use of anti-sweat heaters can often be reduced as well. Such retrofits, because they greatly reduce the need for cooling, usually require the compressor system to be modified. Measured energy savings range from 30% to 60%, with 50% savings most often cited for glass door installations on both low (frozen food) and medium temperature cases, while strip curtains save about 15% and 45% on low and medium temperature cases, respectively. [30] [31] [32] [33] [34] It should be noted that strip curtains have not met with universal acceptance where they have been installed. This is particularly true on low temperature cases, where condensation and even frost can obscure the product.

- The Glass door merchandiser

For new installations, the Glass door merchandiser is replacing the Multi-deck case. Although there is no test standard for the Glass door units, [35] their conservation potential appears to be equivalent to the glass door retrofit of the Multi-deck cases, of both the medium and low-temperature types.

- Tub cases

While Tub cases are open to the store air, the fact that they are open only at the top minimizes convective (infiltration) heat gains. Approximately 50% of the heat gain is from radiation, and a radiation shield (a cover suspended over the case to block visible and infra-red light) could reduce the overall heat load by 25%. Such shields yield lesser savings in other case types. [36]

3.1.2.2.2 Load reduction in food service refrigeration

Food service refrigeration consists of a great variety of equipment for an even greater variety of uses. However, reach-in and walk-in refrigerators and freezers are by far the greatest consumers of energy. As a result, the bulk of the conservation opportunity is for these units, which, unlike some of the more exotic equipment, are basically insulated boxes around cold volumes of food and air. [37]

Although there is a lack of performance data on such equipment, we can make a rough estimate of the potential for efficiency improvements based on comparisons to residential refrigeration and observations about the lack of industry attention to significant load-controlling features such as insulation levels and the door-to-case fit. [38] Conservation opportunities include increased insulation levels, double-gasketing of doors, use of plastic strip curtains in doorways, automatic door closers, evaporator fan shut-off during open-door periods, and more efficient evaporator fan motors, which are notoriously inefficient. [39] A recent LBL study estimated that a 25% reduction in conduction and infiltration load should be possible. [40]

3.1.2.2.3 Load reduction in warehouse refrigeration

Since infiltration accounts for up to 50% of the refrigeration load in warehouses, [41] load reduction efforts should begin there, with opportunities including automatically-opened doors, air curtains, strip curtains, air locks, sealing of doors (both to the building and to vehicles transferring food), and sealing of the building shell. Significant savings may also be possible by increasing insulation levels (including on older warehouses built during the era of relatively cheap electricity), and improving evaporator fans, defrost controls, and lighting. See the INFORMATION GAPS section (3.2).

3.1.2.2.4 Interactions between refrigerated enclosure cooling loads and HVAC

See INFORMATION GAPS (3.2).

3.1.3 Meeting the Need More Efficiently: Refrigeration Equipment Technologies

Although reducing the need for mechanical cooling will often prove to be the easiest (fastest, cheapest) way to achieve energy savings in refrigeration, some combination of load reduction and efficiency improvements in the equipment to meet the load will usually be the best overall approach, in terms of realizing the maximum amount of cost-effective conservation. The following subsections address the technologies of heat removal.

3.1.3.1. Compressors and compressor systems

Commercial refrigeration compressors are generally of the reciprocating type, ranging from the fractional horsepower single-cylinder hermetic units common in food service equipment, through semi-hermetic units of a few to a few tens of horsepower, to open-drive compressors with multiple cylinders which may be powered by motors of 100 horsepower or more. All of these operate on some Halocarbon refrigerant (or combination of refrigerants) such as R-12, R-22, or R502. In large systems (supermarkets, e.g.) they may be operated in parallel.

The very large warehouse compressors may be of reciprocating or screw type, may be in a two-stage configuration (in series), and often use R-717 (ammonia); the latter two are most likely to be found in low-temperature freezers.

3.1.3.1.1 Retail food systems

A study of supermarket refrigeration systems concluded that compressor systems need to overcome part-load efficiency penalties in order to achieve significant energy savings. [42] Of the methods analyzed (hot gas bypass, clearance volume control, valve control, speed control, and unequal parallel compressors), the last was judged to be the most efficient technology that can be made available, cost-effectively, for the near term. It is likely that for the long term, solid-state, microprocessor-controlled variable-speed drives will prevail due to their mechanical simplicity.

3.1.3.2 Condensers

As the means for the refrigeration system to reject its heat into the surroundings, the condenser has a profound effect on system performance and efficiency. While there are lower limits, the general energy-saving approach is to reduce the pressure at which the refrigerant condenses, which means reducing the condensing temperature. (This is because, during the phase change, the temperature and pressure of the refrigerant are not independent.) The following section discusses one approach.

3.1.3.2.1 Evaporatively Pre-Cooled Condenser

This strategy can be applied easily as a retrofit as well as in new installations. The idea is to use a simple evaporative cooler (analogous to a "swamp cooler") to pre-cool the air flowing through an air-cooled condenser. Cheaper and more flexible than a water-cooled condenser with cooling tower, this technology has the same basic advantage of being able to cool the condenser with a fluid (in this case, humid air) at a temperature below the dry bulb temperature. The savings estimate (see the NOTES AND REFERENCES section for details) is 8% in the San Francisco and Los Angeles areas, and 11% in Fresno.

3.1.3.3 System Controls

Controls of refrigeration systems, like those of other building environmental systems, often provide opportunities for very cost-effective savings as well as the potential for *reducing* system performance if not properly designed and maintained.

Controls on refrigeration systems are improving, starting with the fundamental head and suction pressure controls [43] on the large systems, and eventually working down to defrost and anti-sweat heater controls on food service equipment. The low cost of microprocessors, and their ability to simultaneously monitor and optimize the entire system, will displace mechanical controls.

An example of near-term control sophistication is that of a combination of a mechanical "floating head" control and a microprocessor-based suction pressure control to optimize the operation of a triple, unequal parallel compressor assembly in supermarket systems. The alternatives (and those that are in common practice) are a minimum pressure control and a mechanical suction pressure sequencer. The floating head control permits the compressor outlet pressure to drop below the point allowed by the minimum pressure control, thus allowing lower condensing temperatures when ambient conditions permit. Compared to the mechanical suction control, the microprocessor suction control allows finer set-points, as well as programming based on *anticipated* load, and compressor operating constraints (such as cycling time).

3.1.3.4 Heat Reclaim

While a substantial heating load (water, space or desiccant regeneration) can be met by otherwise rejected refrigeration heat, the effect on the refrigeration system may be either an improvement or a degradation in energy efficiency. A decrease can be the result of a poorly engineered installation, or to an intentional elevation in condensing temperature to reclaim heat in a more useful form. Conversely, if the condensing temperature is reduced by the heat reclaim system, the refrigeration system performance will also improve, an added bonus to the energy savings from the reclaimed heat.

3.2 INFORMATION GAPS

- Information on interactions between the refrigeration systems and the HVAC systems in retail applications is needed. The computer simulation program DOE-2 is being upgraded to include refrigerated case loads. [44] The use of DOE-2, in combination with sub-metered retail food stores, could provide significant insight into the interactions.
- Automatically-opened doors, strip curtains, and the like promise large savings in warehouse applications (by reducing infiltration loads at open doors). However, their actual performance is not well established, [45] suggesting the need for sub-metered case studies.
- Food service refrigeration is poorly represented in terms of energy performance information from the manufacturers and field studies. More information would help determine the conservation potential in this category.
- The energy performance of variable-speed compressors has been overlooked. Additional research, especially including field tests, is needed to establish the potential savings and reliability of this technology.
- Desiccant dehumidification, especially of the air in retail food store applications, may reduce energy consumption from frost formation, defrosting, and re-cooling after defrost, as well as from a possible reduction in the need for anti-sweat heaters on cases and doors. Desiccant systems, regenerated by condenser reject heat as well as by gas heaters, have resulted in significant savings in humid areas of the country. [46] The comparatively dry California air offers less opportunity for conservation from such systems, but the concept seems worthy of investigation, especially for supermarkets in the relatively humid coastal areas.

Notes and References

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2. Merrill, P.S., et al, *The Development of Minimum Efficiency Standards for Large Capacity Air Conditioners and Commercial Water Heaters, Refrigerators and Freezers,* Contractor Report by Science Applications, Inc. for the California Energy Commission, 1980, No. P400-80-041, p. 9-30.
3. Agboatwala, A.C., "Glass Door Retrofits on Commercial Open Multideck Display Cases", Pacific Gas and Electric Company, Application Note No. 53-43-82, 1982.
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5. Nowell, Steven, "The Effectiveness of Frig-I-Door Plastic Curtains for Multi-Deck Freezer and Cooler Cases", Pacific Gas and Electric Company, Report No. 18D-81-02, 1981.
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7. Jackson, H.Z., *A Study to Determine a Method of Predicting Energy Losses Due to Infiltration in Refrigerated Warehouses,* Phase I, for ASHRAE, Research Project No. 362-RP, 1984.

8. Agboatwala, 1982, and Hudson, 1984.

9. Curtron representative, Novato, California, personal communication with Steve Greenberg, October, 1984.

10. "Covering Refrigerator Display Cases", Energy Saver Series, Commercial Energy Management Service, San Diego Gas and Electric, 1982.

11. Agboatwala, 1982.

12. Watson, Frank, "Refrigeration System, EMS To Save Grocer 30% in Electricity", *Energy User News*, May 21, 1984.

13. Walker, David, et al, "Research and Development of Highly Energy-Efficient Supermarket Refrigeration Systems", Volume 3, Engineering Evaluation, Draft, 1984, p. ES-6. Prepared by Foster-Miller, Inc. for the Oak Ridge National Laboratory.

14. Barber, Jeff, "New Compressor Systems Seen Paring Refrigeration Costs 15%", *Energy User News*, May 5, 1983.

15. Walker, p. ES-37.

16. Barber, 1983.

17. Browne, Frederick, "Feedback Control of Evaporator Pressure", *ASHRAE Journal,* September 1984.

18. *Ibid.*

19. "Energy Saver Pre-Cooler", Energy Saver Manufacturing, Chandler, Arizona, no date.

20. The following analysis was used: the annual bin dry-bulb and mean coincident wet-bulb temperatures were used, with an assumed evaporative efficiency of 60%. (This figure from the Energy Saver literature.) For each temperature bin, the reduction in dry-bulb temperature achieved by the pre-cooler was calculated, then weighted by multiplying it by the fraction of the year corresponding to that bin. Summing all of these "temperature reduction x fraction of year" products resulted in an average temperature reduction for the year. From Toscano, Vol. 1, p.1-38, (see next page) the relation for EER as a function of condensing temperature was obtained, and was assumed to apply to all refrigeration equipment, at least as far as the slope is concerned. Assuming the condensing temperature is a constant number of degrees above the ambient dry bulb temperature, and that the head pressure controls (if any) allow the condensing temperature to follow the ambient, the slope of the curve can be multiplied by the average temperature reduction to obtain the ratio of the new EER to the base EER. Taking the reciprocal of this ratio, and subtracting from 1, gives the fraction of power and energy savings expected.

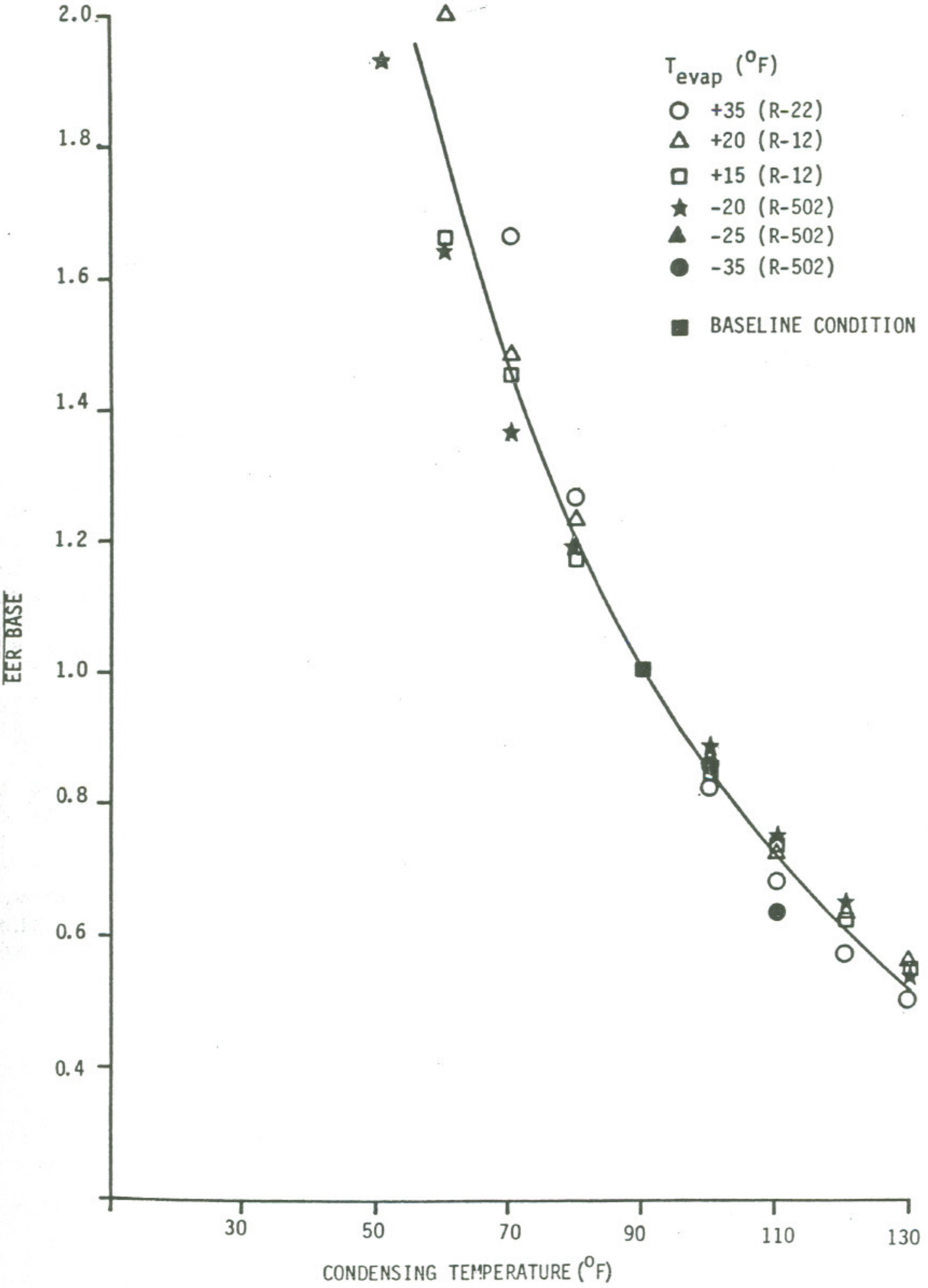


Figure 3-2. Energy Efficiency Ratio as a Function of Condensing Temperature. (Source: Toscano, Vol.1, p. 1-38)

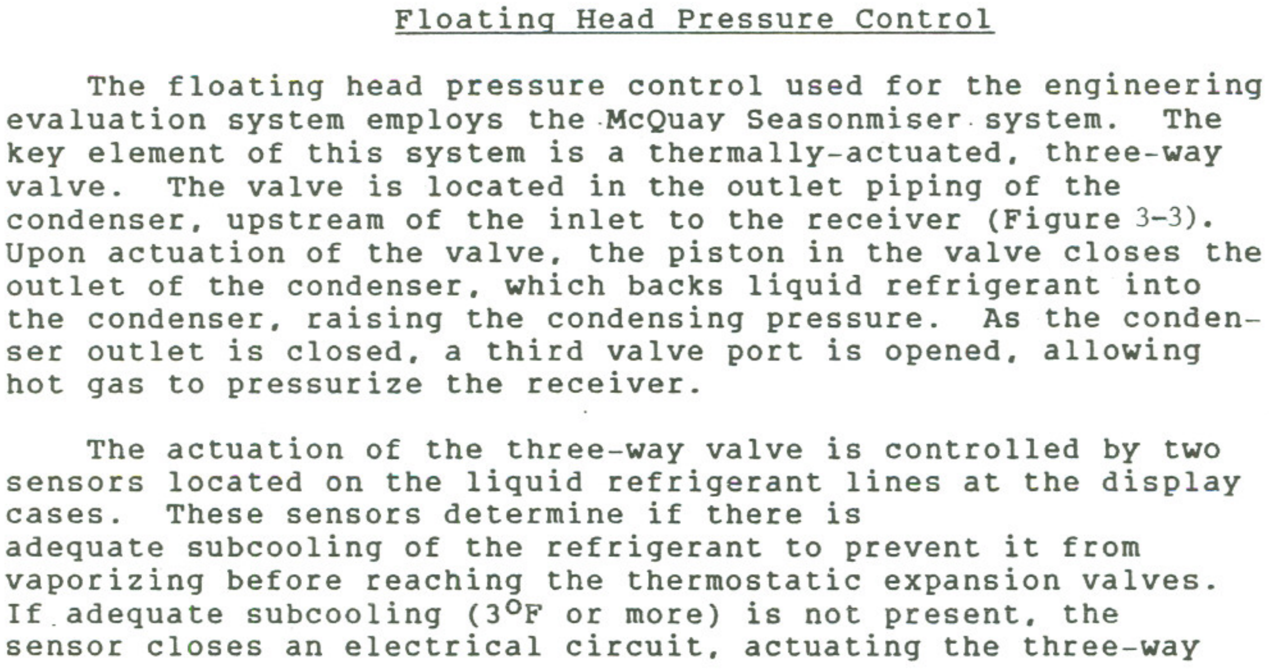
For Reference 20.

21. Nemechek, Jim, of Air Filter Control, Inc., San Francisco, personal communication with Steve Greenberg, September 27, 1984.

22. "Energy Saver".

23. Tischler, Glenn, City of White Settlement, Texas, personal communication with Steve Greenberg, 1984.

24. Walker, David, et al, "Research and Development of Highly Energy-Efficient Supermarket Refrigeration Systems", Volume 3, Engineering Evaluation, Draft, Prepared by Foster-Miller, Inc. for the Oak Ridge National Laboratory, 1984, pp. 1-4, 1-8, 1-9, 1-10 (contents follow). The control was installed on a system serving low-temperature cases, using R-502.



Floating Head Pressure Control

The floating head pressure control used for the engineering evaluation system employs the McQuay Seasonmiser system. The key element of this system is a thermally-actuated, three-way valve. The valve is located in the outlet piping of the condenser, upstream of the inlet to the receiver (Figure 3-3). Upon actuation of the valve, the piston in the valve closes the outlet of the condenser, which backs liquid refrigerant into the condenser, raising the condensing pressure. As the condenser outlet is closed, a third valve port is opened, allowing hot gas to pressurize the receiver.

The actuation of the three-way valve is controlled by two sensors located on the liquid refrigerant lines at the display cases. These sensors determine if there is adequate subcooling of the refrigerant to prevent it from vaporizing before reaching the thermostatic expansion valves. If adequate subcooling (3^{o}F or more) is not present, the sensor closes an electrical circuit, actuating the three-way

Page 1-4 from Walker, et al.

For Reference 24.

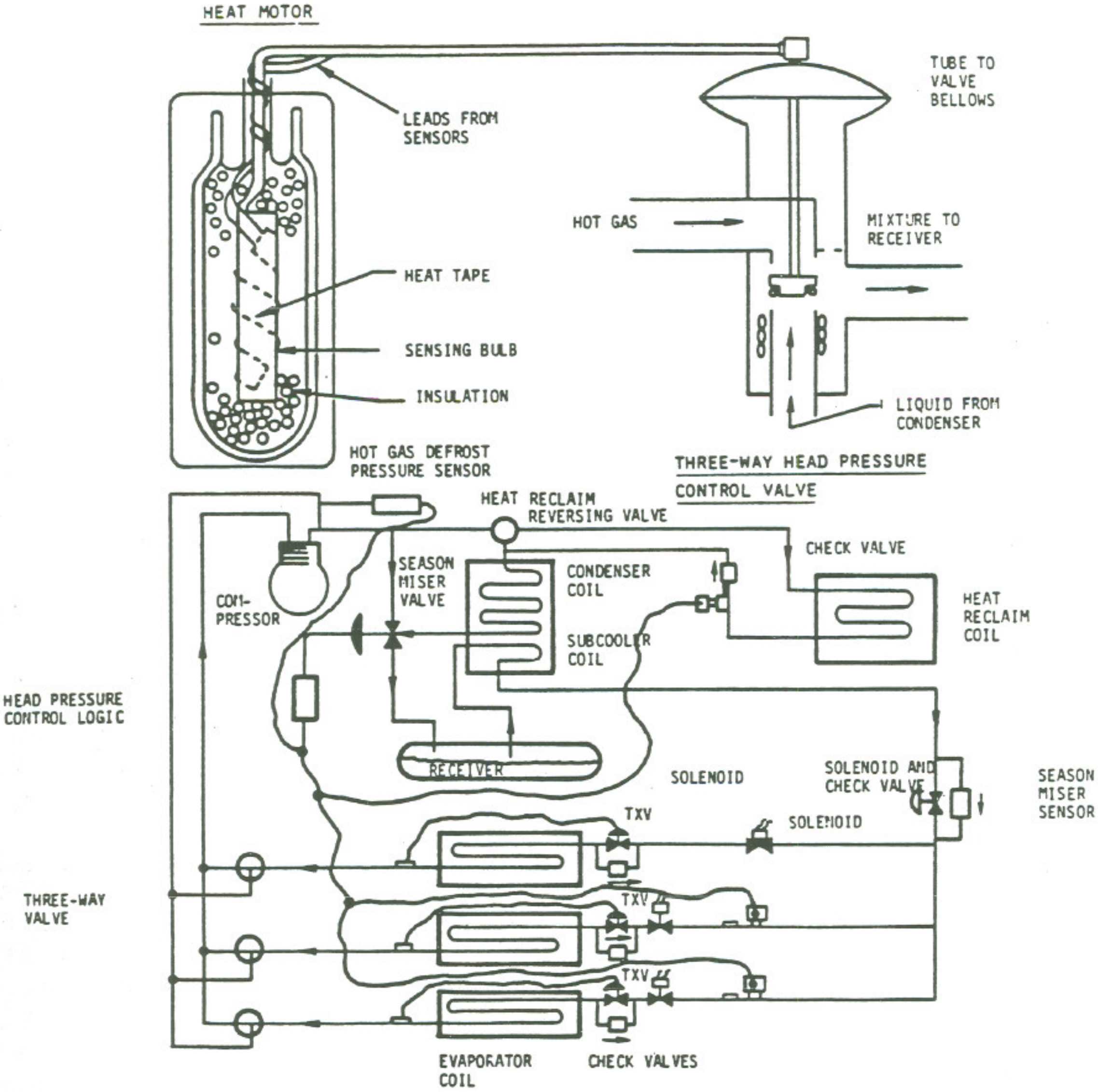


Figure 3-3. Elements of the McQuay Seasonmiser System used for Floating Head Pressure Control
(Source: Walker, et al., p. 1-8.)

For Reference 24.

valve. The electrical diagram for the control circuit is shown in Figure 3-4. With each sensor is a lock-out relay that deactuates the sensor when the refrigeration circuit is shut down by the display case thermostat. A pressure switch is also provided to control liquid refrigerant pressure. In this fashion, a reasonable pressure difference is maintained across the thermostatic expansion valves. The initial setting for the pressure switch is 70 psig, which will provide approximately a 50 psi pressure difference across the expansion valves which should be large enough to prevent erratic behavior in the operation of the expansion valves.

Proper expansion valve sizing must be performed when using a floating head pressure system. For conventional refrigeration systems, the expansion valves are sized to deliver the required refrigerant flow rate at a pressure difference of 100 psi or more. When the head pressure is allowed to track with the ambient temperature, the expansion valves may not be able to supply adequate refrigerant during low head pressure conditions. The expansion valve must, therefore, be resized for low head pressure operation. The resizing was performed for the engineering evaluation system.

Included in the liquid refrigerant piping is an air-cooled subcooling coil. The liquid refrigerant, after leaving the receiver, passes through the subcooling coil. The refrigerant temperature leaving the coil is close to ambient, maximizing the subcooling of the refrigerant. By subcooling the liquid, the minimum condenser pressure can be lowered before liquid flashing will occur.

During defrost, a high head pressure is required to provide high temperature refrigerant to the defrosting display case. High temperature refrigerant is required to minimize defrost time and to insure complete frost removal. With the floating head pressure system, during low ambient temperature periods, it is necessary to raise the head pressure during defrost. This is accomplished by cycling the condenser fans. When defrost is initiated, the condenser fans are shut off until condenser pressure rises to a value of 200 psig (95°F). The condenser fans are then cycled to maintain this temperature through the defrost.

The unequal parallel compressors are mounted on a rack which has all necessary electrical and control hardware required for operation. The compressor rack was fabricated by the Friedrich Refrigeration Company.

Page 1-9 from Walker, et al.

For Reference 24.

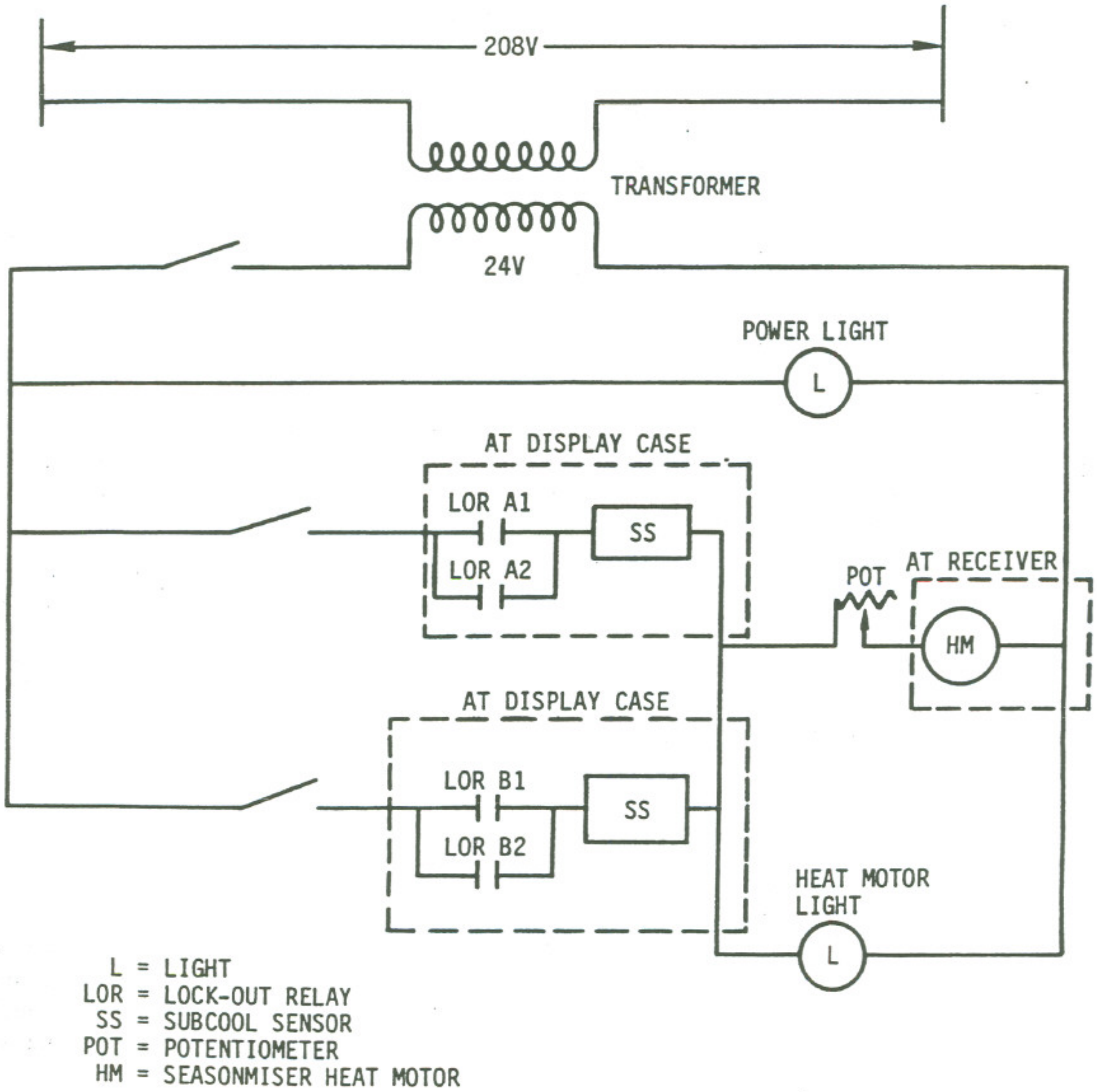


Figure 3-4. Electrical Diagram of the Seasonmiser Control Circuit.
(Source: Walker, et al., p. 1-10.)

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CHAPTER 4

MOTOR EFFICIENCY

Table 4-1

SUMMARY TABLE - MOTOR EFFICIENCY TECHNOLOGIES

Measure	Applicability (R= Retrofit; N = New)		Efficiency Improvement	Cost	Comments
Energy Efficient Motors	R, N ¾ to 250 horsepower (hp)		8% to 3%, typically(1)	$390 to $12700 (for ¾ to 250 hp) 20-50% higher cost than standard motors	Broad applicability. Improved life over standard motors.
Mechanical Variable Speed Drives	Eddy current drives	½ to several thousand hp R, N	Depends on base equipment.	$900 to $63/hp (for 1 to 150 hp)	Proven technology. High reliability. Relatively long life.
	Variable ratio belt drives	5 to 125 hp R, N	Depends on base equipment.	$350 to $50/hp (for 5 to 125 hp)	High efficiency at part load. 3:1 speed range limitation. Requires good maintenance for long life.
Electronic Variable Speed Drives	1 to 1,500 hp R, N		Typical part load improvement of 40% over eddy-current drive.(2)	$1,500 to $110/hp (for 1 to 300 hp)	Relatively new technology. Lifetime uncertain. Cost and reliability are improving.

(1) See Table 4-2.

(2) See Tables 4-4 and 4-6.

Commercial Technology Summary Data Sheet

TECHNOLOGY: ENERGY-EFFICIENT MOTORS

GENERAL DESCRIPTION: These motors are also known as high-efficiency motors and premium motors. They are essentially interchangeable with standard motors, but differences in construction make them more efficient.

PHYSICAL CHARACTERISTICS: Energy-efficient motors achieve their improved efficiency through reducing losses in the conversion of electrical energy to mechanical energy. Magnetic losses are reduced by using thinner steel laminations in the stator and rotor core, as well as more and better grades of steel. The air gap between rotor and stator is also minimized. To reduce resistive losses energy-efficient motors use more copper in the stator windings. On motors with fans (e.g. TEFC), smaller, more efficient fans are used. Different manufacturers may use any or all of these improvements in their designs.

APPLICABILITY: The greater the percentage of the time that a motor runs, the more likely it is that an energy-efficient motor will be cost-effective in that application.

Energy-efficient motors can be applied virtually anywhere a standard motor would otherwise be used: for fans, pumps, and mechanical cooling systems (in HVAC applications), and for refrigeration compressors and fans. New installations allow a wider range of efficient motor applications. For example, some air conditioning and refrigeration equipment has the motor sealed in the hermetic compressor. However, in most cases, interchanging standard units with energy-efficient motors poses no major problems, allowing for broad retrofit applications.

ENERGY PERFORMANCE AND COSTS: The following table lists average efficiencies at one-half, three-quarters, and full load for three-phase, 1800 rpm dripproof induction motors of NEMA design B (normal starting torque) of a major manufacturer. (Full load is the horsepower rating of the motor; 1/2 and 3/4 are fractions of this output load.) Prices shown are list, which are usually discounted to the contractor, but are approximate consumer prices. [1]

Table 4-2

Efficiencies and Prices for Standard and Energy-Efficient Motors

MOTOR SIZE (horse-power)	STANDARD MOTORS				ENERGY-EFFICIENT MOTORS			
	Efficiency at fraction of full load (%)			Price ($)	Efficiency at fraction of full load (%)			Price ($)
	1/2	3/4	Full		1/2	3/4	Full	
3/4	68.0	74.0	76.0	314	73.0	78.0	80.0	393
1	62.0	70.0	72.0	262	79.0	82.0	84.0	328
1 1/2	68.0	75.0	77.0	290	81.0	84.0	84.0	363
2	73.0	78.0	80.0	316	79.0	82.0	84.0	395
3	77.0	80.0	80.5	358	85.5	88.0	88.5	448
5	82.5	83.5	82.5	401	87.0	88.5	88.5	501
7 1/2	84.0	84.5	84.0	408	93.0	92.9	91.7	538
10	86.5	86.5	85.5	516	93.1	92.8	91.7	650
15	85.6	86.5	87.5	677	93.8	94.0	93.0	864
20	87.5	88.5	88.5	843	94.4	94.4	93.6	1055
25	91.0	91.0	89.5	993	94.8	94.8	94.1	1226
30	91.0	91.0	90.2	1160	95.0	94.9	94.1	1425
40	88.5	90.2	90.2	1446	95.3	95.4	94.5	1772
50	90.2	91.0	90.2	1688	95.4	95.4	94.5	2066
60	92.0	92.4	91.0	2125	94.7	95.4	95.4	2532
75	93.0	93.0	91.7	2703	95.3	95.8	95.4	3084
100	92.4	93.0	91.7	3483	95.7	96.2	96.2	3933
125	93.0	93.0	92.4	4006	96.1	96.0	95.4	4709
150	93.8	94.0	93.0	5760	96.0	96.5	96.0	6801
200	94.1	94.5	93.6	7022	96.4	96.5	96.2	8592
250	94.1	94.1	93.0	8863	96.4	96.8	96.2	12701

Except for the largest motors, the added cost is 18 to 25%, and the efficiency increase is typically 8% for the smaller motors, decreasing to 3% for the larger units.

Note that the efficiency increases as the motor size increases (this is true for standard and energy-efficient motors). Also, especially with the larger units, the part-load efficiency (at 3/4 and even 1/2 load) is often greater than that at full load. This means that oversizing the motor may prove to be cost-effective. Due to conservative engineering of motor-driven systems, motors are often oversized in the original installation.

Oversizing motors, for whatever reason, should be done only with caution, as there are potential problems with doing so. One danger of oversizing motors is that the power factor decreases as the motor load decreases (less so with energy-efficient units), which also increases the current in the motor wiring. If the current becomes too large as a result, or if the reduction in power factor threatens to cause the utility to impose power factor charges, power factor correction equipment might be needed. Thus the cost premium of the oversized motor will often be increased by the cost of power factor correction. Another danger of the oversizing strategy is that motor efficiency generally drops off sharply at loads below 1/2, so loads which are variable or not well known could result in an excessively oversized motor, with poor economics for both the initial investment and operating costs.

RELIABILITY/LIFETIME: While motor lifetime is difficult to predict without knowing the specific application details, all other things being equal, energy-efficient motors will considerably outlast conventional units. Since their higher efficiency means less waste heat to dissipate, energy-efficient motors run cooler; this extends operating life. This longer life at least partly offsets the additional cost of the energy-efficient motor.

Energy-efficient motors can be rewound without significant loss of efficiency. That is, when an energy- efficient motor fails and is rebuilt through the rewinding process, the rebuilt motor will have essentially the same efficiency as the original motor.

UTILITY SYSTEM IMPACTS: Reductions in energy consumption and peak power and improvement in power factor.

USER IMPACTS: Reductions in electricity costs for both energy and power. Improvement in power factor. Depending on motor location, reduction in waste heat dissipation may lower cooling loads. See notes in Comments, below.

PRODUCT AVAILABILITY: Energy-efficient motors are available from most motor manufacturers, typically in sizes from 3/4 to 200 horsepower.

EXPERIENCE: These motors have been in use for several years, with good results.

COMMENTS + CAVEATS: Very old motors (for example, U-frame designs of the 1950's) may be as, or more, efficient than the current crop of energy-efficient units.[2]

Energy-efficient motors must be carefully applied to loads which are sensitive to speed because they have lower slip values than standard units, and thus run closer to synchronous speed (i.e., faster). For example, a centrifugal fan's power requirement increases with the cube of its speed; if the energy-efficient motor runs 1% faster, (which is typical) there will be an increase in both the airflow and the power required of about 3%, possibly negating the difference in motor efficiency. In this case, re-sheaving the fan would be in order to keep its speed constant. [3]

When comparing efficiencies of motors, extreme care should be exercised to make sure all of the units in question were rated by the same method (IEEE Method 112B, described in NEMA standard MG 1-12.53a is generally preferred) and the same efficiency term is used (nominal or average as opposed to minimum, guaranteed minimum, or apparent; efficiency at full load, or some fraction of full). NEMA has created a standard (MG 1-12.53b) for marking the full-load efficiency (only) on the motor nameplate, as follows. [4]

Table 4-3

NEMA Motor Efficiency

Index Letter	Nominal Efficiency (%)	Minimum Efficiency (%)
A	-	95.0
B	95.0	94.1
C	94.1	93.0
D	93.0	91.7
E	91.7	90.2
F	90.2	88.5
G	88.5	86.5
H	86.5	84.0
K	84.0	81.5
L	81.5	78.5
M	78.5	75.5
N	75.5	72.0
P	72.0	68.0
R	68.0	64.0
S	64.0	59.5
T	59.5	55.0
U	55.0	50.5
V	50.5	46.0
W	-	less than 46.0

Existing motor efficiency may be improved in one type of single-phase motor by means of the Wanlass modification. The Wanlass modification uses capacitors in series with a second set of motor windings to improve motor efficiency under all loading conditions. Wanlass motors can be supplied new, or the Wanlass modification can be encorporated into motors when they are rewound. Capacitor-start, induction-run single-phase motors are candidates for the Wanlass technique: their efficiency improvement is documented both theoretically [5] and experimentally. [6] [7] Efficiency improvements of ten percent over standard motor efficiency are typical.

There is some controversy associated with the efficiency claims of three-phase motors using the Wanlass technique. There is currently no widely accepted theoretical explanation for the purported efficiency increase; rather, a slight degradation in efficiency is indicated both theoretically [8] and experimentally. [9]

Commercial Technology Summary Data Sheet

TECHNOLOGY: VARIABLE SPEED DRIVES-MECHANICAL

GENERAL DESCRIPTION: Mechanical variable speed drives (MVSDs) consist of either magnetic clutches (eddy current drives) or variable ratio belt drives. In either case they allow the motor to run at a constant speed while the motor-driven equipment speed varies.

PHYSICAL CHARACTERISTICS: The magnetic (eddy current) clutches contain two rotating parts (one connected to the motor, the other to the motor-driven equipment) which are linked together by a magnetic field. The strength of the field is controlled by varying the electrical current to the electromagnet. By changing the field strength, the amount of slip between the rotating parts is varied, and thus the speed of the motor-driven equipment varies while the motor runs at a nearly constant speed. At least one manufacturer fills the air gap between the rotating parts with a fine powder of magnetic particles in order to improve the coupling efficiency. Air and/or water cooling of the clutch is used to dissipate the heat generated during operation.

The variable-ratio belt drive uses a variable-diameter pulley (sheave) to provide a range of driven-equipment speeds for a given motor speed. Since the belt length doesn't change when the pulley diameter varies, the difference must be taken up by either changing the diameter of the other pulley, or by moving the motor to change the distance between pulleys.

Both systems require a controller to sense the equipment speed or load, and to use that signal to control the effective drive ratio.

APPLICABILITY: Eddy-current drives are applicable to any variable-speed equipment from 1/2 to several thousand horsepower. Their speed range is typically from 50 rpm to a few per cent less than the full motor speed. In other words, they increase the motor slip slightly, even when set to run at maximum speed.

Variable-ratio pulleys are applicable to variable-speed equipment from 5 to 125 horsepower; their speed ratio is adjustable over a 3:1 range.

ENERGY PERFORMANCE: MVSDs reduce the efficiency of the mechanical power transmission between the motor and the driven load; however, the reduced speed of the load may result in considerable energy savings. This is especially true for variable-air-volume air transport systems, and for variable water pumping requirements. Since the power requirements of centrifugal fans and pumps vary as the cube of their shaft speed, a reduction in speed (and thus flow) of 25% (for example) results in a 58% reduction in power requirement. Overall savings depend on the load profile and type of motor-driven equipment.

As for the drives themselves, the eddy-current units are about 90% efficient at maximum speed, and decrease with speed. The following table shows this trend in efficiencies (including motor and clutch): [10]

Table 4-4

Typical Eddy-Current Drive Efficiency

RPM (% of maximum)	EFFICIENCY (%)
100	89
90	82
80	74
70	65
60	55
50	45
40	34
30	25

Variable-ratio pulleys range from about 85% to 90% efficient over the speed range from minimum to maximum.

COSTS: List prices for eddy-current drives (including controller) are approximately as follows: [11]

Table 4-5

Prices of Eddy-Current Drives

Size (horsepower)	Price ($ per horsepower)
less than 2	900
5	380
10	280
20	170
30	160
50	110
75	89
100	77
125	71
150	63

For variable-ratio pulleys, typical list prices range from $350/hp to $50/hp in the size range from 5 to 125 horsepower.

RELIABILITY/LIFETIME: Eddy-current drives have proven to be quite reliable when properly applied; since their rotating parts do not touch, there is virtually no wear.

Variable-ratio pulleys use special belts to transfer the power. While these belts are designed for this particular use, they are subject to unusual wear. The pulleys (which vary their effective diameter by changing the width between flanges) are subject to sticking. However, with proper maintenance (similar to of maintenance for typical belt drives) these systems should operate reliably.

UTILITY SYSTEM IMPACTS: Energy savings, peak power reduction, reduction in power factor. The peak power reduction will generally be less than the energy savings, but is still possible, even on peak cooling days (which correspond to the utilities' peaks). For example, the use of variable-speed drives for variable-air-volume systems allows the building zones whose cooling peak does not coincide with the utility peak (typically, the zones on the east sides of buildings) to reduce their electrical demand.

USER IMPACTS: Cost savings from energy savings and demand reduction; possible penalty from power factor reduction.

PRODUCT AVAILABILITY: Eddy-current drives are available in sizes from fractional horsepower to thousands of hp; variable-ratio pulleys are available in sizes from 5 to 125 horsepower; both types are presently available from multiple manufacturers.

COMMENTS + CAVEATS: Special "definite purpose" motors are available which are most efficient at 1/4 to 1/2 of full load, and are thus well suited to variable load situations where standard motor efficiency drops off severely. Another approach to improving the part-load efficiency and power factor of the drive motor is through the use of an electronic power factor controller, a device which senses the load on the motor and reduces the input voltage to the partially-loaded motor. The additional energy savings of either of these methods must be weighed against their added costs. Wherever mechanical variable-speed drives are considered, electronic VSDs are also generally applicable. While the electronic units are more expensive and not as well proven, their higher efficiency makes them worthy of consideration.

Commercial Technology Summary Data Sheet

TECHNOLOGY: VARIABLE SPEED DRIVES-ELECTRONIC

GENERAL DESCRIPTION: Electronic Variable Speed Drives (EVSDs) adjust the speed of the motors they control by electronically varying the input voltage and frequency to the motor. They are also commonly known as variable-frequency solid-state inverters.

PHYSICAL CHARACTERISTICS: EVSDs are installed in the wiring supplying power to their motors. They control the voltage and frequency of the motors' power supply by first rectifying to direct current the incoming constant frequency alternating current signal. This DC signal is then processed by the EVSD electronics to obtain the desired output frequency (which determines the motor operating speed) and voltage, which is generally kept at a constant ratio to the frequency. The high power switching takes place in the inverter section of the EVSD. The inverter thus converts the DC signal back to an AC signal to drive the motor.

The operation of the EVSD is unique among variable speed drives in that it maintains a low-slip condition of motor operation (and thus maintains relatively high efficiency and power factor) over a wide range of motor speeds and loads.

The inverter components are less than 100% efficient in handling the power flowing through them. The resultant waste heat is dissipated through the use of a finned metal heat sink, which is cooled by a small fan in the larger EVSDs.

Since the output frequency is independent of the input frequency, it is possible for an EVSD to operate its motor at higher than normal speed, as well as to reduce the motor speed.

The output of the EVSD can be varied in response to manual control, or automatic signal in the form of a voltage, current, or pressure.

APPLICABILITY: EVSDs are applicable wherever a varying load calls for a variable speed motor drive. This includes variable-volume air distribution and water pumping, air-conditioning chillers, and possibly refrigeration (though the last has not been applied on a wide scale). They are suitable for both new and retrofit installations, and are more easily retrofitted than mechanical variable-speed drives.

ENERGY PERFORMANCE: While some power is lost, the EVSD reduces the speed of the load, which may result in considerable overall energy (and to a lesser extent) peak power savings. This is especially true for variable-air-volume air transport systems, and for variable water pumping requirements. Since the power requirements of centrifugal fans and pumps vary as the cube of their shaft speed, a reduction in speed (and thus flow) of 25% (for example) results in a 58% reduction in power requirement. Overall savings depend on the load profile and type of motor-driven equipment.

As for the drives themselves, manufacturers claim efficiencies of 90 to 97 per cent. Together with the motor, base-speed, full-load efficiencies of 80 to 90 per cent are typical. This efficiency drops somewhat at low speed, constant torque, and drops considerably at low speed and light load. This degradation in efficiency is not generally serious, because the load is small: therefore the energy consumption is also small, even at relatively poor efficiency. [12] The following table shows typical efficiencies (including motor and drive efficiency) for a variable speed fan drive: [13]

Table 4-6

Typical Combined Efficiency: Motor plus Electronic Variable Speed Drive

RPM (% of maximum)	EFFICIENCY (%)
100	86
90	85
80	82
70	80
60	74
50	63
40	43
30	25

COSTS: The following table gives a range of list prices for 13 U.S. suppliers of EVSDs. [14] It should be noted that as advances are made in high power solid-state devices, and as the market for EVSDs expands, the price of the units is likely to drop.

Table 4-7

Equipment Cost for Electronic Variable Speed Drives

EVSD Size (horsepower)	Cost ($ per hp)
1	1500
10	370-1100
25	280-600
100	180-500
300	110-150

RELIABILITY/LIFETIME: While the reputation of EVSDs is improving, many potential users are reluctant to try this relatively unproven technology.

UTILITY SYSTEM IMPACTS: Reduction in energy consumption and peak power. The peak power reduction will generally be less than the energy savings, but is still possible, even on peak cooling days (which correspond to the utilities' peaks). For example, the use of EVSDs for variable-air-volume systems allows the building zones whose cooling peak does not coincide with the utility peak (typically, the zones on the east sides of buildings) to reduce their electrical demand. Harmonics may be introduced into transmission lines, due to the reshaped waveform being used to drive the motor.

USER IMPACTS: Cost reductions from energy savings and possible peak power savings. Possible Electro-Magnetic Interference (EMI).

PRODUCT AVAILABILITY: EVSDs are presently available from many manufacturers, in sizes ranging from 1 to 1500 horsepower.

COMMENTS + CAVEATS: The higher cost and less-certain reliability of the EVSD (compared to the MVSD) must be weighed against the superior part-load efficiency and power factor of the electronic drive.

Chapter 4

Motor Efficiency

4.1 INTRODUCTION

While electric motors are not in themselves an electricity end-use, they are the means by which the vast majority of cooling, air transport, and refrigeration electricity is consumed in commercial buildings.

In the PG&E service territory, these three end-uses consume roughly 5430 Gigawatt-hours per year, or 36% of the commercial sector electricity. They contribute 1260 megawatts, or 49%, to the peak demand in this sector. [15]

In the SCE territory, these same end-uses consume about 8100 Gigawatt-hours per year or 45% of the commercial electricity. 58% of the peak demand (2700 megawatts) is attributed to them. [16]

There are two general approaches to energy conservation and peak power reduction in these end-uses. One is to reduce the load on the motor-driven equipment; this approach is covered in the cooling, air transport, and refrigeration chapters of this report. The second approach is to meet the mechanical load with more-efficient motors and motor drives. This chapter covers the latter strategy. The optimum approach to energy and demand savings often includes some combination of the two.

The documentation for this chapter is contained within the summary sheets rather than in a separate section.

4.2 MOTORS IN COMMERCIAL BUILDINGS

Electric motors convert electrical energy into mechanical energy. In commercial buildings, this mechanical energy is used to operate the fans, pumps, and compressors that comprise cooling, air transport, and refrigeration systems. (Motors are also used to power a host of other devices, from elevators to typewriters, that are not specifically addressed in this series of reports. However, the technologies discussed in this chapter often apply to these other end-uses.)

The size of motors used in commercial buildings ranges from fractional horsepower units in food service refrigeration equipment to motors of over 100 horsepower driving the air transport fans of large buildings.

4.3 ENERGY AND POWER SAVINGS IN COMMERCIAL BUILDING MOTORS

The most straightforward way of reducing the amount of energy and power required to meet mechanical loads is to replace the existing motors with units having a greater efficiency. The Summary Sheet on Energy-Efficient Motors addresses this strategy. These motors have great near-term conservation potential due to their wide applicability across end-uses, size ranges, and for both new and retrofit applications. The second method, somewhat more subtle, takes advantage of the fact that most motor-driven loads vary over time (for example, variable-air-volume air transport systems). These variable loads are met by varying the speed at which the equipment is driven. The Mechanical Variable Speed Drive Summary Sheet discusses ways to reduce the supply speed with a constant motor speed, while the Electronic Variable Speed Drive Summary Sheet describes the technology for varying the speed of the motor itself.

Conventional variable-flow air and water transport systems achieve flow reductions by introducing restrictions (inlet vanes or discharge dampers on fans; throttles on pumps) in the flow circuit. While this technique meets the variable flow requirements of these systems, the additional resistance causes some of the motor power to heat the air or water as it flows through the restriction. By varying the speed of the fan or pump, the reduction in flow can be achieved without this wasteful heating. Thus, both types of speed variation have enormous conservation potential, but the electronic drives are more efficient and more costly.

4.4 CHOOSING ENERGY-SAVING MOTOR DRIVES

Because of the tremendous variation in application specifics, it is difficult to generalize about the cost-effectiveness of any of the technologies covered in this chapter. Probably the most important variables are the number of hours per year of motor drive operation, as well as the profile of load during those hours.

In order to determine what combination of motor and drive to use for a commercial building application, the designer must trade off initial vs. operating costs. A "life-cycle cost" (LCC) can be determined by including all costs (purchase, installation, energy and power, and maintenance) over the lifetime of any particular motor drive. These costs should be appropriately discounted according to the purchaser's time value of money. The life-cycle cost for any drive combination (motor and speed control, if any) can be compared against the LCCs of competing systems to determine the economic optimum choice.

To determine the LCC, the designer must know (or estimate) the following over the life of the equipment: the load profile (horsepower required as a function of time) of the motor-driven equipment, the performance (energy efficiency) of the motor and drive when delivering this load, the utility rates for energy and power, initial equipment costs, parts and labor costs for maintenance, the lifetime of the equipment itself, and the purchaser's discount rate.

It is not the purpose of this report to detail the procedure used to obtain LCCs. The reader is referred to the considerable literature on the subject; for examples, see Ganeriwal, Gupta and Lobodovsky, [17] Krishnan, [18] and Thumann. [19]

4.5 INFORMATION GAPS

In order to determine the overall potential savings of energy-efficient motors and motor drives, improved data on the existing stock and usage of motors in the utilities' service areas is needed. This would include sizes, efficiencies, operating loads, and age. Utility commercial surveys may be of some use in gathering this information, but audits and rebate program records will probably be of greater value.

Sub-metered case studies of retrofit installations are lacking for most of these technologies. Such case studies would be invaluable in determining potential savings, as well as identifying problems with applying the technologies.

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CHAPTER 5

ELECTRIC LIGHTING TECHNOLOGY

Table 5-1
SUMMARY TABLE - ELECTRIC LIGHTING

Measure	Applicability (R=Retrofit; N=New)	Base Conditions[1]	System Efficacy[2] (lumens/watt)	Savings[3] Energy	Peak	Costs[4]	Lifetime[5] (hours)	Comments
High Efficiency core/coil ballasts.	N/R. All standard fluorescent sizes. All building types with fluorescents.	1) 4-foot, F-40, 2 lamp luminaire with standard ballast.	~70	10%	10%	+$4-12	50,000	These ballasts are the same as standard ballasts except for higher quality materials. High efficiency ballasts are now required in California.
Electronic (solid-state) ballasts N/R.	N/R. All standard fluorescent sizes. All building types with fluorescents.	1) 4-foot, F-40, 2 lamp luminaire with standard ballast.	77	20-25%	20-25%	$30-40	50,000	Some models permit lamp dimming. All models operate at 10-30 kHz. Early models experienced reliability problems. Current models have improved reliability.
		2) 4-foot, F-40, 2 lamp luminaire with efficient core/coil ballast.	77	10-15%	10-15%	Dimmable $32-64		
Fluorescent delamping	R. Situations where lighting levels are too high or area lighting is changed to task/ambient. Measure has already been widely implemented.	Standard fluorescent luminaire (63 lumens/watt)						Lighting output will be reduced in all cases. Uneven lighting patterns may result.
–without replacement			63	50%	50%	$0	N.A.	-Light output will decrease by 50%
–with 'dummy' tube replacement			50	50-66%	50-66%		Indef	-Light output will decrease by 75%
–with reactive impedance replacement			63	33-50%	33-50%			-Light output will decrease by 33 to 50%
Compact fluorescent replacement for incandescent.	N/R. Replacement for 40, 60, 75 watt incandescents	Standard Incandescents	40-60	75%	75%	$20-30	7,500-10,000	Good color qualities (CRI 80 and Color Temperature 2800 °K).
Circline fluorescent replacement for incandescent	N/R. 60, 100, 50/100, equivalents	Standard Incandescents	35-40	55-65%	55-65%	$6-20	7,500-12,000	Large diameter may limit application. Relatively poor color quality. Ballast lifetime 50,000 hrs. Lamps are replaceable.

[1] The standard 4-foot, 2-lamp system with cool white lamps is assumed to have a light output of 6000 lumens and an efficacy of 63 lumens/watt.

[2] The system efficacy includes the combined efficacy of the lamp and ballast, where applicable.

[3] Savings do not include the effects of reduced internal loads on building heating, air conditioning, or air handling equipment. In California air conditioning energy savings predominate. See section 2.5.2, Magnitude of Cooling Load Components, for details.

[4] Per unit cost excluding labor costs for installation. P- indicates this is a projected cost. + - indicates incremental cost over the base condition.

[5] Unless otherwise noted, the lifetimes are the rated hours of operation under specified standard lamp or ballast test conditions.

Table 5-2

SUMMARY TABLE - ELECTRIC LIGHTING

Measure	Applicability (R=Retrofit; N=New)	Base Conditions[1]	System Efficacy[2] (lumens/watt)	Savings[3]		Cost[4]	Lifetime[5] (hours)	Comments
				Energy	Peak			
Ellipsoidal incandescent	N/R. Used in recessed incandescent fixtures. Replacement for 75-300 watt lamps.	A or R type incandescent lamps in recessed fixtures	~15 - 20	33 - 60%	33 - 60%	20 to 40% more than R-type	2000	Lamps are not more efficacious. They simply permit more light to leave fixture. Most manufacturers recommend installing ER units that are one-half to one-third the wattage of the A or R lamps.
Coated-filament incandescent	N/R. Replacement for incandescents ranging from 40 to 150 watts. Currently under development. May be available 1986-88.	Standard Incandescents	30	45-50%	45-50%	$5 P	2000	Experimental prototype only. Utilizes heat mirror to improve efficacy.
High Pressure Sodium	N/R. Mostly for new applications, although retrofit is possible. Warehouses, schools, offices, shoppings malls. 35 to 400 watts	Mercury Vapor or Fluorescent	55-120	45-60%	45-60%	~$50-90	16,000 -24,000+	Can be used for either direct or indirect lighting. Warmup time 3-4 minutes, restrike one-half to one and one-half minutes.

[1] The standard 4-foot, 2-lamp system with cool white lamps is assumed to have a light output of 6000 lumens and an efficacy of 63 lumens/watt.

[2] The system efficacy includes the combined efficacy of the lamp and ballast, where applicable.

[3] Savings do not include the effects of reduced internal loads on building heating, air conditioning, or air handling equipment. In California air conditioning energy savings predominate. See section 2.5.2, Magnitude of Cooling Load Components, for details.

[4] Per unit cost excluding labor costs for installation. P- indicates this is a projected cost. + - indicates incremental cost over the base condition.

[5] Unless otherwise noted, the lifetimes are the rated hours of operation under specified standard lamp or ballast test conditions.

Table 5-3
SUMMARY TABLE - ELECTRIC LIGHTING

Measure	Applicability (R=Retrofit; N=New)	Base Conditions[1]	System Efficacy[2] (lumens/watt)	Savings[3]		Costs[4]	Lifetime[5] (hours)	Comments
				Energy	Peak			
Low-wattage fluorescents	R.Available in most standard sizes.	4-foot,F-40, T12 lamps	55-90	12-15%	12-15%	+$2	20,000	Widely used conservation measure. Can decrease light output substantially.
Electrodeless Fluorescent	R/N.May be available 1987-1988	100 watt incandescent	55 (68-77P)	70%	70%	$15P	10,000	Lamp is still under development.
Advanced fluorescent technologies	Isotope Enchancement, Magnetic Loading, Two-Photon Phosphors.	Best current fluorescent system (100 lumens/watt)[6]	110-200	10-50%	10-50%	Unknown	Unknown	See narrative for details. No summary data sheets.
Occupant Sensors and Timers	R/N. Any location where occupancy is intermittent, e.g. conference rooms, warehouses. Also locations where lights are left on during unoccupied hours.	Refer to Section 6.4.5 for additional details						

[1] The standard 4-foot, 2-lamp system with cool white lamps is assumed to have a light output of 6000 lumens and an efficacy of 63 lumens/watt.

[2] The system efficacy includes the combined efficacy of the lamp and ballast, where applicable.

[3] Savings do not include the effects of reduced internal loads on building heating, air conditioning, or air handling equipment. In California air conditioning energy savings predominate. See section 2.5.2, Magnitude of Cooling Load Components, for details.

[4] Per unit cost excluding labor costs for installation. P- indicates this is a projected cost. + - indicates incremental cost over the base condition.

[5] Unless otherwise noted, the lifetimes are the rated hours of operation under specified standard lamp or ballast test conditions.

[6] The highest efficacy fluorescent lamp and ballast system with electronic ballast, narrow lamp tubes, and high output phosphor can reach a efficacy of 100 lumens per watt.

Commercial Technology Summary Sheet

END-USE: Interior Lighting

TECHNOLOGY: **Energy Efficient Core/Coil Ballasts for Fluorescent Lamps**

GENERAL DESCRIPTION: The efficiency of conventional fluorescent ballasts can be improved by use of so-called "high-efficiency" ballasts. These ballasts are designed to operate fluorescent lamps at or close to full light output with lower ballast losses than typical fluorescent lamp ballasts. These ballasts are now required by California Title-24 regulations. [1]

PHYSICAL CHARACTERISTICS: The high-efficiency core and coil ballast have a design similar to a conventional core and coil ballast except that the iron cores are larger and the windings are of copper rather than aluminum. Consequently, internal losses are less.

APPLICABILITY: These ballasts provide an intermediate step in ballast efficiency improvements between the conventional ballast and the higher efficiency solid-state or electronic ballast. These units are available in most all size ranges and can be used with both standard and reduced-wattage lamps.

ENERGY PERFORMANCE: Energy savings average about 10% above standard ballasts. For example, energy saving ballasts reduce energy use about 4 to 5 watts per lamp in a 4-foot unit. [2]

These estimates do not include additional energy and power effects from reducing air conditioning loads or increasing heating or reheat requirements. Refer to the narrative section for additional details.

COSTS: Costs for these ballast range from $4 to $12 more than conventional ballasts. [3]

RELIABILITY/LIFETIME: Reliability of these ballast should be comparable to or better than standard ballast because of their improved materials and construction.

Most ballast are designed to operate, at a 50% duty cycle and at proper temperatures, for about 10 to 12 years. We have used a lifetime of 50,000 hours. [4]

UTILITY SYSTEM IMPACTS: Efficient core and coil ballast will result in energy and power savings for the utility.

USER IMPACTS: The user should notice no difference in lamp operation or light output with these ballasts other than the above noted energy and power savings and improved lifetime.

PRODUCT AVAILABILITY: Efficient core and coil ballast are now required in California and are available in all standard ballast types and sizes.

EXPERIENCE: Core and coil ballast are widely available throughout California and have been installed with no significant adverse reactions.

COMMENTS + CAVEATS: California law now requires that only efficient core and coil ballasts be sold.

Notes

1. California Energy Commission, "Fluorescent Lamp Ballast Energy Efficiency Standards," Adopted June 2, 1982, P-400-82-064.
2. Illuminating Engineering Society (IES), *Lighting Handbook, Reference Volume,* 1981, p 8-35.
3. Ibid, Figure 8-118, p 8-105.
4. Ibid, p 8-35.

Commercial Technology Summary Sheet

END-USE: Interior Lighting

TECHNOLOGY: **Electronic (Solid-State) Fluorescent Ballasts**

GENERAL DESCRIPTION: The electronic or solid-state fluorescent ballast provides the same primary function as a conventional core-coil ballast: starting and operating a fluorescent lamp. The energy use of the electronic ballast, itself, is small (4 to 6 watts) and the efficacy of the lamp is improved.

PHYSICAL CHARACTERISTICS: Standard core and coil ballasts operate at 60 Hz. The electronic ballast converts this 60 Hz into 10 to 30 kHz current. Fluorescent lamps driven at these kilohertz frequencies operate at a higher lighting efficacy and generally without flicker (depending on circuit design). Both fixed and dimmable ballasts are available.

APPLICABILITY: These ballasts can be used in new, retrofit, and remodelling applications. They are available in 120 and 277 volt models for 3, 4, and 8-foot fluorescent fixtures. Ballast are also available, which can drive 2, 3, and, 4 lamps. [1]

ENERGY PERFORMANCE: Electronic ballasts have demonstrated combined lamp and ballast efficacy improvements of from 20 to 25% compared to standard (not high-efficiency) core and coil driven systems. For example, the efficacy of a standard F-40 lamp increases by 10 to 15 % and the heat dissipated by the ballasts drops from 16 watts to 4 to 6 watts. The energy performance of lamps may vary significantly from this range depending on such factors as temperature, voltage regulation, and ballast factor. See the narrative section for a discussion of these factors. [2]

These estimates do not include additional energy and power effects from reducing air conditioning loads or increasing heating or reheat requirements. Refer to the narrative for additional details.

COSTS: The typical retail cost of non-dimmable electronic ballast ranges from $30 to $40 for 3, 4, and 8 foot, two-lamp models. This represents a $15 to $20 premium above conventional ballasts. Dimmable ballasts range in price from $32 to $64.

RELIABILITY/LIFETIME: Initial experience with electronic ballast was poor. When these ballasts were first released some were prone to premature failure. Most ballast now available have overcome these problems.

Most ballast are designed to operate for about 50,000 hours under standard operating conditions. Ballast warranties are now provided by some manufacturers.

UTILITY SYSTEM IMPACTS: Installation of these ballasts will result in energy and power savings.

USER IMPACTS: The high frequency operation of these ballast eliminates lamp flicker if the circuit is correctly designed.

PRODUCT AVAILABILITY: Product currently available on the market, although the number of manufacturers and distributors is limited.

EXPERIENCE: Electronic ballast have been commercially available for several years. Two ballast retrofit demonstration projects are the Pacific Gas and Electric Building in San Francisco, and the Veterans Administration Medical Center in Long Beach. The Long Beach study demonstrated annual energy savings of about 25% with simple cleaning and ballast installation. Savings were increased to more that 35% when the savings from lamp dimming were included. More details of these case projects are included in the narrative section, below.

COMMENTS + CAVEATS: At present there are no voluntary American National Standards Institute (ANSI) standards for electronic ballasts. The performance of ballast will vary dramatically with changes in temperature, voltage and other factors. See Table 5-7 for details.

Dimming equipment is also available for core and coil ballasts, however, the cost is very high. Solid state ballasts permit dimming at a significantly lower cost. With these ballasts it is possible to respond more easily to available daylighting.

The high frequency operation of the ballast eliminates lamp flicker and may decrease the level of audible ballast noise.

The more efficient operation of the ballast also results in less internal heat load to the building and significantly less heat load on the ballast itself.

Notes

1. Personal communication with Rudy Verderber, Lighting Group, Applied Science Division, Lawrence Berkeley Laboratory.
2. See references 21 through 24 in the narrative section for addition citations on energy performance, costs, lifetime, and experience.

Commercial Technology Summary Sheet

END-USE: Interior Lighting

TECHNOLOGY: **Fluorescent Delamping**

GENERAL DESCRIPTION: Delamping is the selective removal of fluorescent lamps from luminaires. Delamping is used when existing lighting levels are known to be excessive and a non-hardware solution is desired. Delamping is also used when interior lighting patterns are changed from uniform lighting over a broad area to task-ambient lighting. The lamps that have been removed may be replaced with "dummy" tubes or reactive impedance devices.

PHYSICAL CHARACTERISTICS: So-called "dummy tubes" do not produce light and act merely as an impedance device replacing the standard lamp. Dummy tubes are necessary in fixtures where two lamps are wired to a single ballast. In such instances the removal of one lamp will also disconnect the other lamp. Reactive impedance lamps or devices reduce the wattage and light output of the luminaire. They are available either as integral parts of the lamp or as add-on devices to existing lamps. [1]

APPLICABILITY: Delamping is chiefly a retrofit measure, although it may be applicable at time of renovations where no lighting hardware changes are made. It can be used where lighting levels can be decreased without adverse impacts on worker productivity or appearance of merchandise, and hardware changes are deemed too expensive or not feasible.

ENERGY PERFORMANCE: The energy savings from delamping depends on a) the type and number of lamps removed, b) whether the ballasts have been disconnected when the lamp is removed, and c) whether the lamps are replaced with dummy tubes, or impedance devices. Energy savings are typically 50 to 66% for dummy tubes, and 33% or 50% for reactive impedance devices or lamps.

These estimates do not include additional energy and power effects from reducing air conditioning loads or increasing heating or reheat requirements. Refer to the narrative for additional details.

COSTS: The major costs for simple delamping are labor costs for removing the old tubes.

RELIABILITY/LIFETIME: Delamping replacements should last at least as long as normal fluorescent tubes, perhaps significantly longer.

UTILITY SYSTEM IMPACTS: Delamping results in energy and power reductions for the utility.

USER IMPACTS: Delamping will result in lower lighting levels and possibly uneven light distribution. A properly designed delamping program will require attention to these factors.

PRODUCT AVAILABILITY: Delamping is probably the most widely used lighting conservation strategy. Dummy tubes and impedance devices have been available for a several years and are widely marketed.

EXPERIENCE: Delamping has been widely employed over the last ten years. Case study discussions of some of these applications are included in the narrative section of this chapter.

COMMENTS + CAVEATS: The major limitation with delamping is aesthetic. If replacement devices are not used the resultant lighting pattern can be irregular. In open strip fixtures (i.e. no covering lenses) the appearance of unlit lamps can be unpleasant. The Illuminating Engineering Society (IES) cautions against using any lamp on a ballast other than those listed specifically on the ballast. Use of such a lamp may be violate the National Electric Code. [2] Most delamping opportunities have already been taken and there is probably little additional potential for this measure.

Notes

1. Sorcar, Prafulla, *Energy Saving Lighting Systems,* 1982, pp 24-27. and Illuminating Engineering Society (IES), *Lighting Handbook, Reference Volume,* 1981, pp 8-23,24.
2. op.cit., (IES), p 8-24.

Commercial Technology Summary Sheet

END-USE: Interior Lighting

TECHNOLOGY: **Screw-in Fluorescent Replacements for Incandescent**

GENERAL DESCRIPTION: There are several types of screw-in fluorescent lamps available that can be used as replacements for small (up to 100 watt) incandescent lamps in Edison-type sockets. The principal types are the so-called compact models, the PL and SL lamps and ballast, and the adaptive circline lamps. [1]

PHYSICAL CHARACTERISTICS: Both the compact and circline lamps consist of a lamp and ballast package that can be placed in a medium-size Edison-type base. The circline units are driven by a separable core and coil ballast, while the SL lamps contain an integral 20 kHz solid-state (electronic) ballast. PL units have separate lamps and ballasts.

The circline lamps are typically 8 to 12 inches in diameter and can weigh up to 2 pounds. The compact lamps have a much smaller diameter, but are longer than the circline type.

Circlines are available in both rapid and non-rapid start models.

APPLICABILITY: Compact fluorescents can be used in new, retrofit, and remodelling applications. The most widely available units are the PL-7, PL-9, and SL-18 models. These have equivalent light outputs to 40, 60, and 75-watt incandescents, respectively.

The circlines are available in 60, 100, and 50/100 two-way replacement sizes. These units consume 22, 44, and 16/44 watts, respectively. The larger diameter and weight of the circline limit their application and appeal in commercial buildings. For example, circline lamps would be unlikely to fit most recessed fixtures; compact lamps would probably fit many such fixtures.

Both types of lamps are particularly well suited for hallways, stairways, and other areas where incandescents lamps may now be in use and where lamp replacement is difficult and expensive.

ENERGY PERFORMANCE: Incandescent lamps have efficacies ranging from 12 to 18 lumens/watt. Circline-type fluorescents have system (ballast and lamp) efficacies in the range from 35 to 40 lumens/watt. The compact fluorescent, PL and SL types, have system efficacies of from 40 to 60 lumens/watt.

These estimates do not include additional energy and power effects from reducing air conditioning loads or increasing heating or reheat requirements. Refer to the narrative for additional details.

COSTS: The SL-type lamps are currently available at $25/lamp, although volume discounts at $20/lamp are sometimes obtainable. The costs are projected to fall to $15/lamp (in 1983 dollars) within the next few years.

Circline lamps are available at prices ranging from $6 to $20/lamp.

PL lamps cost about $10 and the ballast cost about $20.

RELIABILITY/LIFETIME: Lifetimes for all these lamps are substantially greater than comparable incandescents. The compact units have operating lifetimes of from 7500 to 10,000 hours. The circline units have lifetimes from 7500 to 12000, with their ballasts rated at 50,000 hours. By comparison lifetimes for incandescents are 750 to 800 hours. "Long-life" incandescents have lifetimes of about 2500 hours.

The longer lifetime of compact fluorescents also means that lamp replacement will be less frequent and labor costs will be lower.

UTILITY SYSTEM IMPACTS: The use of these lamps will result in reductions in both energy and power usage for lighting. SL and PL lamps have a lower power factor than incandescent (60 to 75%), but this should have little effect on the utility system.

USER IMPACTS: The color rendering characteristics of both types of lamps differ from standard incandescents. The special phosphor coating used in the SL lamp improves its color rendering substantially. The CRI for the SL is 80 and the color temperature is 2800 °K.

PRODUCT AVAILABILITY: Circline type lamps are produced by a several lighting manufacturers and are available in most lighting and hardware stores. Compact lamps are currently produced by Westinghouse and Phillips, but are generally less widely available than circline lamps.

EXPERIENCE: Circline and compact fluorescents particularly designed for residential uses; however, some units are being used in commercial buildings. Compact fluorescents are commonly used in European hotels and hostels.

COMMENTS + CAVEATS: None of these lamps currently available can be used effectively as point sources. Consequently, they do not provide a good substitute for point source incandescents, such as retail store track or display lighting.

The rather high initial cost, despite the major improvement in lighting efficacy, may be a significant barrier to the widespread acceptance of compact lamps.

Table 5-8 in the narrative contains more detailed technical characteristics of the compact fluorescents compared to a 75-watt conventional incandescent.

The high-frequency electronic ballast used in the compact fluorescent eliminates lamp flicker. Although the circline lacks an electronic ballast, its circular shape makes lamp flicker significantly less noticeable.

Notes

1. See reference 25 in the narrative section for citations.

Commercial Technology Summary Sheet

END-USE: Interior Lighting

TECHNOLOGY: **Ellipsoidal Lamp Replacements for A/R type Incandescents**

GENERAL DESCRIPTION: In a recessed incandescent fixture with a conventional A or R type lamp a significant amount of light is lost within the fixture itself. Ellipsoidal lamps are designed such that the focal point of the lamp is below the fixture aperture thus minimizing interior absorption light loss.

PHYSICAL CHARACTERISTICS: Ellipsoidal lamps have a similar efficacy to the A or R type lamps, however, when they are installed within the luminaire they emit more light outside of the luminaire than the conventional lamps. Consequently the efficacy of the luminaire is increased.

APPLICABILITY: Recessed fixtures are most widely used in retail businesses and restaurants. Lamps are available in sizes from 50 to 120 watts and can be used to replace existing 75 to 300 watt lamps.

ENERGY PERFORMANCE: It is generally recommended that ER-type lamps should be one-half the wattage of the A or R-type lamps currently contained in the fixture. (For A-type lamps, ER lamp placements of one-third to one-fourth the wattage may be possible.) [1]

These estimates do not include additional energy and power effects from reducing air conditioning loads or increasing heating or reheat requirements. Refer to the narrative for additional details.

COSTS: Ellipsoidal lamps range are about 20 to 40% more expensive than R-type lamps. However, in certain cases the ER type lamps can be less expensive than R-type (e.g. 120 watt ER replacement for a 300 watt R-type) [2]

RELIABILITY/LIFETIME: The lifetime of ellipsoidal lamps is 2000 hours under normal operating conditions. [3]

UTILITY SYSTEM IMPACTS: Installation of ellipsoidal or other "energy-efficient" lamps will result in utility energy and power savings.

USER IMPACTS: If the recessed luminaire is not specially designed for a specific lamp, the user should notice no appreciable difference in light level or distribution.

PRODUCT AVAILABILITY: The ellipsoidal reflector lamp is widely available.

EXPERIENCE: Ellipsoidal reflector replacements are standard lighting conservation measures recommended by California utilities.

COMMENTS + CAVEATS: The ellipsoidal reflector lamps should be avoided if the luminaire is specifically designed to work with a special lamp with candle power distribution highly dependent on the reflecting surface. Use of these lamps in such luminaires will result in lower spacing-to-mounting-height (S/MH) ratio and uneven lighting distribution. [4]

Notes

1. For example see, the Pacific Gas and Electric, 1984 Customized Rebate Program for Large Businesses, Lighting Brochure.
2. General Electric, *Lamp Price Schedule*, 9200-T. Suggested trade net price as of August 24, 1984.
3. General Electric *Lamp Technical Guide*, Form 9200, 1984.
4. Sorcar, Prafulla, *Energy Saving Lighting Systems, 1982, p. 12.*

Commercial Technology Summary Sheet

END-USE: Interior Lighting

TECHNOLOGY: **Coated-Filament Incandescent Lamps**

GENERAL DESCRIPTION: The coated-filament incandescent is an experimental prototype lamp with similar size and shape to a conventional incandescent lamp. The luminous efficacy of the coated-filament model is significantly improved over standard incandescents. [1]

PHYSICAL CHARACTERISTICS: To improve the efficacy of the lamp, the interior surface of the lamp globe is coated with an infrared-reflective, visually transparent material. The coated globe, which is composed of two optically precise hemispheres, increase the efficacy of the lamp by focusing back onto the filament a portion of the infrared radiation that is normally lost. This reradiation enables the filament to retain a high radiant temperature with less electrical energy input than a conventional incandescent.

APPLICABILITY: The lamp could be used in any application where conventional small to medium size incandescents are now being used. The prototype unit has a 1500 lumen output (comparable to a 75 to 85 watt conventional incandescent). Lab test indicate that it is technically feasible to develop coated-lamps in the range from 400 to 2800 lumens (equivalent to 40 to 150 watt conventional lamps).

ENERGY PERFORMANCE: The prototype units so far tested have used 54 watts to produce 1550 lumens of light output. This results in an efficacy of 29 lumens/watt. A conventional incandescent with comparable light output has an efficacy range from 15 to 17 lumens/watt.

These estimates do not include additional energy and power effects from reducing air conditioning loads or increasing heating or reheat requirements. Refer to the narrative for additional details.

COSTS: No units are on the market. It is estimated that the lamps will have to sell for about $5.00 (1983 dollars) to be sufficiently marketable. See the narrative for a simple example of the life cycle cost of these units compared to conventional lamps.

RELIABILITY/LIFETIME: Only laboratory prototypes exist on which to base an estimates of expected lifetime. The ten prototypes tested at the Lawrence Berkeley Laboratory had a mean lifetime of 2000 hours under standard lamp-life test procedures. This compares to approximately 750 hours for a conventional incandescent or roughly 2000 hours for a "long-life" incandescent.

UTILITY SYSTEM IMPACTS: Installation of these lamps will result in utility energy and power savings. The prototypes had a power factor of approximately 71%. This may have some effect on utility system power factor if lamps are widely used and power factor is not improved in commercial models. It is unlikely, however, that it will be significant.

USER IMPACTS: The appears to be no significant difference between these lamps and conventional incandescent. Their color, general appearance, and color rendering qualities are similar to comparable conventional lamps.

PRODUCT AVAILABILITY: The lamp is not currently available, however, preliminary design and production is underway and the units may be available within the next 2 to 4 years years (i.e. 1986-88).

General Electric markets a 900-watt quartz incandescent lamp that operates on the filament/reflection process.

EXPERIENCE: Experience is currently limited to laboratory prototypes.

COMMENTS + CAVEATS: There is some concern about the robustness of the selective coatings used on the glass hemispheres. [2]

Notes

1. See section 5.5.4, Advanced Lighting Technologies, for additional material and references.
2. Personal communication with Francis Rubinstein, Lighting Group, Applied Science Division, Lawrence Berkeley Laboratory.

Commercial Technology Summary Sheet

END-USE: Interior Lighting

TECHNOLOGY: **High Pressure Sodium Lamps**

GENERAL DESCRIPTION: High pressure sodium (HPS) lamps have traditionally been used in outdoor applications especially street lighting. Their high luminous efficacy, however, has lead to their use in commercial building ranging from warehouse to office buildings.

PHYSICAL CHARACTERISTICS: The HPS lamp is one of a group of lamps referred to as High Intensity Discharge (HID). Other members of this group include metal halide, and mercury vapor lamps.

APPLICABILITY: HPS lamps are used for interior lighting in wide range of commercial buildings, including warehouses, offices, shopping malls, display halls, and schools. The poor color qualities a HPS are often cited as a constraint to their use in locations such as retail sales areas. HPS can be used for both new and retrofit applications, although most retrofit installations have been in warehouses.

HPS lamps are available in 35, 50, 70, 100, 150, 200, 215, 250, 310, 400, and 1000-watt sizes with both clear and diffuse bulb finishes. [1] of August 24, 1984.

ENERGY PERFORMANCE: Efficacies of HPS lamps and ballasts range from about 60 to 127 lumens/watt with efficacy improving as lamp wattage increases.

These estimates do not include additional energy and power effects from reducing air conditioning loads or increasing heating or reheat requirements. Refer to the narrative for additional details.

COSTS: Typical costs for 200-watt HID lamps and ballast are $50 to $90 per lamp. [2]

RELIABILITY/LIFETIME: HPS lamps operate for 16,000 (35 watt lamp) to 24,000 (all other sizes) hours based on a minimum of 10 hours of operation between starts. More frequent starting will decrease lamp life.

UTILITY SYSTEM IMPACTS: Use of HPS lamps will result in both energy and power savings for the utilities.

USER IMPACTS: In addition to energy and power savings, the user will have to adapt to the different color qualities of HPS lights

PRODUCT AVAILABILITY: HPS lamps are widely available.

EXPERIENCE: HPS lamps have become the standard for most highway illumination in California. There are also many HPS installations for interior illumination throughout the U.S. See the narrative section for details. In general, workers expressed little objection to these installations once the had adapted to the modified color qualities.

COMMENTS + CAVEATS: Paint charts are available that list 50 colors that can be used with few color rendering under HPS illumination. [3]

The HPS lamp typically takes 3 to 4 minutes of warm-up before it reaches its fullest brightness. The lamps also require from one-half to one and one-half minutes to restrike after they have been turned off.

Notes

1. General Electric, *Lamp Technical Guide* 9200, 1984 Edition.
2. General Electric, *Lamp Price Schedule*, 9200-T. Suggested trade net price as of August 24, 1984.
3. Richard Corth, "Practical Features of Illumination with High Pressure Sodium Lamps", presented at the *10th Energy Technology Conference*, June 1983, Washington, D.C.

Commercial Technology Summary Sheet

END-USE: Interior Lighting

TECHNOLOGY: **Lower-Wattage Fluorescent Lamps**

GENERAL DESCRIPTION: Lower-wattage fluorescent lamps are available and can be used in place of standard lamps with a 10 to 20% decrease in wattage and a 5 to 10% decrease in light output. [1]

PHYSICAL CHARACTERISTICS: Lower wattage lamps take advantage of improvements in lamp phosphors. These improved phosphors permit significant decreases in lamp wattage with small decreases in light output. Thus the lamps have an improved efficacy.

APPLICABILITY: Low wattage lamps are available in most standard wattages and sizes including 3,4,5, and 8-foot lengths, and U-shapes. In addition, there are both cool-white and warm-white colors.

ENERGY PERFORMANCE: Lower wattage lamps decrease lighting energy usage by 10 to 15% with a decrease in light output of about 5 to 7%. Thus the efficacy of the lamp is increased about 7% on average.

These estimates do not include additional energy and power effects from reducing air conditioning loads or increasing heating or reheat requirements. Refer to the narrative for additional details.

COSTS: The most widely used low wattage fluorescent, T-12 34 watt, Low-wattage fluorescents lamps in the most common 4-foot T12 size cost about $2.00 more than standard lamps.

Across the entire range of lamp sizes and types the cost premium for low wattage lamps ranges from 8 to 28% more than standard lamps. [2]

RELIABILITY/LIFETIME: Under standard testing conditions F40 T-12 type low wattage lamps have a 20,000 hour rated lifetime.

The performance of low-wattage lamps ar cool temperatures is generally poor. They are often difficult to start and the light output is substantially reduced.

When installed in older ballast (pre-1978), the low-wattage lamps may result in ballast failure.

UTILITY SYSTEM IMPACTS: Use of lower wattage fluorescent lamps will decrease utility energy and power loads. No adverse impacts are likely.

USER IMPACTS: Use of lower wattage lamps will result in less overall light output than comparable standard lamps. If the user is careful to determine lighting requirements properly then no adverse impacts should occur.

PRODUCT AVAILABILITY: Low wattage lamps are produced by all of the major lamp manufacturers and can be obtained in a wide range of sizes, shapes, and colors.

EXPERIENCE: Low wattage lamps have been used successfully in many commercial establishments through the United States. In some instances, where the buildings occupants have not recognized that light output will decrease, results have been negative. However, if the lamps have been installed in "overlit" areas the results have been favorable.

COMMENTS + CAVEATS: The is presently no ANSI standard for low-wattage fluorescent lamps.

The IES warns that low-wattage lamps should only be installed in luminaires that have ballasts designed to accept these type of lamps.

Notes

1. See section 5.5.1 more additional details and references.
2. General Electric, *Lamp Price Schedule*, 9200-T. Suggested trade net price as of August 24, 1984.

Commercial Technology Summary Sheet

END-USE: Interior Lighting

TECHNOLOGY: **Electrodeless Fluorescent Lamp**

GENERAL DESCRIPTION: The electrodeless fluorescent lamp is a compact fluorescent lamp without electrodes that can be used in place of a conventional incandescent lamp in an Edison-type socket. The lamp is in advanced experimental development with several prototypes tested. [1]

PHYSICAL CHARACTERISTICS: The lamp consists of a fluorescent, phosphor-coated bulb and very high-frequency ballast (100+ kHz) in roughly the shape of a conventional incandescent. The electrodeless operation is possible because of the very high frequency of the ballast and the high lamp-loading (arc watts/phosphor area). Lamp loading is typically 3 watts/in^2 or about 10 times greater than conventional fluorescent lamps.

APPLICABILITY: The prototype lamps are comparable in output to 100-watt incandescent lamps (about 1700 lumens) and can, in theory, be used wherever incandescents are now being used. The low color-rendering index (CRI) of 57 may limit their replacement potential in retail stores where the color quality of lighting is often very important. The lamps are eventually expected to be available in output ranges from 400 to 2300 lumens. These ranges will cover most commonly used conventional incandescent sizes.

ENERGY PERFORMANCE: The combined lamp and ballast energy use for 1700-lumen unit is about 31 watts, yielding an average efficacy of 55 lumens/watt. Developers of these prototypes estimate that the bulbs will eventually reach efficacies from 68 to 77 lumens/watt.

These estimates do not include additional energy and power effects from reducing air conditioning loads or increasing heating or reheat requirements. Refer to the narrative for additional details.

COSTS: The target price for these lamps is $15/unit (in 1983 dollars). This includes both the lamp and ballast. The greatest production cost is apparently the cost of the power field effect transistors (FETs) used in the ballast circuit. At an energy price of $0.07/kWh the cost will be about $2.23/10^6 lumen-hours.

RELIABILITY/LIFETIME: The units that have been tested so far have had an estimated lifetime of 10,000 hours under normal operating conditions.

UTILITY SYSTEM IMPACTS: Replacement of incandescent lamps with electrodeless fluorescents will result in energy and power savings for the utility.

USER IMPACTS: The lower color rendering index than conventional incandescents may limit the replacement application. In addition, the high frequency of operation may create interference with other electronic appliances.

PRODUCT AVAILABILITY: It is estimated that this lamp may be available on the market within the next few years, e.g. 1987-88.

EXPERIENCE: To date, experience with these bulbs is limited to laboratory experiments.

COMMENTS + CAVEATS: Early experimental units exhibited a very poor color rendition (CRI 16 ±2). Later models showed marked improvement in the CRI up to an average of 57.

These lamps use a diode in the base to convert AC current to DC, consequently their power factor is only 71%. It is unclear from the literature reviewed whether it will be possible to improve the power factor at a reasonable cost and without performance degradation.

A dimmable version of the bulb in under development.

Notes

1. See Section 5.5.4 for more details and references.

Chapter 5

Electric Lighting Technology

5.1 SUMMARY

The tables and sheets preceding this section summarize lighting conservation technologies. This chapter contains additional documentation of our analysis of interior, commercial-sector, electric lighting conservation technologies and strategies. We considered technologies that are currently available and those that are under development, but likely to be commercialized by the end of the century. Daylighting and fenestration strategies also hold substantial promise for lighting energy savings. They are discussed in detail in Chapter 6. This chapter discusses our key findings as well as gaps in knowledge and data. A basic framework for generalized lighting conservation analysis is also presented, followed by a discussion of PG&E and SCE lighting energy use. Finally, we consider each of the conservation technologies and strategies presented in the summary tables and sheets. Case study material is included wherever possible.

5.2 INTRODUCTION

Interior illumination is often the largest single-user of electric energy in commercial buildings. The PG&E and SCE commercial end-use models estimate that nearly one-half of 1982 commercial-sector electric energy was devoted to lighting. Similarly, 39% of SCE's annual commercial electricity peak and more than 45% of PG&E's annual peak are a direct result of electric lighting loads. [1] Moreover, the influence of lighting on total energy and power use is even more significant than these figures would suggest. The "waste" heat generated by lights is an important contributor to the internal loads of most commercial buildings. Chapter 2, Cooling and Air Transport, address these secondary impacts of lighting.

Both PG&E and SCE have long recognized the importance of this end use and have devoted much of their commercial-sector conservation efforts toward decreasing both lighting energy and power use. For example, in 1983 PG&E rebated nearly $1.4 million to commercial customers for lighting hardware conversions. These rebates were estimated to save nearly 2.6 billion kWh over the life of the products. [2]

5.2.1 Key Findings

In our investigation of lighting we have found that lighting offers enormous energy and power conservation opportunities. The utilities have done a good job of capturing many of these opportunities. However, the continuation of past successes and the exploitation of new ones require continuing efforts on several diverse fronts. Our findings reflect the need for a balanced mix of new technologies, careful attention to lighting design, and a regular lighting maintenance.

- Current fluorescent lamps and ballast systems have a combined efficacy of 50 to 70 lumens/watt, with the most common 4-foot units averaging about 60 lumens/watt. Electronic ballasts, improved phosphors, narrow lamp tubes, and higher output fixtures are currently available and can boost efficacy to the 100 lumens/watt range.

- Research on advanced fluorescent lamps hold promise of efficacies of up to 200 lumens/watt. However, many of these technologies remain far from commercialization (often even from the prototype stage).
- Compact fluorescent lamps such as the PL- and SL-types are available as replacements for incandescents. Compact fluorescent lamps' color rendering is good, their lifetimes are much longer than incandescents, and their energy use is typically one-fourth to one-fifth that of incandescents. First costs, however, remain high and they are often not available even to those who might consider them cost-effective. Hotel and motel hallway and commercial building security lighting are two of the more obvious candidates for these lamps.
- The successful use of high-pressure sodium and other HID lamps in warehouses, offices, and schools suggests that these lamps may have wider applicability in commercial establishments than has historically been the case.
- A well-designed lighting system, with low lighting power densities and lighting levels, requires a good cleaning and maintenance program to insure that adequate lighting levels will be maintained over the life of the systems.
- New, Title 24, office lighting levels of 1.5 watts/ft^2 (effective in 1987) are achievable with currently available technologies.
- Lighting conservation technologies are currently available that can permit lighting power densities in offices down to 0.75 to 1 W/ft^2. However, effective lighting design becomes critical at such low levels to achieve an acceptable lighting environment.
- Lighting in the retail sector is critically related to merchandising strategies. Energy efficiency gains and positive merchandising impacts are possible, but there is a need for documentation of additional successful cases.
- Lighting design is a key factor for all conservation technologies considered in this chapter. Without proper lighting design energy and power savings may not be achieved, building occupants may complain, and task performance may suffer. [3]
- Lighting designers and users of lighting systems need education on the proper design and use of lighting systems. The need is underscored by the recent revisions of the Title 24 Non-Residential building standards that rely on lighting power budgets rather than specific design criteria.
- Lighting research and development is progressing rapidly. Utilities, state regulatory agencies, lighting designers, and others concerned with lighting issues should continue to monitor developments in these areas.
- Lighting controls, schedules, and maintenance are also important factors in lighting system energy and power savings. As with HVAC systems, even the best system design and hardware will not function well without good management.
- Lighting conservation measures save an additional 5 to 35% because of reductions in cooling and ventilation loads. Savings will depend on the climate, cooling system characteristics, and other building characteristics.

5.2.2 Information Gaps

There is abundant information on the technical specifications of existing lighting hardware and conservation measures. Yet many data gaps remain about the applicability and field performance of measures, the relationship of electric lighting to daylighting, and the fundamental underpinnings of lighting system performance and worker productivity.

- More detailed information on lighting power densities, illumination levels, and operating schedules in existing commercial buildings are needed before more accurate assessments of the conservation potential can be completed. Commercial mail-out surveys will probably not provide this information. For example, building managers rarely know the interior lighting levels, operating hours, and usage profile of their lighting systems. Consequently, commercial audit data, special site visits, and, in some instance, instrumentation of the lighting systems will be required.
- Many utility programs have concentrated on lighting conservation measures. However, data on what measures were installed, what problems arose, and how long conservation effects persisted is still sparse.
- Although the relationships between illumination levels, lighting design, color quality, visual performance, occupant comfort, and other lighting elements have been studied they are still not completely understood. Field and laboratory data on these factors will be critical as lighting power densities change, new technologies are used, and illumination recommendations modified. [4]
- The tradeoffs between more efficient electric lighting hardware, daylighting strategies, and system operation/maintenance efforts also are not always well understood. They have mostly been investigated through computer simulations. Thorough field studies are essential.
- There is a critical need for more instrumented case studies that measure the effect new lighting technologies and strategies have on electricity use and especially peak demand.
- There remain great uncertainties in knowledge of the costs, lifetimes, and market availability of recently developed lighting technologies.

5.3 A SIMPLIFIED FRAMEWORK FOR LIGHTING CONSERVATION ANALYSIS

The electrical energy and power usage of a commercial lighting system embraces several elements. Before examining specific lighting conservation technologies and strategies, it is important to have a simple framework of the major components that contribute to the energy and power used by lighting systems. One way to illustrate these components is by the following simple relationship. [5]

$$E_l = f(\text{OH}, \text{FC}, \text{LPW}, \text{CU}, \text{LLF}, \text{A})$$

where:

E_l = Energy used by a lighting system

OH = Hours of operation per day

FC = Footcandle illumination level at the work surface

LPW = Efficacy of the lighting source in lumens/watt

CU = Coefficient-of-utilization

LLF = Light-loss-factor (sometimes called the maintenance factor)

A = Working task area

Although this relationship is most applicable in an office environment (with a well-defined working task area) it can also be used for other commercial activities. We briefly examine each of the elements of the relationship, below. This discussion not only illustrates the nature of lighting energy and power use, but also highlights areas where conservation efforts can be concentrated.

5.3.1 Hours of Operation (OH)

A common method for describing lighting systems is installed power density (kW/ft^2) terms . For example, the recently adopted revisions to the California Title 24 Non-Residential Building Standards mandate lighting standards largely in power density terms. [6] Although such an approach may simplify analysis of the peak electricity contributions of a certain system, power density by itself tells us nothing about total energy use or even load profile. To determine a lighting systems' energy use and, in turn, estimate the savings potential of certain measures one must know the hours of operation and ideally, the operating schedule of the system. For example, are lights usually turned off during the lunch hour? What lighting schedules are commonly used by the janitorial staff? Are there area where occupancy is intermittent, but lights remain on all day?

There are several strategies available to reduce operating hours of the lights while maintaining the same commercial operating hours. These include:

- Install automatic timing systems or accessible manual overrides that turn off the lights during periods when portions of the building are normally unoccupied.
- Use occupancy sensors to turn off lights in unoccupied areas.
- Reschedule janitorial services in buildings to permit zoning of the lighting system or minimize the additional hours of operation of the system.
- Use lighting sensors and dimming devices to decrease the use of artificial light and maximize the use of daylighting. (This approach is discussed in detail in Chapter 6, Daylighting and Fenestration, of this report.)

5.3.2 Footcandle Illumination (FC)

How much light is needed to do necessary tasks within the building? The purpose of lighting equipment in commercial establishments is to provide enough illumination to display products for sale, to permit completion of work with minimum difficulty, to provide a pleasant working environment, etc. The amount of light needed for a given task depends on numerous factors including the type of task, the age and visual acuity of the person performing the work, etc.

Clearly, more illumination is necessary for a drafting room than for nighttime security lighting in a hallway. In most instances, the lighting levels recommended by the Illuminating Engineering Society are used as the basis for current lighting design. [7]

Our analysis of lighting conservation technologies does not address the issue of the reasonableness of lighting level requirements or recommendations. Where discussions of illumination levels are relevant to our work, the IES recommendations are used as "standard-practice". We do discuss technologies and practices for achieving recommended lighting levels. These include:

- Restructure or redesign commercial sector activities to minimize the lighting level requirements. One common method is to move from area-wide lighting patterns to task/ambient designs.
- Decrease lighting levels in areas that are "over illuminated" Delamping, low-wattage fluorescent replacements, and use of lower light output lamps are the most common methods used.

5.3.3 Luminous Efficacy (LPW)

How efficiently does the lamp convert electricity into light? [8] The luminous efficacy of a lamp is the amount of light produced for a given amount of energy input. The higher the efficacy, the less energy required to achieve a given illumination level. There are a wide range of technologies currently on the market, under development, or being tested in the laboratory that promise increases in lighting efficacy. Because of the prevalence of fluorescent lamps in commercial establishments (see below) we have concentrated our analysis in this area. The following technologies are examined:

- Lower-wattage fluorescent lamps (e.g. 34 watt)
- Energy efficient core/coil ballasts
- Solid-state electronic ballasts
- Screw-in fluorescents
- Electrodeless fluorescent
- Isotope enhancement
- Magnetic loading
- Two-photon phosphors

For incandescent lamps several technologies are evaluated:

- Efficient ellipsoidal lamps
- Coated-filament incandescent bulbs

Finally, there are several other high efficacy lighting sources available that can be used in place of either traditional fluorescent or incandescent lamps. Historically these technologies have had widespread use for exterior lighting, but have not been used for interior illumination. As the chapter will illustrate, this usage limitation is beginning to disappear.

- Mercury-vapor

- Metal-halide
- High-pressure sodium
- Low-pressure sodium

5.3.4 Coefficient of Utilization (CU)

How much light is "lost" once it leaves the lamp? The coefficient of utilization expresses the relationship between the amount of light emitted by a lamp and the light that reaches the task surface. The reflective characteristics of the fixture portion of the luminaire, the shape of the room, the reflective properties of the surrounding walls, ceiling, and floor surfaces, and the distance between the luminaire and task surface all determine the CU. (However, CU does not consider obstructions such as partitions.) The efficiency of the fixtures and the surface characteristics room shape are the most significant of these factors. Conservation measures include:

- Improve the reflective characteristics of the fixture either through retrofit or installation of a new fixture.
- Change the color or surface characteristics of the wall, floors, or ceiling, to improve reflectance. (This is strategy is not considered in this report)
- Implement a lighting maintenance program to minimize light loss from dirt build-up on luminaires and other surfaces.

5.3.5 Light-Loss Factor (LLF)

How well does the luminaire maintain its initial light output? The lamp, fixture, and ballast, in a luminaire will experience a degradation in performance and light output with age. The light-loss factor or maintenance factor is a quantitative expression of this decline in performance. The type of light source, the conditions surrounding the luminaire, and several other factors will determine the extent of degradation. Methods to minimize degradation include:

- Implement a regular lighting maintenance program (cleaning and replacement) to improve the long-term light output characteristics of luminaires.
- Decrease the amount of dust and dirt in the working area to diminish the need for luminaire cleaning.

5.3.6 Working Task Area (A)

How large are the areas to be illuminated? In an office environment, it is often unnecessary, or even undesirable, to illuminate all the floor area to the same level. This permits the use of more intensive task lighting on the work surface and less intensive lighting in the surrounding areas (ambient lighting). By reducing the working area, less higher-intensity task lighting will be required and the lighting load can be correspondingly decreased. As this is a change in business practice, it is beyond the scope of this project and will not be considered further in this report.

5.3.7 Lighting Design

Lighting design is not one of the factors in the simplified relationship, nonetheless, proper lighting design is of critical importance in saving electric energy and power. An improperly installed high-efficacy, low-energy luminaire that produces glare or shadows on the work surface, or doesn't provide enough light for a task is a very poor conservation technology. Any energy savings that might result from such a unit will be rapidly overwhelmed by losses in worker productivity. J.R. Knisley [9] aptly summarized the importance of design as follows:

> More than being just a search for the best lumens/watt efficacy, good lighting encompasses color rendition, brightness, contrast, and how much light each person needs for a task. In the past, these considerations and many others might have 'fallen through the cracks' in the rush to get a job finished and the space occupied; but today the interdependencies cannot be overlooked, and all available tradeoffs must be considered and clarified.

The physical tools and basic strategies for lighting energy conservation can be used by a knowledgeable lighting designer, engineer, or architect to achieve both energy savings and proper illumination. Or they can be misapplied with disastrous consequences. Only with proper consideration of design will lighting energy conservation and good quality illumination be obtained. We illustrate, through discussions of installation, whenever possible, the impacts of both good and poor lighting design on the overall performance of lighting systems- including, but not limited to energy performance.

5.4 BASELINE DATA

With this basic framework established we can now look at specifics. How much energy do each of the commercial building-types in the SCE and PG&E service territories use for lighting and what is the usage intensity? Tables 5-4 and 5-5 summarize current and projected lighting energy use and intensity (expressed as EUIs) for the two utilities. [10] There is a high degree of similarity in lighting energy intensity between the two utilities. The average 1982 EUI, across all building-types, is 6.5 for PG&E and 5.8 for SCE, roughly a 13% difference. This variation is probably attributable to differences in building stock mix and building classifications. One can reasonably assert that the two utilities' usage patterns are nearly identical. By the year 2000 the utility difference is expected to diminish to less than 4%.

Compared to other end-uses, such as cooling and refrigeration, there is much less variation in EUI across commercial building types. Excluding food stores/groceries, the range is barely three-fold.

5.4.1 Variations in Lighting Use by Building Type

This small variation in EUIs, however, does not mean that lighting hardware, hours of operation, lighting power densities, and other usage factors are also similar. Unfortunately, we lack detailed data on these variations and must rely chiefly on generic lighting characteristics for different end uses. Table 5-6, Hours of Operation by Building Type, illustrates this paucity. While it appears that we have good information on lighting energy use and can determine the potential for conservation measures such as lighting timers, such is not the case. The average operating hours only tell us how long a establishment is open, they do not tell use what percentage of lights are on during these hours, or how many lights were on when the building is closed.

Table 5-4
PG&E LIGHTING ENERGY USE BY BUILDING TYPE

BLDG TYPE	END USE	YEAR	ELEC USE (10E3 KWH)	ELEC FRAC	AVERAGE EUI (KWH/SQFT)	SQFT (1000S)	AVERAGE USAGE (10E3 KWH)	ADJ EUI (KWH/SQFT)
RETAIL	LIGHTING	1982	2939810.	1.000	7.788	377479	2939810	7.79
OFFICE	LIGHTING	1982	2681014.	1.000	6.895	388835	2681014	6.90
GROCERY	LIGHTING	1982	804510.	1.000	14.186	56712	804510	14.19
E/S SCHL	LIGHTING	1982	780871.	1.000	4.978	156864	780871	4.98
MISCELL.	LIGHTING	1982	752952.	1.000	3.768	199828	752952	3.77
HEALTH	LIGHTING	1982	541270.	1.000	7.548	71710	541270	7.55
COL/TRDE	LIGHTING	1982	423207.	1.000	5.000	84641	423207	5.00
RESTRANT	LIGHTING	1982	406376.	1.000	7.671	52976	406376	7.67
WAREHSE	LIGHTING	1982	389919.	1.000	2.907	134131	389919	2.91
HOT/MOTL	LIGHTING	1982	202521.	1.000	3.964	51090	202521	3.96
			9922450	1.00	6.47	1574266	992245	
RETAIL	LIGHTING	2000	3558983.	1.000	6.220	572184	3558983	6.22
OFFICE	LIGHTING	2000	2980688.	1.000	5.340	558181	2980688	5.34
GROCERY	LIGHTING	2000	985188.	1.000	13.177	74766	985188	13.18
MISCELL.	LIGHTING	2000	883797.	.990	2.969	297675	874959	2.94
WAREHSE	LIGHTING	2000	793882.	1.000	2.925	271413	793882	2.93
E/S SCHL	LIGHTING	2000	737673.	.990	4.421	166857	730296	4.38
HEALTH	LIGHTING	2000	495703.	1.000	6.634	74722	495703	6.63
HOT/MOTL	LIGHTING	2000	424732.	1.000	3.830	110896	424732	3.83
COL/TRDE	LIGHTING	2000	385001.	.990	4.486	85823	381151	4.44
RESTRANT	LIGHTING	2000	258807.	1.000	4.532	57107	258807	4.53
			11504454	0.997	5.45	2269622	1148439	

PG&E Commercial-Sector Model Run, October 5, 1983

Table 5-5

SCE LIGHTING ENERGY USE BY BUILDING TYPE

BLDG TYPE	END USE	YEAR	ELEC USE (10E3 KWH)	ELEC FRAC	MARGINAL EUI (KWH/SQFT)	AVERAGE EUI (KWH/SQFT)	SQFT (1OOOS)	AVERAGE USAGE (10E3 KWH)	ADJ EUI (KWH/SQFT)
LOW RISE	LIGHTING	1982	1502175.	.996	6.471	6.660	225552	1496166	6.63
SMALL ST	LIGHTING	1982	1107547.	1.000	6.484	6.745	164203	1107547	6.75
FOOD STO	LIGHTING	1982	769845.	1.000	12.366	12.690	60665	769845	12.69
ELEMENTA	LIGHTING	1982	729729.	.991	4.017	4.414	165321	723161	4.37
MISCELLA	LIGHTING	1982	703647.	1.003	2.743	2.913	241554	705758	2.92
SMALL WA	LIGHTING	1982	689556.	1.002	2.827	2.960	232958	690935	2.97
HIGH RISE	LIGHTING	1982	595168.	.997	6.505	6.769	87926	593382	6.75
DEPARTME	LIGHTING	1982	436698.	1.000	6.559	6.821	64023	436698	6.82
HOSPITAL	LIGHTING	1982	424048.	1.000	8.512	9.323	45484	424048	9.32
UNIVERSI	LIGHTING	1982	267544.	.992	4.435	4.966	53875	265404	4.93
RESTAURA	LIGHTING	1982	245255.	.993	5.926	6.775	36200	243538	6.73
HOTELS/M	LIGHTING	1982	227829.	1.000	4.185	4.208	54142	227829	4.21
LARGE WA	LIGHTING	1982	163829.	1.002	2.827	2.959	55366	164157	2.96
MEDICAL	LIGHTING	1982	151062.	1.000	6.297	6.506	23219	151062	6.51
			8013932	0.998	5.73	6.1	1510488	571395	
LOW RISE	LIGHTING	2000	3163447.	.995	6.437	6.437	491447	3147630	6.40
SMALL ST	LIGHTING	2000	1393899.	.993	6.401	6.401	217763	1384142	6.36
HIGH RISE	LIGHTING	2000	1252256.	.995	6.437	6.437	194540	1245995	6.40
FOOD STO	LIGHTING	2000	990667.	.993	12.259	12.312	80464	983732	12.23
MISCELLA	LIGHTING	2000	909433.	.992	2.997	2.966	306619	902158	2.94
SMALL WA	LIGHTING	2000	877742.	.993	2.837	2.837	309391	871598	2.82
ELEMENTA	LIGHTING	2000	636124.	.985	3.850	3.850	165227	626582	3.79
DEPARTME	LIGHTING	2000	556990.	.994	6.557	6.557	84946	553648	6.52
HOSPITAL	LIGHTING	2000	513455.	.990	8.381	8.394	61169	508320	8.31
HOTELS/M	LIGHTING	2000	328999.	.991	4.142	4.142	79430	326038	4.10
UNIVERSI	LIGHTING	2000	270350.	.989	4.289	4.331	62422	267376	4.28
RESTAURA	LIGHTING	2000	246303.	.989	5.932	5.932	41521	243594	5.87
LARGE WA	LIGHTING	2000	208786.	.994	2.837	2.837	73594	207533	2.82
MEDICAL	LIGHTING	2000	192473.	.991	6.163	6.163	31230	190741	6.11
			11540924	0.99	5.68	5.69	2199764	818506	

Source: SCE, Commercial-Sector Model Run, September 1983.

Table 5-6

Hours of Operation by Building Type

(Annual Total)

Building Type	SCE	ADL(PG&E)[b]
Offices	2610	4380
Restaurants	3361	3650
Retail	2876	5110
Food Stores	4514	5110
Warehouses	2631	----
E/S Schools	2818	3258
Col/Trade	3021	5110
Hospitals	6396	5840
Hotel/Motel	7176	----
Misc [a]	3218	2555

Sources: Harbicht Research Incorporated, *Summary of Findings: 1982 Commercial Energy Use Survey,* prepared for Southern California Edison Company Table 12, Page 13.

[a] For the Southern California Service Area Public Assembly, Miscellaneous, and Other Commercial are all included under the Misc. category.

[b] The values listed in the ADL(PG&E) column are derived from Arthur D. Little, *Pacific Gas and Electric Company Technology Options Documentation: Commercial Sector,* December 1982. The annual values were calculated from Table 6.71 (p. 106) assuming the 'Lighting Usage Without Timers (hr./day)' values represent the average usage. These hourly values were multiplied by 365 to obtain annual total (It is unclear from the ADL study whether this is a correct interpretation of their material).

The wide range of activities covered by the commercial end-use category causes large variations in lighting characteristics. Currently the utility models deal with this diverity by dividing lighting requirements by building types. Although building types may not be the most instructive categories for lighting conservation analysis there are enough differences to warrant further discussion. The following briefly highlights some of the variations in a few of the end uses.

Offices*

Office lighting is a large user of commercial electricity in both utility service territories, second only to retail in total consumption. Most offices have the 4-foot fluorescent troffers and it has been estimated that from 80 to 98% of all fluorescent-lamp purchased for California offices are of the 4-foot F-40 type lamps. (this includes the low-wattage F-34/35 lamps). [11] Consequently, improvements in fluorescent lighting technologies are the most applicable conservation options. Many office have already delamped, switched to lower wattage lamps, and conducted other lighting conservation measures. Unfortunately we have little data on the utility-wide

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*This includes both the low and high rise office building categories as used by SCE.

prevalence of these measures.

Retail

Tables 5-4 and 5-5 show that retail lighting is the single largest user of lighting energy in the utility service areas. Retail buildings are also one of the largest users of incandescent lighting, especially for display and spot lighting purposes. Color quality is an important element in lighting design and retail marketing efforts. This may limit the applicability of fluorescent retrofits, except perhaps for the higher-color quality phosphors (so-called "tuned phosphors") available in compact and some conventional fluorescent lamps.

Warehouses

In the PG&E forecasting model warehouse lighting energy use shows a more than two-fold increase from 1982 to 2000. The SCE warehouse lighting increase (including both large and small warehouses) is less dramatic- roughly a 27% increase during the same time period. Warehouses are present a particularly good opportunity for applications of technologies that may not be accepted in other commercial establishments. Mercury vapor, metal halide, high-pressure sodium and, sometimes, even low-pressure sodium lamps can be used in warehouses where color rendition is often not of major concern. [12] Similarly, the use of control strategies, including timers, occupant sensors, and centralized lighting controls can also yield major energy and power savings in warehouses.

Hotels and Motels

Hotels and motels apparently have the highest penetration of incandescent lighting of any of the major commercial building types. This building type presents the possibility of replacement of these lamps with compact fluorescent and perhaps higher efficiency incandescents in the future. One potential problem with installation of higher cost compact fluorescents, especially in rooms, is that they may be stolen.

Hotels often have many recessed fixtures, where ellipsoidal reflector lamps can be used.

5.4.2 Interactions with HVAC

All lighting systems, produce heat as a byproduct of their operation. Higher efficacy units have a lower heat to light ratio, but nonetheless produce some heat. [13] This "waste" heat has positive energy impacts during periods of heating or reheating and negative impacts during cooling periods.

In most commercial buildings in California the cooling energy requirements predominate. Consequently, a decrease in lighting energy use usually results in an additional fractional decline in net HVAC energy use. We have performed selected DOE-2 computer simulations, using different lighting power densities, systems configurations, climate zones, and other factors, to estimate the size of these additional energy savings As one would expect the percentage change in annual HVAC energy requirements varied by climate zone, building type, HVAC system type, and other factors. For an office building in Fresno without economizers, HVAC savings add more than 35% to the total savings. In the same office building located in San Francisco and equipped with an economizer, the net savings increase is only 5%. The other locations and systems types showed savings percentages between these two extremes. More detailed discussions of lighting loads and HVAC impacts are contained in section 2.5.2, Magnitude of Cooling Load Components, and in the Heat Gain Reductions from Equipment, summary sheet also in Chapter 2. Chapter 6, Daylighting and Fenestration, includes additional discussions of lighting, daylighting, and HVAC system interactions.

Changes in lighting loads also influence, both directly and indirectly, the load-profile of a building. The DOE-2 simulations indicated that about 30% of a building's cooling peak results from lighting heat-gains. Section 2.5.4, Internal Loads, provides additional details.

Air Handling Luminaires

Luminaire manufacturers and designers have begun to recognized the significance of the HVAC impacts of lighting systems and as a result are designing and marketing a variety of air handling luminaires. We have chosen to include a discussion of these technologies in the Internal Loads discussion (section 2.5.4) and the Chapter 2 summary data sheet on Venting Heat Gains. [14]

5.5 ENERGY CONSERVATION TECHNOLOGIES

The summary tables and sheets provided substantial information on lighting conservation measures. The following material supplements and expands on that material. Wherever possible we have tried to include case study discussions of actual applications.

5.5.1 Fluorescent

Fluorescent luminaires are the most common lighting technologies in commercial buildings. There are many technologies available to decrease their fluorescent lighting energy and power use.

Delamping

Delamping is a lighting conservation strategy that has been widely used in commercial buildings where lighting levels are higher than recommended. High lighting levels have been most common in buildings constructed or remodelled in the 1950s, 60s, and 70s. In those decades recommended lighting levels were higher than current IES guidelines and the "rule-of-thumb" was to over light rather than risk under illumination. Consequently, delamping is a simple, generally inexpensive lighting retrofit measure.

The net savings realized will depend on the extent of the delamping, the type of lamps and ballasts in place at the time of delamping, whether the ballasts were disconnected, whether lamps were reconnected at a latter date, and the type of 'dummy-tube' or other replacement device used. [15]

One problem with delamping occurs in fixtures where two lamps are wired to a single ballast. In such instances (for example in the standard 4-foot fixtures) the removal of one lamp will also disconnect the other lamp. One way to avoid this problem is to install a so-called 'dummy lamp', which produces no light but completes the circuit. In some instances the remaining lamp will produce about two-thirds of the original light output with about two-thirds of the energy consumption. [16] Lighting levels can also be decreased by different percentages with the use of various reactive impedance devices.

The major problem with delamping, whether it occurs by itself, or with the addition of dummy lamps, is that the light-source pattern is asymmetric. This may present more of a problem in working areas than it would in lobbies, hallways, corridors, etc. Where lamps are removed in fixtures without lenses, as is common in some retail buildings (such as supermarkets), the appearance of the luminaire may be unattractive.

One example of successful delamping with replacement by reactive impedance devices is the Westin Bonaventure Hotel in Los Angeles. [17] In this establishment 600 two-lamp, eight-foot fixtures were retrofitted with 'No-Watt' impedance units and reduced energy use per fixture over 30%. Total savings were about $1288/month (@ 7 cents/kWh) and cost (including labor) were about $8000.

See the summary sheet, "Fluorescent Delamping", for additional details.

Low wattage fluorescent replacements

Another, less dramatic, alternative to delamping is the use of low wattage fluorescents. Instead of removing lamps and replacing them with no lighting producing units, lower wattage lamps cut energy use with a less dramatic decrease in light output. Low wattage lamps are available in a wide range of wattages, shapes, sizes, and colors. In fact, one can find a low wattage lamp replacement for nearly any conventional lamp. [18]

The most commonly used lamps now on the market that are rated at 34 watts and are intended to replace conventional 40 watt (F40) lamps. [19] As with delamping these lower wattage lamps have been used as retrofits for a several years. California Energy Commission (CEC) estimates suggest that up to 95% of lighting maintenance company lamp sales are 'energy savers' [20]

One problem with lower wattage lamps is that their use in conventional fixtures with older ballasts (pre-1978) may cause these ballasts to fail. In addition, there is currently no ANSI standard for low-wattage fluorescent lamps.

Additional information is provided in the "Lower-Wattage Fluorescent Lamps" summary sheet.

Energy efficient core/coil ballasts

Fluorescent lamps ballast limit the current during lamp operation, provide sufficient starting voltage, improve the power-factor, provide a coil for cathode heating (rapid-start and trigger-start lamps) and help suppress radio interference. While performing these functions, ballast consume energy. For example, a standard F40 two lamp/one ballast system will consume about 92 watts-80 watts for the lamps and 12 watts for the ballast.

The energy-efficient ballast, now required by California law, decreases the energy used by the ballast. These ballast perform the same function as standard ballast and achieve their higher efficiency through use of larger iron cores and copper in place of aluminum windings.

Additional information on these ballasts is contained in the summary sheet, "Energy Efficient Core/Coil Ballasts for Fluorescent Lamps".

High frequency electronic ballasts

Higher efficiency core/coil ballasts do not exhaust the energy and power saving potential. Solid-state, high-frequency ballasts are a recent addition to the lighting conservation market. Not only do these ballast (often referred to a electronic ballasts) significantly reduce the energy consumption of the ballast and boost the light output of the lamp, but in some designs, they also permit dimming of lamps to more effectively capture the benefits of daylighting. Dimmable ballast can also be used to increase light output to offset the effects of lamp lumen depreciation.

Solid-state ballasts have been shown to improve efficiency of lamp operation by 20 to 25 percent compared to a standard coil and core type. A field test of these ballasts, conducted at the Veteran's Administration Medical Center in Long Beach, California suggests that a program of fixture cleaning, retrofit of energy efficient lamps, and installation of dimmable solid state ballast can yield power and energy savings of 33 to 37%/year (excluding HVAC effects). [21] Prices for the dedicated (non-dimmable ballast) can range from $18 to $35 with dimmable ballast at $32 to $64. Estimates are that retail prices for these ballasts will reach $16 and $32 (1981 dollars) by 1988. [22]

Some first solid state sold ballasts experienced a moderately high failure rate. [23] Many of these early failure problems seem to have been alleviated, manufacturers have begun to offer long term warranties on their products. [24]

There are no ANSI standards for electronic ballasts and substantial variations in the lighting output are possible under certain conditions. Table 5-7 compares a standard core/coil ballast with a solid state ballast under a range of different operating conditions.

Additional information of solid state ballasts can be found in the summary sheet, "Electronic (Solid State) Fluorescent Ballasts"

Table 5-7
Tested Performance of Solid-State Fluorescent Ballasts

Design Factor	Standard System[a]	Solid-State ballast[b]
Ballast Factor	95±2.5%	81.0 to 97.5%
Voltage Resolution[c] ±10%	±25% permitted ±5.5% actual	0.5 to 20%
Thermal Regulation[d] 39 ° C to 50 ° C	-10% actual	-4 to -8%
Light output (standard condition)	6000 lumens	6140 to 5100 lumens
Efficacy (lumens/watts)	62	66 to 76

a Two-lamp, F-40, T-12, rapid start lamps at 39°C

b Based on nine types of solid-state ballasts from five manufactures. Three ballasts of each type were tested and results averaged.

c Voltage applied to the ballast was varied by ±10% from the rated voltage of the unit.

d The ambient operating temperature was increased from a normal operating range temperature of 39 ° C to a hot environment of 50 ° C.

Source : R. R. Verderber "Fluorescent Fixtures and Ballasts", presented at the Electric Power Research Institute (EPRI) Lighting and Utility Seminar, San Francisco CA, May 21-22, 1984.

Circline and Compact Fluorescents

Compact fluorescent lamps have been available for several years They can be used in place of incandescent lamps in many retrofit applications. Table 5-8 summarizes the most important characteristics of these lamps. [25] In commercial installations such as restaurants, motels/hotels, and retail stores, these lamps can decrease energy use by three- to four-fold, improving efficacies from the 12-18 lumens/watt range of incandescent lamps to 50-60 lumens/watt. They also have much longer lifetimes, thus significantly reducing labor cost for lamp replacement. For example, a commercial establishment which burns incandescent lamps an average of 10 hours/day will have to relamp about every two-months. The same establishment using compact fluorescents would only have to relamp, on average, every 20 months. However, an additional level of complexity is added to the labor/cost relationship if the conventional incandescents are replaces with long-life incandescents (typically 2500 hrs instead of 750 to 800).

Table 5-8 presents additional technical data on the performance of compact fluorescents compared to a standard 75-watt incandescent lamp.

The summary sheet, "Screw-in Fluorescent Replacements for Incandescent", contains additional material

Table 5-8

Characteristics of Compact Fluorescents

Criteria	High Light	Medium Light	Low Light	Incandescent
Power (watts)	34±0.5	18±0.2	16±0.5	75
Initial Light (lumens)	1700±60	1020±10	490±70	1210
System Efficacy (l/w)	50±2	56±1	32±5	16
Retail Cost ($)	17(e)	25 15(e)[a]	15 10(e)[a]	0.70
Total Cost* ($)	2.64(e)	5.03 3.52(e)	5.28	4.26(e)
Life (hr)	8000(e)	6500(e)	10000(e)	750
Input Voltage (v)	120	120	120	120
Frequency (Hz)	50	60	60	60
Power Factor (%)	75±1	62±0.3	61±0.2	100
Color Rendering Index	82±2	81±0.4	39±6	93
Color Temp (°K)	2620±70	2790±70	4507±240	2800

Source: R.R. Verderber and F.M. Rubinstein,
"Comparison of Technologies for New Energy-Efficient Lamps" Presented at the IEEE/IAS Annual Meeting, Mexico City, Mexico, Oct 3-7, 1983 p 1293.

[a] The first value in the column is the typical current cost (1983), the second value represents an estimate of the eventual cost of the lamp in a mature market (in 1983 dollars).

(e)-estimate

* Total cost of producing 10^6 lumen hours at $0.07/kWh excluding labor costs lamp replacement.

Lighting Timers, Switches, and Occupancy Sensors

The basic lighting-framework section noted that hours of operation of a lighting system are an important determinant of lighting energy usage. Timers, switches, and occupancy sensors are technologies that can decrease "unnecessary" hours of operation and save energy. (Power savings are more problematic as it is unclear whether there will be lights to turn off during peak periods.) The California Energy Commission has recognized the importance of such controls by requiring manual switches and provide lighting credits for use of occupancy sensors and daylighting controls. [26] Further discussions of lighting controls, including those for daylighting, can be found in section 6.4.5.

High Efficiency Fixtures

The coefficient of utilization (CU) of a luminaire depends on several factors. One of the most important is the efficiency with which the light fixture delivers the light generated by the lamp.

Cleaning and Maintenance of Luminaires

The light output from luminaires does not remain constant, but declines over time because of lamp burn out, accumulation of dirt, and a variety of other factors. This light loss factor is the product of several nonrecoverable and recoverable factors (see below). [27] The recoverable factors are ones that can be improved by a regular maintenance program, while the nonrecoverable factors represent elements that are intrinsic to the luminaire.

$$LLF = \text{Nonrecoverable X Recoverable Factors}$$

$$LLF = (LAT * VV * BF * LSD) * (LLD * RSDD * LLD * LBO)$$

where:

LAT = Luminaire ambient temperature
VV = Voltage variation
BF = Ballast factor
LSD = Luminaire surface depreciation

LDD = Luminaire dirt depreciation
RSDD = Room surface dirt depreciation
LDD = Lamp lumen depreciation
LBO = Lamp burn out

The designer of a new lighting system must take into account this light-loss factor (LLF) to insure that minimum lighting requirements will be maintained over time. If the designer can be reasonably certain that periodic maintenance will occur and the LLF will be minimized the initial oversizing of the lighting system can be minimized and both power and energy requirements decreased. [28]

Similarly, a luminaire cleaning and maintenance program applied to existing installations can dramatically increase lighting levels. This, in turn, can result in substantially energy savings if delamping, use of low-wattage fluorescents, dimmable ballast, or other conservation measures are instituted. In the Veterans Administration example cited above, the cleaning of fixtures permitted light levels to be decrease (via dimmable solid-state ballasts) and raised total energy savings from 25 percent up to 35 percent. [29] The amount of savings that will result from various maintenance programs and the cost of such programs depends on all the factors listed above. Consequently, we have not attempted to estimate either cost or savings in this report.

5.5.2 Incandescent

Ellipsoidal reflector lamps are discussed in the summary sheet, "Ellipsoidal Lamp Replacement for A/R Type Incandescents". Other more efficient incandescent lamps are discussed in the advanced technologies section below.

5.5.3 HID (Mercury Vapor/Metal Halide/High Pressure Sodium)

High-Intensity Discharge such as metal-halide, mercury vapor, and high-pressure sodium have traditionally been used for outdoor lighting applications. * However, because of the attractive efficacies, they are now beginning to be used in indoor applications. The following discussion concentrates on HPS and LPS applications.

High-Pressure Sodium

The high pressure sodium (HPS) lamp have lighting efficacies (including ballast) from 60 to more than 125 lumens/watt, with efficacy increasing with lamp size. The lamps are most commonly used in outdoor applications, especially street lighting, and are marked by a distinctive color concentration in the yellow-orange part of the spectrum. Their use, however, is not restricted merely to outdoor applications. There are several instances where HPS luminaires have been installed in commercial buildings, ranging from storage warehouses to office complexes.

The decision to use HPS lamps in commercial buildings has been the result, primarily, of their high luminous efficacy, compared to fluorescent, metal-halide, and mercury lamps. HPS lamps are also desirable as a point-source illuminator. However, their limited color spectrum and color rendering characteristics often substantially restrict their usage. Under these lamps red objects take on an orange appearance and blue or green colors appear gray. In a warehouse, where color quality is often not critical, these color changes many not be important. On the other hand, in offices and especially sales areas, where color characteristics can be crucial, the color properties of the lamp may be intolerable. In such cases, metal halide, mercury, or even incandescent lamps are placed in the same fixture with the HPS lamp. This improves the color quality with only a small decrease in total fixture efficacy.

The Sherman Williams paint company has addressed the issue of color rendering under HPS illumination by issuing a paint chart of 50 colors that can be used with HPS lamps. [30] We have examined the Buildings Energy Use Compilation and Analysis data base for new commercial buildings (BECA-CN) for instances of HPS installations in commercial buildings. [31] The data base contains 6 commercial establishments (2 schools, 1 city hall, 2 office buildings, 1 arboretum) that use high-pressure sodium luminaires for most of the interior lighting requirements. Power densities in the sample ranged from 1 to 2 watts/ft^2 and ambient illumination levels (where available) were 20 to 60 footcandles.

In most applications the HPS luminaires were sources of indirect illumination and were either suspended from the ceiling or were in stand-alone kiosk-style structures. To minimize the color rendering problems, one of the office buildings used blue, brown, and white panels, which have good quality under HPS lighting. The carpeting, lobby fascia panels, and wall coverings, are in warm neutral to gold tones to blend well with the color of the light source.

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* Strictly speaking low-pressure sodium lamps are not lamps HID lamps, however, we will not strictly adhere to that distinction in this report.

Although our information sources may provide somewhat biased information, they contain no major complaints with the lighting quality or level of illumination. A common statement is that once the occupants became accustomed to the 'non-standard' color they were no less content than under 'conventional' fluorescent systems.

Low-Pressure Sodium

Low pressure sodium lamps have the highest efficacy of any of the lighting technologies currently available on the market. At ratings of up to 185 lumens/watt these lamps have more than twice the efficacy of most fluorescent systems. However, the monochromatic light they produce is vastly different from most commercial lighting sources and, therefore, has very limited applications. In certain applications, such as warehousing, where the color characteristics of the light may be less important LPS lamps may be useful. [32] Table 5-9 illustrates the energy savings and changes in illuminance that would result from the replacement of mercury vapor lamps with high- and low-pressure sodium lamps. Such replacements are most common in warehouses. One warehouse retrofit project involved the replacement of 1500 400-watt mercury vapor fixtures with 200-watt high-pressure sodium luminaires. The total conversion cost about $200,000 and had a straight line payback on materials and labor of 24 months. [33] One further limitation with LPS illumination is that the fixtures for these lamps usually have low CUs. [34]

Table 5-9
Light and Energy Characteristics for Conversion
from Mercury Lamps to High and Low Pressure Sodium

Light source		Rated lamp mean lumens			System watts		
Original mercury	Converted to	Original mercury	Alternate source	Light output difference	Original mercury	Alternate source	Power difference
100 W	35-W LPS	3650	4800	+32%	118	60	-49%
	50-W HPS	3650	3600	-1%	118	66	-44%
	70-W HPS	3650	5670	+55%	118	88	-25%
175 W	55-W LPS	7560	8000	+6%	200	80	-60%
	100-W HPS	7560	8850	+17%	200	130	-35%
250 W	90-W LPS	11000	13500	+23%	285	125	-56%
	150-W HPS	11000	14400	+31%	285	188	-34%
400 W	200-W HPS	20100	19800	-1%	454	240	-47%
	135-W LPS	20100	22500	+12%	454	178	-61%
	250-W HPS	20100	24750	+23%	454	300	-34%
	180-W LPS	20100	33000	+64%	454	220	-52%
	310-W HPS	20100	33300	+66%	454	365	-20%
700 W	400-W HPS	38000	45000	+18%	760	465	-39%
1000 W	400-W HPS	48500	45000	-7%	1075	465	-57%

HPS - High-Pressure Sodium
LPS - Low-Pressure Sodium

Source : Ernest M. Freegard, "Sodium Alternatives to Mercury Lighting", *Electrical Construction and Maintenance*, Nov. 1983, p56.

5.5.4 Advanced lighting technologies

All lighting technologies discussed above are currently available for use in commercial buildings. There is much research underway that gives promise of significantly improving lighting efficacy beyond the maximum now available. Much of the research work on these advanced technologies is being conducted or sponsored by the Lighting Systems Research Group at the Lawrence Berkeley Laboratory (LBL). [35] None of the technologies discussed below are available on the market. In some case, several prototype lamps have been tested and the technical feasibility is reasonably well demonstrated. In other cases, the product is only in the research stage. We have tried to provide our best estimates of the technical characteristics, cost, and commercial availability of each. Costs and date of availability, however, depend on many factors, some of which relate to market forces that we have not tried to forecast. Consequently, all estimates presented here should be considered tentative.

Incandescent

The efficacy of general-service incandescent lamps ranges from 10 to 22 lumens/watt, with most lower-wattage lamps (30 to 150 watts) concentrated between 12 to 18 lumens/watt. Since incandescent lamps do not require ballast for operation the net efficacy need only account for the lamp and the coefficient-of-utilization. [36] A prototype incandescent lamp has been developed and tested which yields an efficacy of 29 lumens/watt at a nominal energy consumption of 50 watts. The dramatic improvement in efficiency results from the addition of a infrared-reflective transparent coating on the interior of the lamp globe. The coated globe, which is composed of two optically precise hemispheres, increases the efficacy by focusing back onto the filament the infrared radiation that is normally lost. Consequently, the filament is able to retain a high temperature with less electricity usage. Tests with ten prototypes have resulted in an estimated 2500-hour average lifetime (compared to a conventional incandescent lifetime of about 750 hours), and a luminous efficacy of 29.0 ±2.5 lumens/watt. [37] Verderber and Rubinstein have estimated that this lamp will eventually reach a retail cost of $5.00 per 50-watt lamp (1500 lumen output) and that it is technically possible to produce lamps from 400 to 2800 lumens. This price would produce a cost of $3.71 for per 10^6 lumen-hours at $0.07/kWh. [38]

General Electric currently has a 900-watt quartz incandescent on the market that operates on the filament/reflection process, and lower-wattage coated-filament lamps are possible on the market within the next 2 to 4 years. [39]

Fluorescent

There are four areas of fluorescent lighting research that promise major improvements in efficacy: electrodeless lamps, isotopically-enhanced gasses, magnetically-loaded lamps, and two-photon phosphors. Only the first three concepts have been tested in the laboratory.

The electrodeless fluorescent lamp is a compact fluorescent lamp without electrodes that can be used in place of a conventional incandescent lamp in an Edison socket. The lamp consists of a fluorescent, phosphor-coated bulb and very high-frequency ballast (100+ kHz). The electrodeless operation is possible because of the very high frequency of the ballast and the high lamp-loading (arc watts/phosphor area). Lamp loading is typically 3 watts/in^2, or about 10 times greater than conventional fluorescent lamps. [40]

The lamps are expected to be available in the output ranges from 400 to 2300 lumens. These ranges will cover most of the commonly used conventional incandescent sizes.

The combined lamp and ballast energy use of the experimental 1700-lumen output units is about 31 watts, yielding an average efficacy of 55 lumens/watt. The developers of these prototypes estimate that they will eventually obtain efficacies from 68 to 77 lumens/watt.

The target price for these lamps is $15/unit. This includes both the lamp and ballast. The greatest expense is the cost of the power field effect transistors (FET) used in the ballast circuit. At an energy price of $0.07/kWh the cost will be about $2.23/$10^6$/Hr.

The greatest impedement to the widespread adoption of these bulbs in place of incandescent bulbs may be the radio frequency interference (RFI) generated by the very high frequency operation of the ballasts. Also the test bulbs have had a low color rendering index of 57 and they may not be used in areas such as retail sales displays, where the high color quality of incandescent lamps is high desirable. However, different phosphors are available and this limitation can be overcome.

Commercial development of these lamps is underway and it is estimated that this lamp will be available on the market within the next few year, e.g. 1987-88. [41] A dimmable version of the lamp is also under development.

In isotopic enhancement, the percentage of rarer isotopes such as Hg_{196}, is increased to improve the efficacy of the lamp. [42] Experimental results show a 2 to 5 percent improvement in efficacy, compared to the best currently available fluorescent lamps, with solid-state ballasts, for T-12, T-9, and T-8 lamps [43] It has been estimated that the ultimately achievable improvement should approach 10%, i.e. efficacy increases from 100 lumens/watt to 110 lumens/watt. [44] We have no estimates of the additional cost of isotopic improvements. Research is underway to devise a commercial viable method of Hg isotope separation. [45]

Application of a transverse magnetic field to an isotopically-enhanced lamp could provide additional efficacy improvement. Preliminary tests with a magnetic field applied to a 14 watt T-12 fluorescent lamp have shown a 9.1 percent improvement in efficacy. [46] Estimates have been made that the eventual cumulative improvement of isotopic enhancement and magnetic loading may approach 35% i.e., 100-lumens/watt increased to 135 lumens/watt. Cost remain uncertain and indications are that this technology will not be available before 1990. [47]

Two-photon phosphors, which hold promise of luminous efficacies of 200 lumens/watt, may be available by the mid-1990s. Because this technology has not yet been tested in the laboratory we do not discuss it further.

Notes and References

1. Electric energy and power estimates for Southern California Edison, are taken from the November 15, 1983 "Commercial Sector Model Run". The peak usage value is for September, 1982 at 1 pm.
   Pacific Gas and Electric energy estimates are from the, October 5, 1983 "Commercial Sector Model Run". Peak estimates are from the A.D. Little *Conservation Potential Market 1983-2000: A Factbook,* March 1984, p III-9.
2. This expenditure does not include $8.1 million in rebates to small customers that contained numerous lighting retrofits. Robin C. Calhoun, "The Great PG&E Energy Rebate", presented at the *ACEEE 1984 Summer Study on Energy Efficiency in Buildings,* August 14-22, Santa Cruz, CA.

   Other utility conservation programs that have included commercial-sector lighting measures are: 1) PG&E Energy Saver Fluorescent Program, 2) PG&E Commercial Lighting Incentive Program, 3) PG&E Lighting Analysis Program, 4) PG&E Commercial Conservation Rebate Program, 5) SCE Conservation Hardware Rebate Program, and 6) SCE Energy Saver Fluorescent Lamp Program.
3. H. Bradston, "Reality for the Potential of Energy Savings Through Lighting" presented at the: *11th Energy Technology Conference,* March 19-21 1984, Washington, D.C.
4. See the Illuminating Engineering Society, *Handbook,* 1981 for more discussion of these topics.

5. This discussion is adapted from Clark W. Gellings, "Load Management, Lighting Codes, Energy and Pumpkins", *Lighting Design and Application,* February 1983, pp 34-37.

6. California Energy Commission, Building Conservation Committee, *Committee-Proposed Energy Efficiency Standards ("15-Day Language") New Standards for Office Buildings, Consolidated and Streamlined Standards for Other Nonresidential and Residential Buildings* November 19, 1983 (revised January 11, 1984), Section 2-5342(d).

7. Illuminating Engineering Society, *Handbook,* 1981.

8. Throughout this report the terms "luminous efficacy" and "efficacy" are synonymous with the "luminous efficacy of a light source". One should proceed carefully when comparing the luminous efficacy of different lamps and lighting systems. The efficacy can be for the lamp alone, the lamp(s) plus the ballast, or the entire fixture (i.e. including the coefficient-of-utilization term). In most instances when we refer to efficacy we include both the lamp and ballast system in our estimates. Where other factors are included or excluded, we so state.

9. Knisley, Joseph R., "Saving Lighting Energy-More Ways to Do It", *Electrical Construction and Maintenance,* November 1981, p 9.

10. See Reference 1

11. California Energy Commission, "Energy-Savings Potential in California's Existing Office and Retail Buildings", Staff Report, P300-83-003, p 42.

12. McPartland, J.F. "Energy Conservation in Warehouses", *Electrical Construction and Maintenance,* November 1982, p 69.

13. See Chapter 1, Sorcar, Prafulla, *Energy Saving Lighting Systems,* 1982, for breakdowns of the energy distribution of representative incandescent, fluorescent, mercury vapor, high-pressure sodium, and low-pressure sodium lamps.

14. A good discussion of air handling luminaires is contained in Chapter 8 of Sorcar (1982), op. cit.

15. Southern California Edison *Commercial/Industrial Book of Standards,* August 1, 1983, Table 1.0T1, provides a summary of expected energy savings for delamping of various lamp types.

16. Sorcar, Prafulla, op.cit., p.25.
There are a wide variety of 'dummy' tubes on the market, that have a different fractional reduction effect.

17. " Lighting Program at L.A.'s Westin Leaves No Room for Energy Waste", *Energy Management Technology,* April 1984, pp 22-23.

18. The General Electric *Lamp Technical Guide,* Form 9200, 1984 edition list low wattage "watt-miser" lamps in F30, 40, 48, 96 equivalent sizes. These lamps use 25, 34, 30, and 60 watts, respectively.

19. Much of this discussion and the material presented in the summary data sheet was taken from R.R. Verderber and F.M. Rubinstein, "New Lighting Technologies, Their Status and Impacts on Power Densities", presented at the *ACEEE Summer Study on Energy Efficiency in Buildings,* August 14-22, 1984, Santa Cruz, CA.

20. CEC, P300-83-003, 1983, op. cit., p 42.

21. Verderber, Rudolph, R., Oliver C. Morse, Allan A. Arthur, and Francis Rubinstein, "Energy Savings with Solid-State Ballasts in a Veterans Administration Medical Center", *IEEE Transactions on Industry Applications,* Vol. 1A-18, No. 6, November/December 1982, p 663.

22. Verderber, Ibid, p 663.

23. See James Jewell, Stephen Selkowitz, and Rudy Verderber, "Solid-State Ballast Prove to Be Energy Savers", *Lighting Design and Application,* January, 1980, pp 38, for a discussion of the ballast failure problems at the Pacific Gas and Electric building.

24. Hunt Electronics, for example, offers a three year warranty on their solid-state ballasts. Hunt Electronics, Trade Net Price List, January 2, 1984.

25. For more detailed information on the technical characteristics of these compact lamps (both the SL and PL models) see: A. Bouwknegt, "Compact Fluorescent Lamps", *Journal of the IES,* July 1982, pp.204-212., and L.E.Vrenken and W. Veenstra, "Compact Single-Ended Fluorescent Lamps: Some Performance and Application Aspects", *Lighting Research and Technology,* Vol. 15 No.2, 1983, pp.99-104.

26. California Energy Commission, "Energy Conservation Manual-Designing for Compliance: 1985 Office Building Energy Conservation Standards," Sept 1984 Final Draft. The credit for lighting controls are

Table 5-10
California Title-24 Lighting Control Credits

Control Type	Power Savings Adjustment Factor
Occupancy Sensing Devices	0.30
Daylighting Controls	
Continuous Dimming	0.30
Stepped Controller	0.20
Lumen Maintenance Controls	0.10
Daylighting Controls with Occupancy Sensing	0.44
Occupancy Sensing Devices with Lumen Maintenance	0.37

27. Sorcar, 1982, op.cit., pp 115-127.

28. R. Phil Woolery, "Luminaire Upkeep - Effect on Lamp Lumen Output", presented at the EPRI symposium, *Lighting and Utilities: Planning for the Future,* May 21-22, 1984, San Francisco, CA.

29. Verderber, Morse, Arthur, Rubinstein, op. cit., p 663.

30. Richard Corth, "Practical Features of Illumination with High Pressure Sodium Lamps", presented at the *10th Energy Technology Conference,* June 1983, Washington, D.C.

31. The BECA-CN data base is described in: "A Summary Report of BECA-CN: Building Energy-Use Compilation and Analysis of Energy-Efficient New Buildings", L.W. Wall, M.A. Piette, and J.P. Harris, May 1984, presented at the *ACEEE Summer Study on Energy Efficiency in Buildings,* August 14-22, 1984, Santa Cruz, CA.
The case studies described here are taken from unpublished BECA-CN data files.

32. Freegard, Earnest M., "Sodium Alternatives to Mercury Lighting", *Electrical Construction and Maintenance,* November, 1983, p 54.

33. "HPS Ballast/Lamp Retrofit Provides Rapid Payback *Energy Management Technology,* April 1984, p 18-20.

34. Personal Communication with Francis Rubinstein, Lighting Program Applied Science Division, Lawrence Berkeley Laboratory, Berkeley, CA.

35. The LBL group manages the National Lighting Program of the U.S. Department of Energy. Their activities include evaluation of the HVAC impacts of lighting, visibility and performance, and the development and testing of new lighting technologies. For a concise summary of recent activities see *Energy and Environment Division Annual Report: Energy Efficient Buildings Program FY 82,* Lawrence Berkeley Laboratory, LBL-15297, March 1983, pp. 3-35 to 3-41.

36. Sorcar, 1982, op.cit., p 6-7.

37. Lawrence Berkeley Laboratory, Duro-Test Corporation, *Energy-Efficient Incandescent Lamp: Final Report,* LBL-14546, April 1982.

38. Verderber, R.R., and F.M. Rubinstein, "Comparison of Technologies for New Energy-Efficient Lamps", presented at the IEEE/IAS Annual Meeting, Mexico City, Oct 3-7, 1983, pp. 1290-1293.
    They acknowledge that the 'major challenge will be to manufacture these lamps to meet the five-dollar retail price.'
39. Personal conversation with Francis Rubinstein, Applied Science Berkeley Laboratory.
40. R.R. Verderber and F.M. Rubinstein, "Comparison of Technologies for New Energy-Efficient Lamps", presented at the IEEE/IAS Annual Meeting, October 3-7, 1983, Mexico City, Mexico.
41. Personal communication with Francis Rubinstein, Applied Science Division, Lawrence Berkeley Laboratory.
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CHAPTER 6

DAYLIGHTING AND FENESTRATION

SUMMARY TABLE - A COMPARISON OF SELECTED FENESTRATION AND DAYLIGHTING DESIGN OPTIONS

Vertical Windows

Measure	Base Conditions	Modified Condition	Bldg. Zone	Climate Zone	*Base Electricity*(2)		*Percent Reduction*		Incremental Cost ($/ft²)(3)	Cooling Equip Cost Reduction(4) ($/ft²)	Life Expectancy (years)
					Energy kWh/ft^2	Demand W/ft^2	Energy	Demand			
1. Add dimming control	WWR = 0.5 Tv = 0.40 SC = 0.60 SCM = 0.6 W/ft^2 = 2.7(1)		N	SF	12.3	5.2	45	30	1.00 to 1.50 new	1.20	5-15
			S	SF	13.7	6.2	44	30	1.00 to 4.50 retro	1.07	
			N	Fr	15.2	6.4	39	33		1.07	
			S	Fr	17.3	7.2	37	34		.93	
2. Reduce lighting power density		W/ft^2 = 1.7	S	SF			23	18	<1.00>	.40	15-20
			S	Fr			19	16		.40	
3. Add dimming to 2)			S	SF			27	26	1.00 to 1.50 new	.80	5-15
			S	Fr			23	23	1.00 to 4.50 retro	.53	
4. Use exterior blinds in lieu of interior		SCM = 0.35	S	Fr			5	5	1.40 to 2.50	.40	15-20
			W	Fr			11	12		1.73	
5. Add dimming to 4)			S	Fr			40	33	1.00 to 1.50 new	1.07	5-15
			W	Fr			33	32	1.00 to 4.50 retro	.98	
6. Use reflective glass or add solar control film	WWR = 0.5 Tv = 0.54 SC = 0.80 SCM = 0.6 W/ft^2 = 2.7	Tv = 0.14 SC = 0.34	S	SF	14.9	7.0	15	22	.40 to 2.00	2.53	5-20
			W	SF	15.4	7.4	15	21		2.80	
			S	Fr	19.2	8.2	20	19		2.80	
			W	Fr	20.8	9.0	22	22		3.33	

(1) Installed electric lighting power density, including lamps and ballasts.

(2) Annual electrical energy consumption and peak demand for base condition includes lights, fans, chiller, and equipment.

(3) For consistency in comparison all costs are per square foot of floor area based on 15ft deep perimeter zone. Measures 4) and 6) are fenestration treatments. In these cases cost per square foot of window area is 2.5 times the indicated value. Product cost estimates have been provided by product suppliers.

(4) Based on $2000/ton cooling equipment cost.

Chapter 6

Daylighting and Fenestration

6.1 SUMMARY AND RECOMMENDATIONS

Improved fenestration design will decrease the negative impact of solar gain and increase utilization of daylighting in buildings to reduce electric lighting requirements and can save on utility costs (energy and peak demand) while enhancing the visual quality of indoor environments. These benefits, which exist largely as potentials at this time, can be realized in the near future. Our review of the state of fenestration design and daylighting applications uncovered several interesting observations:

Key Findings

- Interest in daylight utilization as an energy saving and load management strategy is high and growing. In particular, daylighting's potential to reduce peak electrical demand charges in summer peaking utility systems is being recognized.
- Unlike some conservation strategies which have unknown or undesired side effects, daylighting is a building design feature associated with positive attributes: view, health, increased productivity, etc.
- Excessive solar gain can negate the benefits of daylighting causing increased cooling loads and thermal and visual discomfort. Proper fenestration design to control solar gain and glare is critical to reducing building energy consumption and imperative to successful daylighting design. Although high interest is widespread, the general level of understanding of the design and technical issues and solutions is typically limited. This is due in part to the many years of neglect of daylighting as a design issue resulting in the almost complete lack of successfully daylighted buildings that can be inspected by an interested person.
- The technical and design skills to optimize daylighted building designs to produce maximimum energy and load savings (while maintaining or improving visual quality and comfort) are virtually non-existent. The designers and consultants who venture beyond the simplest of the proven solutions find themselves in unexplored territory. While optimal solutions will depend on further research, effective solutions are presently attainable.
- The real cost savings to a building owner of a successful daylighting solution can be very high. Conversely, an unsuccessful daylighting design may be costly in terms of subsequent corrections and lost productivity.
- Continued improvements in lighting design strategies and lighting hardware will reduce the energy impact of daylighting savings. New hardware, however, may be costly and energy costs can be expected to increase. Strategies for an economic optimal combination of electric lighting hardware and daylighting are not well understood.

These observations can perhaps best be summed up by noting that while the potentials are high, there are some risks and uncertainties as well. Extensive computer simulations, discussed later, allow us to characterize fenestration energy influences and estimate potential savings, particularly with daylighting. In a daylighted perimeter zone of a building, annual lighting energy consumption can be reduced by 70%. In an office occupancy with typical installed power levels of 2.3 W/ft^2 lighting will require 5.8 kWh/ft^2-yr. Daylighting could thus displace approximately 4 kWh/ft^2-yr. An effective lighting control system might allow 2.4 W/ft^2 savings under peak conditions for 8 month/yr (this includes lighting savings and associated cooling load reductions). At \$0.10/kWh for energy and \$10/kW-month for peak demand the annual savings come to \$0.59/ft^2-yr. This provides a very powerful incentive to examine the potential savings in more detail and find correct fenestration and daylighting design solutions.

Data Gaps

Our review of the current state of the art in fenestration and daylighting design in buildings and the potentials in energy savings and peak load reductions suggests several critical and promising areas for present and future applications.

The influences of fenestration on building energy requirements are discussed quantitatively in section 6.3, Potential Energy Savings. Combinations of fenestration and electric lighting design parameters are presented which demonstrate both negative influences and parameter combinations leading to minimum energy requirements. In section 6.4, State-of-the-Art Assessments, the technologies for utilizing daylighting are discussed. In the section, Building Case Studies, actual buildings are presented showing examples of actual physical configurations that have been used and may be considered for implementation in other buildings. Immediate application recommendations become self evident from these discussions. It must be kept in mind, however, that to maximize the benefits from fenestration more detailed information on actual fenestration performance must be determined from which more reliable design guidelines can be developed. Areas in which fundamental information is weak and must be upgraded to improve the state-of-the-art are discussed below.

- *Daylight Resource Availability*

Data on daylight availability is essential for design purposes and to make accurate estimates of the potential savings in daylighted buildings. In the short term the applicability of existing data bases and calculation techniques to California climates should be investigated and available information should be expanded or modified to ensure that adequate interim data is available for all design and analysis purposes. For the longer term one or more data collection projects should be undertaken to ensure that accurate data is available for key population centers. Specialized studies should also be undertaken to explore subjects such as daylight availablity in built-up urban areas, ground cover effects on daylight, and other unique microclimate and site specific influences.

- *New Technologies*

Detailed examinations of the performance of existing buildings and computer simulation studies of energy use in daylighted buildings will suggest areas where new fenestration and lighting control technologies might be useful.

- *Energy and Peak Load Simulation Studies*

This chapter discusses results of energy and peak load simulation studies in different building modules for different daylighting approaches in different climates. This type of study provides basic guidance for the design community as well as the manufacturing interests who are concerned that their products meet real performance needs. We have used the most advanced and powerful simulation tool presently available. Nonetheless, additional studies are required to more precisely quantify the impact of daylighting for other building types, configurations, and design strategies, and to determine the potentials for load management and peak load savings. This may involve some new algorithm development although much of what is required is already under development.

Results of simulation studies should also be converted into more extensive economics studies that identify the range of cost-effective savings from the perspective of different owners and investors.

- *Building Monitoring Program*

Performance data for daylighted buildings is virtually nonexistent. A review of over 40 "daylighted" buildings described in the architectural and engineering press provided virtually no useful data on the magnitude of daylight savings. These data are necessary, not only to validate computer models that provide guidance to designers, but also to convince hardnosed decision makers that these approaches are viable and cost effective.

6.2 HISTORICAL PERSPECTIVE ON DAYLIGHTING IN COMMERCIAL BUILDINGS

Unlike some of the high technology HVAC and electric lighting systems and control strategies introduced to reduce commercial building energy consumption, daylighting has a history as old as building construction. Prior to the widespread use of electric lighting in commercial buildings, it was routine for fenestration systems to be successfully and sensitively designed expressly to admit daylight and use natural ventilation. Other available light sources, such as candles and oil or gas lamps, were only used in the absence of daylight. Even after the introduction of electric incandescent lighting in buildings and through the first three decades of the 20th century, daylight remained the dominant source and incandescent lighting sources were merely supplements. Recommended illuminance levels were sufficiently low that moderately-sized windows could provide adequate illuminance for daytime activities throughout much of the year. High ceilings and extensive use of light wells and skylights allowed for deep daylight penetration as well as for natural ventilation. The patent literature from 1880 to 1930 is filled with practical and fanciful solutions for admitting daylighting even deeper into building interiors than these architectural solutions allowed.

From 1930 to 1950 profound changes in building technology and design combined to reduce the reliance on daylight as the principal light source. Introduction of fluorescent lamps and affordable electricity made it easy to maintain satisfactory interior illuminance levels without reliance on daylight. The invention of mechanical chillers allowed one to control thermal comfort with mechanical ventilation and cooling systems which replaced natural ventilation. Further, as land and building costs increased so did the demand for increased net usable space and compact building plans. All of these forces tended to reduce the concern for effective daylighting and natural ventilation and the opportunities were then ignored.

From the 1950's to the 1970's these technical and economic trends accelerated influencing both return on investments and architectural design attitudes. The building industry was influenced by the widespread assumption that our technological prowess (and cheap energy) allowed any building design to be executed in any climate and ensure that it could be satisfactorily heated, cooled, and lighted. A brute force approach to providing climate control and desired illuminance was employed to compensate for fundamental design problems. Daylight as the lighting source is rarely discussed as a determinant of building designs during this period. Fenestration is considered almost exclusively in relationship to view and formal design aesthetics with no regard to energy implications or human thermal and visual comfort. The use of daylight as an energy and load management strategy is only rarely mentioned and even more rarely implemented.

Following the recent period of rapidly rising energy and building costs the importance of energy flows through fenestration has been recognized and the potential of daylight has been rediscovered. However, the renewal of interest and activity, has often been painful and awkward since most of the infrastructure for evaluating daylight (e.g., professional education and design practice) had long since disappeared in the architectural community. Further, during the last decade the lighting design profession has struggled to adjust its long-standing emphasis on electric lighting design and concerns for lighting quality with newly imposed requirements for energy efficiency. Lighting designers, trained and practiced in electric lighting design viewed daylight as a peripheral adjunct. Engineers in many cases lacked interest and skills to address the resulting needs. Building owners, operators, and designers lacking immediate daylighting experience were not convinced that daylighting control strategies were a good long term investment. This attitude was reinforced as some early attempts at new daylighted buildings failed to meet expectations.

This situation is rapidly changing and in the next ten years substantial changes can be expected. The need for new and more efficient fenestration systems and lighting controls is now being recognized and such systems are becoming available and will become increasingly more so. Design tools, skills, and confidence have increased to the point where daylighting strategies are now being more frequently incorporated into new buildings. Over the next ten years, feedback from these buildings and advances in other areas should accelerate identification and more widespread use of successful approaches. This chapter examines the energy influences of fenstration, and in particular the overall potential for saving energy with daylighting. It will also help to identify some of the actions that might advance effective fenestration and daylighting design both near-term and in the future.

6.3 POTENTIAL ENERGY SAVINGS

6.3.1 *Introduction*

The influence of fenestration (windows and skylights) on total energy performance involves a complex interaction among the window's thermal and optical characteristics and other building parameters, within the context of climate and orientation.

Defining these effects is a difficult process for several reasons. First, the problem is inherently complex and is linked to many aspects of commercial building performance. In order to understand fully the energy conservation and economic benefits of daylighting, it is necessary to consider lighting energy consumption, thermal performance, and peak electrical demand. Second, until recently the large computer models used for energy analysis were unable to model daylighting effects accurately. Finally, there is little or no operating experience, nor are there measured performance data, on fenestration's net thermal performance, and even less measured field data on daylighting effects.

Detailed data on changes in peak electrical demand and on rate structures are necessary to completely analyze the cost benefits of daylight-responsive electric lighting systems and to accurately determine total electrical costs. Reducing both consumption charges and demand should provide substantial operating savings to building operators and reduce the pressure on utilities for costly new generating capacity.

The studies discussed here focus on improving our understanding of the relationship between fenestration parameters and: 1) electric lighting reductions due to daylighting, 2) thermal loads both with and without daylighting, and 3) the impact of daylighting strategies on building electrical demand. The analytical work has been concentrated on office buildings for a number of reasons. Compared to most other building types the potential energy savings with daylighting in office buildings is high. Lighting requirement, while typically rigorous, can be easily met fully or partially with daylighting in many cases. Office buildings, typically served by mechanical chillers, experience peak electrical demand when daylighting opportunity is also greatest. The complicated thermal interactions between the building envelope and the HVAC operating systems make analysis difficult and non-intuitive. Daylighting results determined with the office module can be disassociated from the thermal interactions and extended to other building types.

Considerable energy savings can be realized in other building types through appropriate fenestration and daylighting design. Classrooms can be considered as quite analagous to office spaces and if operated all year long with similar HVAC systems could be expected to perform similarly. Warehouses would seem to be ideal candidates for daylighting but are quite variable in requirements making generalized analysis difficult within the scope of this project. Air conditioning requirements vary from refrigerated warehouses to those with no conditioning at all. Daylighting apertures without managed shading may produce product damage and cause high glare levels.

We analyzed daylighted building energy performance in California climates using a parametric modeling approach which will be described below. This approach follows methodology developed in ongoing fenestration and daylighting studies at LBL [1,2,3,4].

Results indicate that for a typical daylighted perimeter zone in a commercial office building the annual electric lighting savings can be as high as 80%. Peak electric demand reductions can also be substantial, since during peak demand hours electric lighting required in daylighted zones can be small or even zero. For the prototypical office building module studied, with 62% core area and 38% perimeter area, peak demand reductions for the entire building (all end users combined) reached 25%. Greater percentages of daylighted floor space will yield even greater reductions in peak demand.

Peak demand as a summer phenomenon is made up primarily of electric lighting and cooling. Daylighting benefits (i.e., reduced electric lighting) increase rapidly and then begin level off with window areas much smaller than necessary for maximum lighting energy savings, while cooling load continues to rise monotonically with window area even after daylighting benefits begin to level off. The very large window areas necessary for maximum daylighting also admit solar gain which may cause cooling load increases to exceed daylighting benefits. Approaches to optimum design solutions, which are indicated but not provided in explicit detail in this chapter, will require further research that accounts in detail for energy consumption economics and various building energy interactions (e.g.- variations in HVAC system design and thermal storage systems), as well as fenestration parameters. The optimum solution for any real building will require analysis of the specific relative to that building.

Daylighting in skylighted spaces offers savings potentials of magnitudes similar to those of windows. The energy benefits of daylighting with horizontal skylights, however, can be easily negated because of the less favorable orientation compared to windows for solar gain and higher cooling loads during summer months.

The results, while clearly pointing up the energy conserving potential of daylighting, critically demonstrate the need for more detailed performance data on actual buildings, and for the development of design guidelines and other tools to allow daylighting's potential to be realized.

6.3.2 *Methodology*

Our building model for vertical window simulation (Figure 6.1) consists of four identical perimeter zones, each 15 ft deep, (4.8 m), surrounding a square common core zone. The ceiling and floor were modeled as adiabatic surfaces (having no net heat transfer). Envelope thermal transfer was thus limited to the walls and fenestration in order to isolate solar gain and daylighting effects. Overall envelope thermal conductance was held constant for each parametric set. Thus when glazing area or glazing U-value was changed, the wall U-value was adjusted to maintain a constant overall envelope conductance. After basic performance patterns were established, the overall conductance was varied over a representative range. Fenestration characteristics were varied by changing number of panes of glazing, glazing area, visible transmittance, and shading coefficient. As base-case conditions, we assumed that occupant requirements for thermal and visual comfort result in the use of drapes or shades for any hour in which transmitted direct solar radiation exceeds 20 Btu/hr ft^2, (63 W/m^2) or any hour in which window luminance produces a glare index greater than 20. The interior shading device reduces solar heat gain by 40% and visible transmittance by 65%. These values are typical of many conventional interior drapes or blinds.

For the skylight studies only the perimeter zones were deleted and only the core zone was used. In this case the envelope surface of interest is the roof, so the floor and walls were modeled as adiabatic surfaces. Fenestration and thermal conductance parameters were varied for the roof in a similar manner to that previously described for vertical fenestration. The skylights were modeled with diffusing glazing and no managed shading was deployed. Skylight well light transmission factor was included as another variable parameter.

Electric lighting power density was varied from 0.7 to 2.7 W/ft^2 (7.5 to 29 W/m^2) based on a design illuminance of 50 fc (538 lux). We examined the effects of stepped switching and continuous dimming in response to daylight. A continuous dimming system dims from 100% light output with 100% power to 0% light output with 10% residual power.

The DOE-2.1B building energy analysis program [5] used as the modeling tool incorporates a daylighting model [6] that calculates hourly interior daylight illuminance for each zone of a building based on architectural design and hourly weather data. We completed analysis for three climates in California: San Francisco, Los Angeles and Fresno. WYEC (Weather Year for Energy Calculations) and TMY (Typical Meteorological Year) weather tapes were used. These three climates, representative of populous California communities, provide satisfactory bounds for this study.

Total HVAC plant energy consumption was calculated for the entire five-zone module; however, in order to examine the effects of orientation, we studied zone-by-zone requirements based on zone-level coil loads. The interactions among various HVAC system and building envelope characteristics can be important in actual buildings but were not a primary issue in this study.

6.3.3. *Results*

6.3.3.1 Energy Usage--Vertical Windows

The numerous parametric runs completed provide a data base that demonstrates the complexity of daylighting energy analysis relative to our primary concerns--climate, orientation, and fenestration--along with other physical and operational building parameters. To simplify interpretation of results, we define a new term, *effective aperture*, which is the product of the ratio of glass area to floor-to-ceiling wall area times visible transmittance (or, when appropriate, shading coefficient).

The dimming system is continuously responsive to variations in daylight level; it maximizes the benefit from low daylight levels but does not shut off the 10% residual power even when daylighting is adequate to meet all lighting requirements in the zone. The simple stepped system reduces electric lighting power only when daylight exceeds the design criteria and provides *all* required lighting; at zero electric light output there is zero power consumption. Thus the step-switching system is most effective at high interior daylight levels, where it outperforms the continuous dimming system. Step-switching is least effective in situations in which low daylight levels, providing only a fraction of desired illuminance, occur for a significant fraction of occupied hours.

The principal effect of daylighting is to reduce electric lighting usage. As the effective aperture increases, electrical consumption for lighting first drops off sharply then levels off. For a given effective aperture, the fractional savings depend on the design illuminance level, lighting power density, and the lighting control strategy. Fig. 6-2 illustrates the change in fractional lighting energy savings as a function of effective aperture, for three design illuminance values, with a stepped system. For small aperture areas the savings are not linear with respect to design illuminance level. For larger effective apertures (i.e., above 0.12) the shape of the curves indicates that daylighting becomes saturated and further savings not possible. The choice of lighting control strategy has several consequences. It affects lighting savings and impacts building users. The first can be monitored; the second has yet to be adequately assess for design purposes.

To illustrate the importance of lighting control strategy on energy performance, Fig. 6-3 compares lighting energy consumption between a dimming control and a stepped control both set to 50 fc (538 lux). For small apertures, the dimming control always outperforms the stepped system because for many hours the available daylight is below the control setpoint, allowing partial savings with the dimming system but none with the switched control. As the aperture increases, the difference between the two is reduced. Eventually the switched system outperforms the dimming system because of the dimming system's operating characteristics. This pattern appears on all orientations in all climates.

Total electric lighting energy savings can be substantial. Approximately 50 to 80% of electric lighting in the perimeter can readily be saved (Figs. 6-2 and 6-3). Note, however, that the savings saturate at moderate effective apertures, around 0.2. This suggests that for a 50 fc (538 lux) setpoint, a 40% glazed wall with 50% transmittance or a 30% glazed wall with 90% transmittance will provide most of the possible daylighting savings in a typical 15-foot-deep perimeter zone. Walls that are fully glazed from a 30 in. (0.8 m) high sill to ceiling have 71% glazing, and would provide most of the potential savings with a transmittance as low as 30%. These moderately-transmitting products may also reduce discomfort from glare. However, the highly reflective architectural glasses in common use, which have 8 to 14% daylight transmittance, provide substantially lower daylighting savings. These glazings emphasize sun and glare control at the expense of daylight transmittance. Note that if the design illuminance level was lowered to 30 fc (323 lux), a level that might be used for ambient lighting only, savings in all the above cases would increase notably with the very low-transmittance glazings.

During winter months, the balance-point of a zone shifts when the electric lighting is reduced; this requires additional heating energy. The magnitude of the heating load increase is small and depends on orientation. The most pronounced effect occurs in a north zone, For the south zones the increase can be much smaller because the solar gain that was useless when the electric lights were on is now available to offset part of the increased heating load.

In the summer, reduced electric lighting diminishes cooling loads. An overall picture of total zone energy consumption as a function of orientation, glazing parameters, and lighting load is shown in Fig. 6-4, 6-5, 6-6, which present total energy results for a south zone in Fresno, Los Angeles, and San Francisco for three different installed lighting power levels: 0.7, 1.7, and 2.7 W/ft^2.

For the south orientation with daylighting an optimum effective aperture for minimum energy requirements is reached, after which total energy consumption increases, dominated by the rising cooling load. There is an obvious tradeoff between cooling and daylighting, and the optimum solution is sensitive to installed lighting power. For example, with 2.7 W/ft^2 installed lighting load, in Los Angeles the optimum effective aperture is between 0.10 and 0.12. However, at effective apertures larger than optimum, even at the largest value studied (approximately 0.27), the consumption with daylighting is less than that of an opaque insulated wall (effective aperture of zero). If we drop to an installed lighting load of 0.7 W/ft^2 on the south zone, the optimum shifts somewhat to smaller effective apertures and is less sharply defined. In addition, the energy requirement in the daylighted case now equals that of an opaque wall for an effective aperture of approximately 0.15 and exceeds it for greater aperture values.

The cooling load impact of daylighting has been the subject of much discussion. Generalized claims have been made that since the luminous efficacy of daylight (100-120 lumens/watt) is greater than that of typical fluorescent systems (60-90 lumens/watt) daylight will reduce cooling loads relative to electric lighting. However, this simplistic analysis ignores the details of how light is admitted to a room from a window or light fixture and it ignores the critical difference between total admitted light flux and that fraction that ends up as useful flux on a work surface at a task location. When these factors are accounted for, we conclude that daylight is a cooler source of light in a sidelighted office only if the installed electric lighting power is greater than about 2.0 $watts/ft^2$--for lower power densities daylight will increase cooling loads. Improved fenestration controls and electric lighting controls would shift this balance point even lower.

6.3.3.2 Energy Usage--Skylights

As with vertical fenestration systems, energy savings from skylights vary as a function of the lighting level (fc) and the lighting control system.

Figures 6-7, 6-8, and 6-9 show annual energy use vs. effective aperture for a range of effective aperture extending up to .04. Note that daylighting benefits begin to saturate at very small effective apertures, approximately 0.015. Slightly before daylighting saturation takes place, cooling and total energy consumption are at a minimum. Increasing effective aperture beyond the saturation point provides additional daylighting that exceeds design requirements and imposes an increasing cooling energy penalty. This crossover is typically reached at a much smaller effective aperture in flat skylights than in vertical fenestraton as a consequence of the early daylighting saturation and the less favorable orientation to solar geometry. The use of properly designed exterior shading elements on flat skylights or other skylight configurations can change this relationship to yield improved net annual energy performance.

6.3.3.3 Peak Demand Analysis

Unless electricity is the building's primary heat source in a cold climate, electrical consumption in office buildings typically peaks during summer months when cooling requirements are at a maximum. In building simulations in this study, heating was supplied with a gas-fired boiler and cooling was provided with an open centrifugal chiller. Therefore, the peak demand conclusions of this study are limited to summer peaking. Results might change if other energy source systems are used for heating or cooling.

Using the same prototypical building module as above, we extended our analysis to examine peak demand impacts. Figures 6-10, 6-11, and 6-12 show that daylight from moderate-to-large effective apertures can reduce total building peak demand by 18-25% compared to a nondaylighted building with identical glazing when the electric lighting is 2.7 W/ft^2. The percentage reduction diminishes as lighting power density is reduced. In this case the daylighted perimeter floor space is only 37% of the total. The fraction of total building peak demand saved will vary with the perimeter/core ratio.

A plot of required chiller size as a function of window effective aperture is included in Figs. 6-13, 6-14, and 6-15. The data indicate that the incremental chiller savings due to reduced lighting loads from daylighting increase quickly with effective aperture at low aperture values and then nearly remain constant, while the incremental adverse impact of solar gain continues to increase as aperture size increases. These results emphasize the importance of control of solar gain if daylighting is to be successfully utilized to control peak demand.

Required chiller size as a function of skylight effective aperture is presented in Figs. 6-16, 6-17, and 6-18. In contrast to the results with windows, chiller size immediately decreases as daylighting is used at small effective apertures. In all cases chiller size is minimized with an effective aperture of approximately 0.01. Chiller requirements for spaces without skylights exceed those of spaces with skylights and using daylight out to an effective aperture of 0.015 in Fresno, 0.02 in San Francisco, and 0.025 in Los Angeles. In most cases annual energy consumption and peak electrical demand are also minimized within these effective aperture ranges.

The results described above also depend on installed lighting power density. When the installed electric lighting is very efficient, daylighting without window management requires a larger chiller than window management without daylighting. When installed electric lighting power density is above 2.0 W/ft^2 (21.5 W/m^2), daylighting is always beneficial in terms of chiller size. There is an approximately linear relationship between electric lighting level and chiller size, regardless of daylighting and window management, although the rate of increase in required chiller size will vary with the conservation strategies utilized.

Peak electrical demand as a function of installed electric lighting power density is shown in Figs. 6-19, 6-20, and 6-21. Changes in installed lighting power are assumed to represent hardware changes that increase or decrease luminous efficacy, but maintain the illuminance design criterion of 50 fc (538 lux). For the nondaylighted cases, including a building having no windows, the relationship between peak demand for the total building and electric lighting power is linear and the plots for different values of window area or shading coefficient are parallel. However, for daylighted cases, the relationship between peak and lighting load becomes more complex.

The three nondaylighted cases represent effective apertures of 0, .12, and .27, respectively. These have essentially the same slope. The value includes the cooling impact of lighting as well as the effect of operating schedules. These schedules assume that 90% of the installed lighting power is operating during most daytime hours. These values represent results for core and perimeter zones combined. If we examine results from the perimeter zone alone, we find that, at peak conditions with small windows the electric lighting is operating at about 50% power. For large windows, the lighting is operating at its lowest limit, 10% power. The daylighted case with the small window ($A_e = 0.12$) has a lower peak demand than the case without windows for all values of lighting power density. However, the daylighted case with larger windows ($A_e = 0.27$) may have a higher or lower peak demand than the non-daylighted case with smaller windows, depending on lighting power density. For lighting densities higher than about 1.1 to 1.3 w/ft^2, the daylighted larger window is preferential; for very efficient lighting with densities below 1.1 to 1.3 W/ft^2 the smaller nondaylighted window case is best.

Monthly distribution of peak demand is shown in Figs. 6-22, 6-23, and 6-24. Monthly total electrical consumption is also indicated. In this case, with small glass area and high transmittance, peak demand rises during summer months while daylighting produces maximum peak load shaving benefits. While energy use and cost optimization constitute a complex issue requiring detailed study, daylighting as a design strategy offers important peak load reductions for summer peaking utility systems.

6.3.4 Simplified Performance Analysis

Analysis of data using the preceding figures provides insight into key performance trends, however it remains difficult to evaluate the influence of individual parameters. We therefore developed a simple set of predictive equations which incorporate key fenestration variables. A large integrated data base was created from results of DOE-2 runs, then a series of multiple regressions were calculated to define coefficients for selected variables that could accurately predict relative energy usage. Multiple regression is a statistical analysis procedure in which relationships among variables are established mathematically using a least-squares approach. Generally, sets of independent variables are defined, and used to estimate the value of a dependent variable.

In this analysis distinct regression equations were generated for cooling peak, cooling energy, heating energy, and total electric requirements. Heating peak was not considered in the study, after initial results indicated that its value was usually a function of the startup load and thus could not be related in a meaningful way to the building's fenestration parameters. The analysis of daylighting resulted in correction factors to the lighting heat gain terms. The resulting regression expression for the perimeter zone is of the form:

$$Q_i = b_1 U_o A_T + b_2 A_g SC + b_3 k_d A_f L + b_4 A_f \tag{1}$$

where:

Q_i = component energy requirement
b's = solved for regression coefficients
U_o = exterior envelope overall U-value (Btu/hr-ft^2°F)
A_T = exterior wall area (ft^2)
A_g = window area (ft^2)
SC = shading coefficient
A_f = floor area (ft^2)
L = lighting wattage (W/ft^2)
k_d = correction factor due to daylighting.

This form of the equation was used for each orientation for each of the energy quantities studied. Its compact form and conveniently segregated terms permit a qualitative as well as quantitative analysis of individual components contributing to perimeter zone energy use. Tables 6-1 through 6-4 present the regression coefficients and certain relevant statistical variables to indicate the reliability of the fit. Generally, the r^2 (square of the correlation between the predicted value and actual value) values are on the order of 0.98 and above (an r^2 value of 1.0 represents a perfect correlation), with the exception of the heating energy in the perimeter zones, which is usually below this value. However, in climates where energy requirements for heating approach the magnitude for cooling (this can be seen by observing the mean value of the data), the r^2 would increase correspondingly. The skylight or rooftop envelope portion of the analysis yielded a regression expression similar to Eq. (1); the only difference being the lack of an orientation variation.

The daylighting correction to the lighting term of the basic equation was obtained as a function of effective aperture. The effective aperture, which is a dimensionless parameter, is defined as the product of window to wall ratio and visible transmittance. For skylights, this product is multiplied by the skylight well factor. The following expression was derived:

$$K_d = a_1 \left(1 - e^{-a_2 \, WWR \; T_v}\right) \tag{2}$$

where:

k_d = correction factor to the lighting wattage due to daylighting
a's = regression coefficients
WWR = window to wall ratio
T_v = visible transmittance

This equation can be used for each of the energy quantities analyzed. Figs. 6-25, 6-26, 6-27 and 6-28 present the daylighting correction factor for vertical glazing and skylights. For perimeter zones, an asymptote is approached which yields approximately a 65% reduction in electric lighting at an effective aperture of 0.20.

In order to assess whole building energy performance Eq. (1) was rewritten in the following form:

$$Q_i = b_i U_o A_T + b_2 A_g SC + b_3(k_d A_p + A_c)L + b_4(A_p + A_c) \tag{3}$$

where:

A_p = total perimeter floor area (ft^2)
A_c = core floor area (ft^2)

Whole building energy performance is necessary in determining building coincident peak electrical load and peak load reductions due to daylighting. Regression coefficients for making these calculations are included in Tables 6-1 through 6-6.

The statistical correlations presented in the tables for the various multiple regressions indicate that good predictions of DOE-2 results are obtained by using equations of these forms. The form could be made more accurate by considering quadratic and cross-coupled independent variables of the input heat gain/loss components. Generally, the more detailed the regression model, the better the predictive quality of the final equation. However, although large numbers of independent variables may be more accurate in a mathematical sense, their use is limited in a practical sense. It should be kept in mind that the results of this study are valid only within the range of variables considered. One should not expect to be able to define a building's actual energy use from these results but rather to estimate relative performance among alternative designs.

Note: For coefficients provided in Tables 6-1 through 6-6 the following units are applicable to the regression equations:

Cooling Peak:	Btu/hr
Cooling, Heating, and Electricity Energy:	kBtu
U_o:	Btu/hr-ft^2-°F
A_t, A_g, A_p, A_c:	ft^2
L:	W/ft^2
Mean (Cooling Peak):	kBtu/hr
Mean (Cooling/Heating Energy):	mBtu

6.3.5 *Cost Impacts*

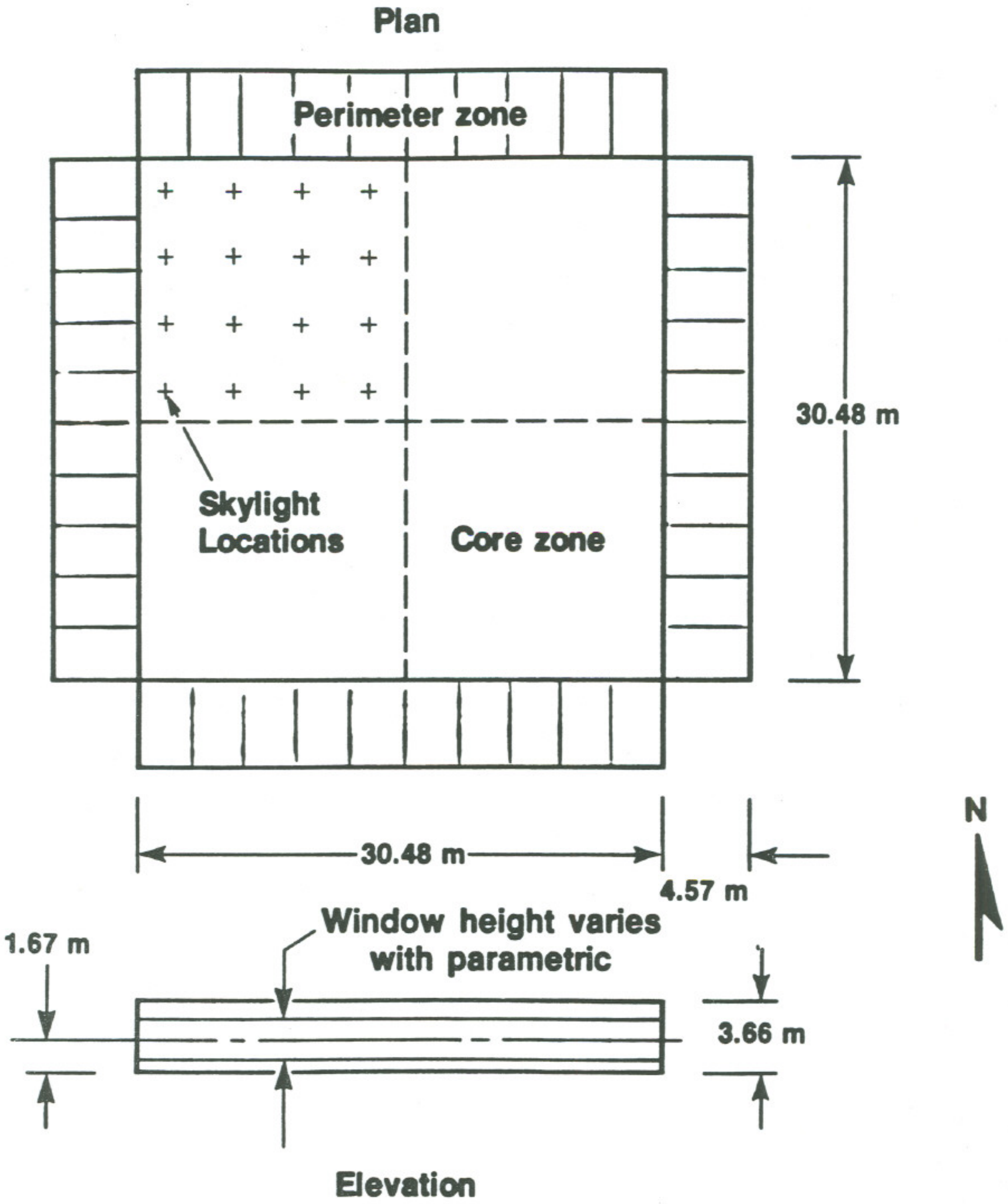
While energy savings from daylighting can be presented in many forms, the ultimate concern is cost savings. Utility rate structures and energy costs vary as a function of source, season, and peak demand. Uncertainities in estimating the installed costs of fenestration and daylight control measures complicates the generalization of cost benefits and emphasizes the necessity of case by case analysis. Some selected design options with cost ranges and energy impacts are presented in the summary table at the beginning of this chapter.

6.3.6 *SUMMARY*

Daylighting is potentially an important design and conservation strategy in nonresidential buildings. Results from an hour-by-hour simulation model that accounts for daylighting impacts help refine our understanding of this complex subject. An extensive data base of parametric analyses results using the DOE-2.1B computer model for a simple office module in several climates was compiled. The results suggest the following generalizations:

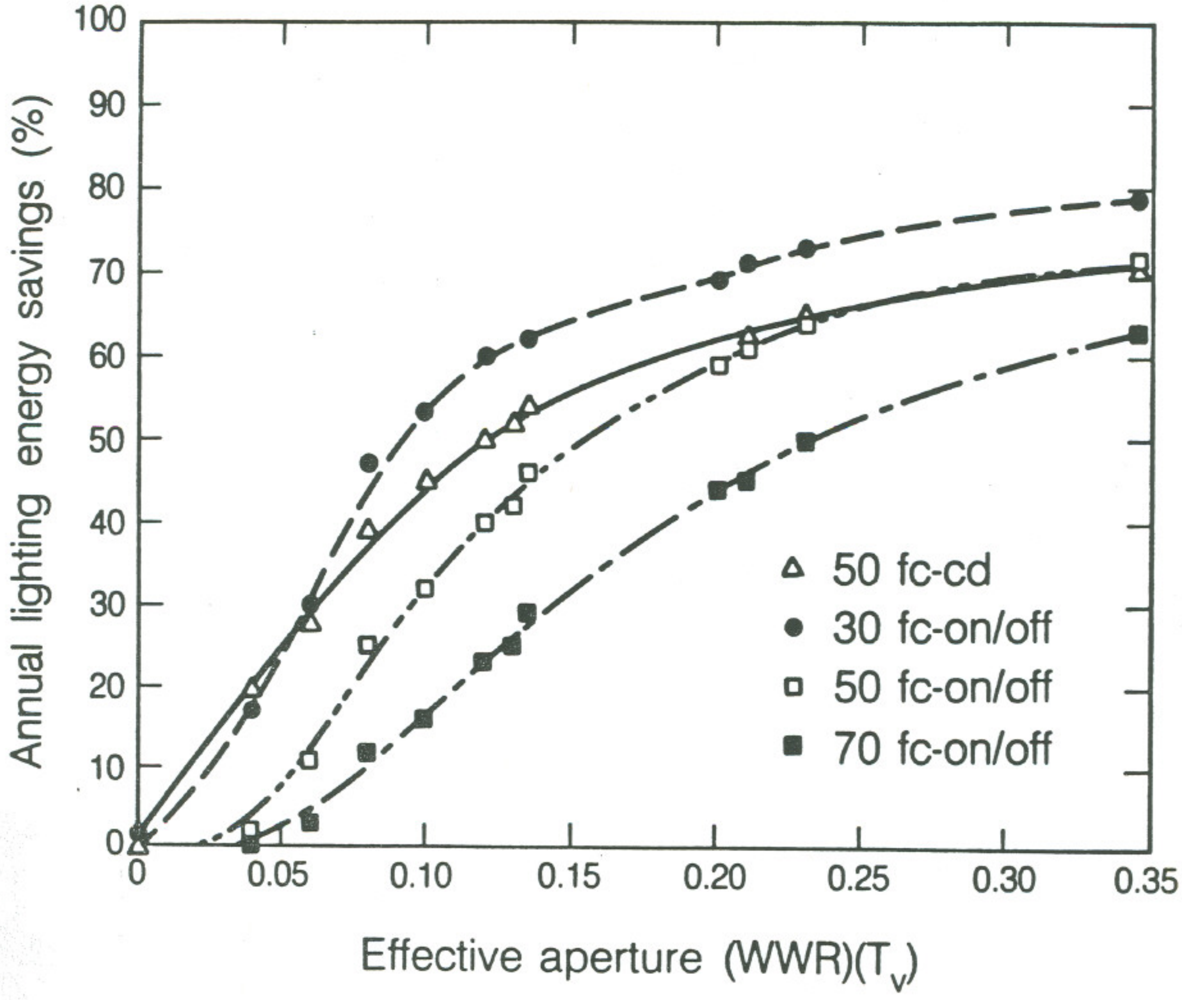
- Increasing window area and/or transmittance to increase daylighting savings reaches a point beyond which total energy consumption increases due to greater cooling loads.
- Control of solar gain is vital if daylighting strategies are to provide net energy benefits.
- Windows with managed window shading devices but without daylighting controls may require less energy than unmanaged windows with daylighting.
- Daylighting may not always be a "cooler" light source than fluorescent lighting--the conditions under which this statement holds true depend on the details of window management and installed lighting power.
- Daylighting strategies provide peak demand management opportunities, but the results are climate-sensitive.
- Daylighted buildings may have lower *total peak electrical demand,* but because of higher solar gain may require larger cooling systems than non-daylighted buildings with smaller windows.
- Installed lighting power and the lighting control system characteristics are major factors in determining the real value of daylighting strategies.
- Most of these conclusions are sensitive to climate, orientation, and other building modeling assumptions.

While we believe that these results represent a comprehensive perspective on this subject, we caution the reader that there are still very few measured building data to verify simulation results. Changes in base-case conditions and operating assumptions may also modify some conclusions.



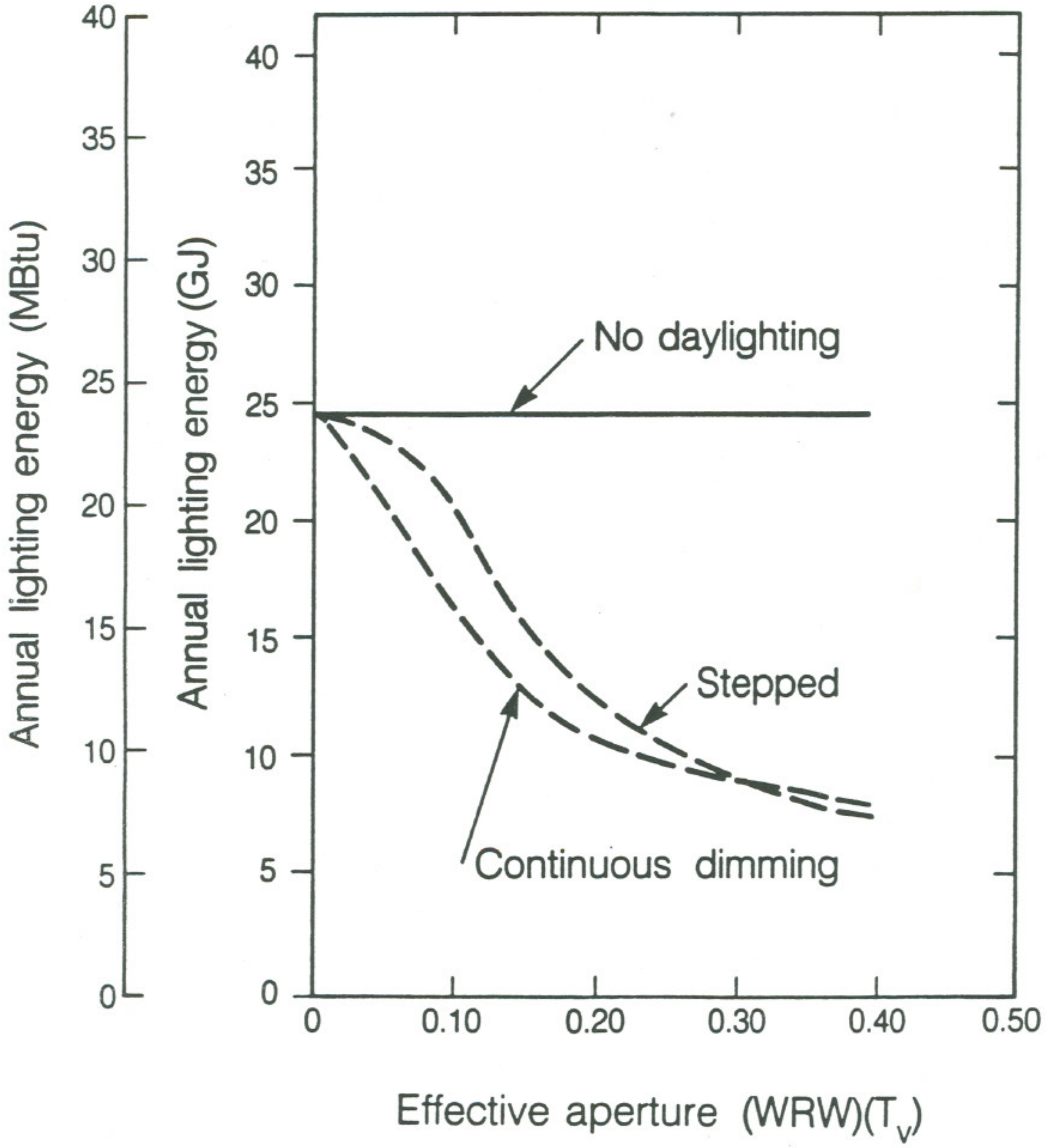
XBL 838-2960

Figure 6-1. Building module description.



XBL 847–9804

Figure 6-2. Annual electric lighting energy savings as a function of effective aperture in a perimeter zone with daylighting.



XBL 847-9806

Figure 6-3. A comparison between the effects of stepped switching and continuous dimming on annual electric lighting energy consumption with daylighting.

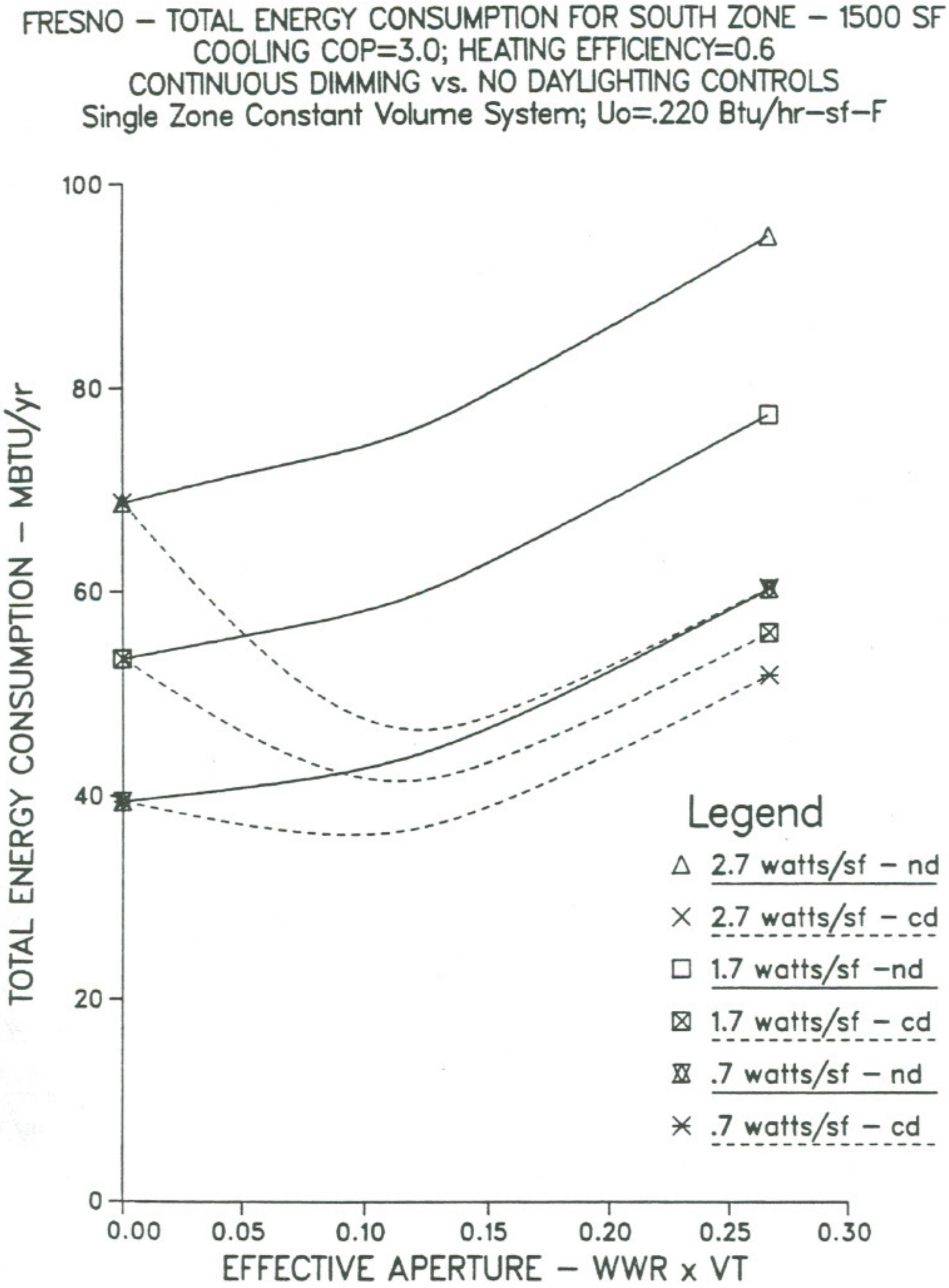


Figure 6-4. Net annual energy consumption as a function of effective aperture at three electric lighting power densities. South zone, Fresno.

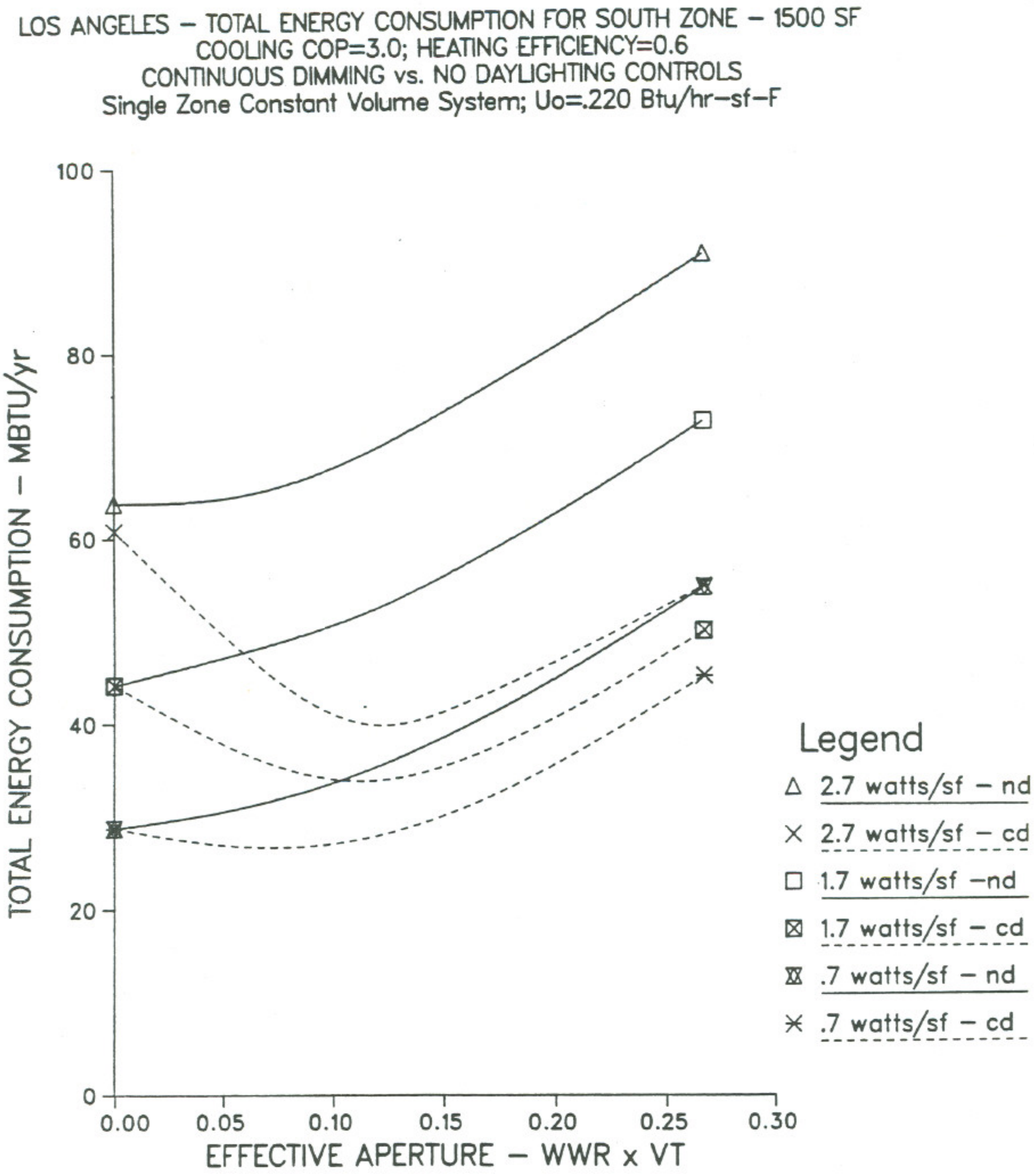


Figure 6-5. Net annual energy consumption as a function of effective aperture at three electric lighting power densities. South zone, Los Angeles.

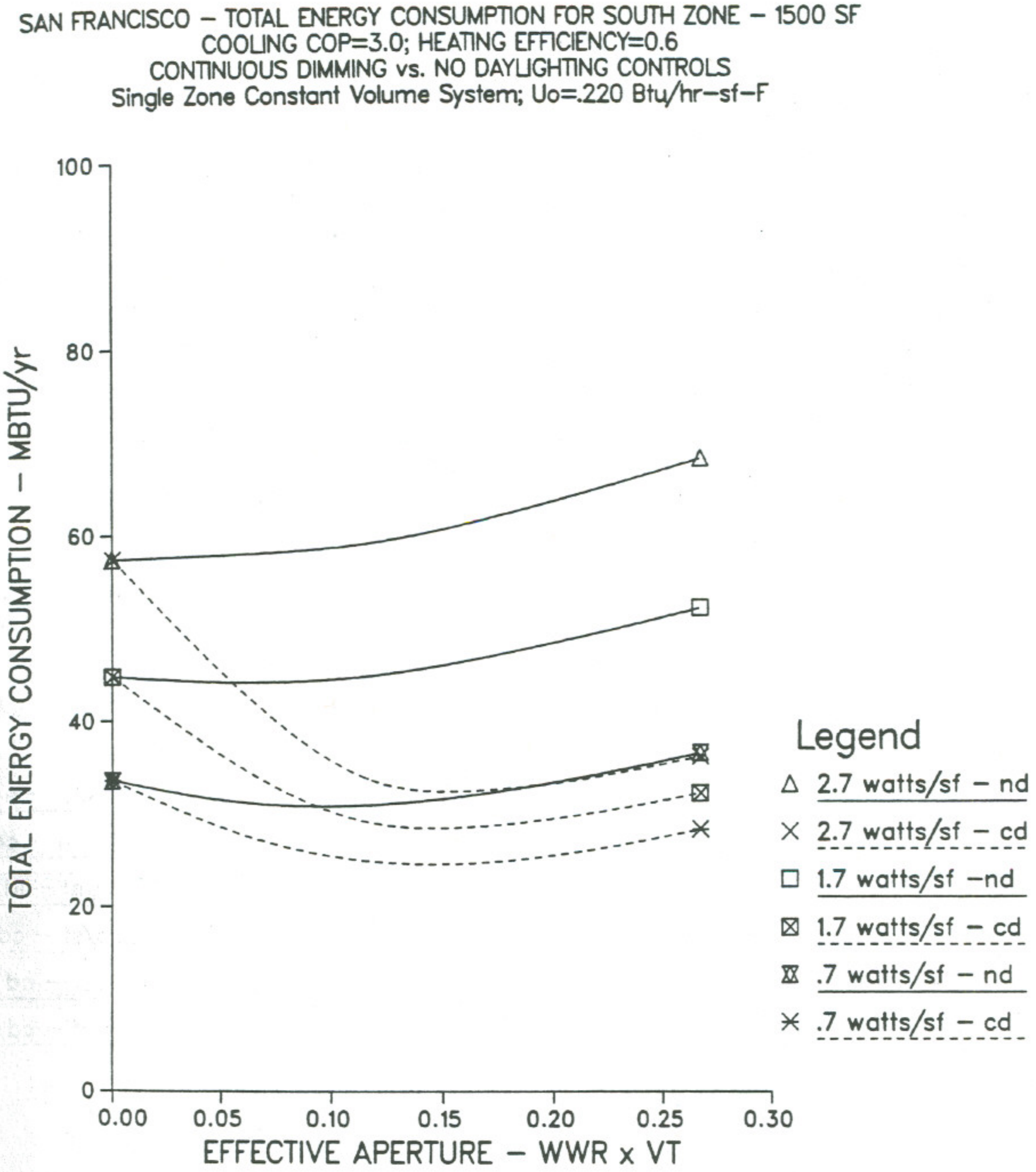


Figure 6-6. Net annual energy consumption as a function of effective aperture at three electric lighting power densities. South zone, San Francisco.

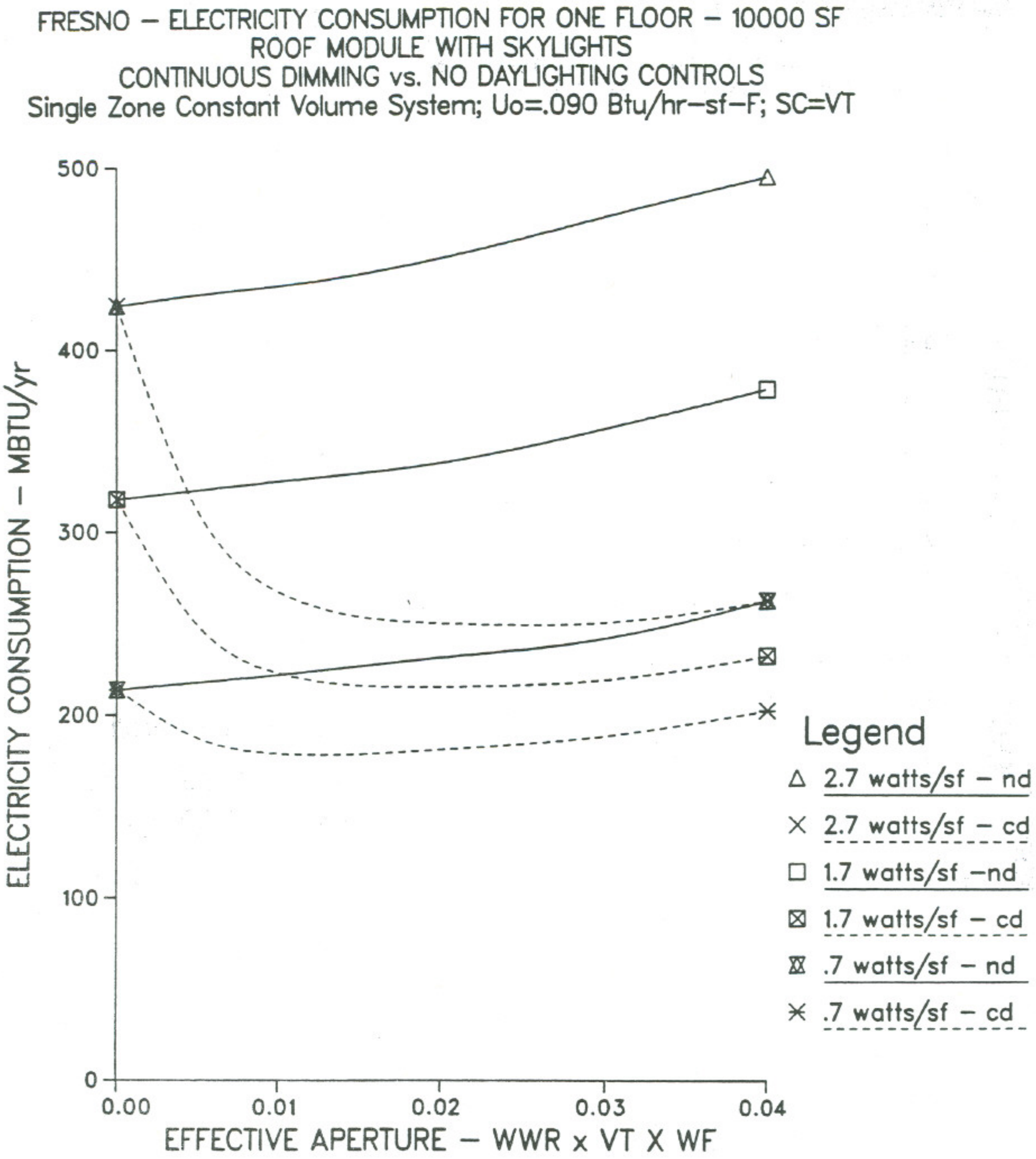


Figure 6-7. Net annual electricity consumption as a function of effective aperture at three electric lighting power densities, Skylighted zone, Fresno.

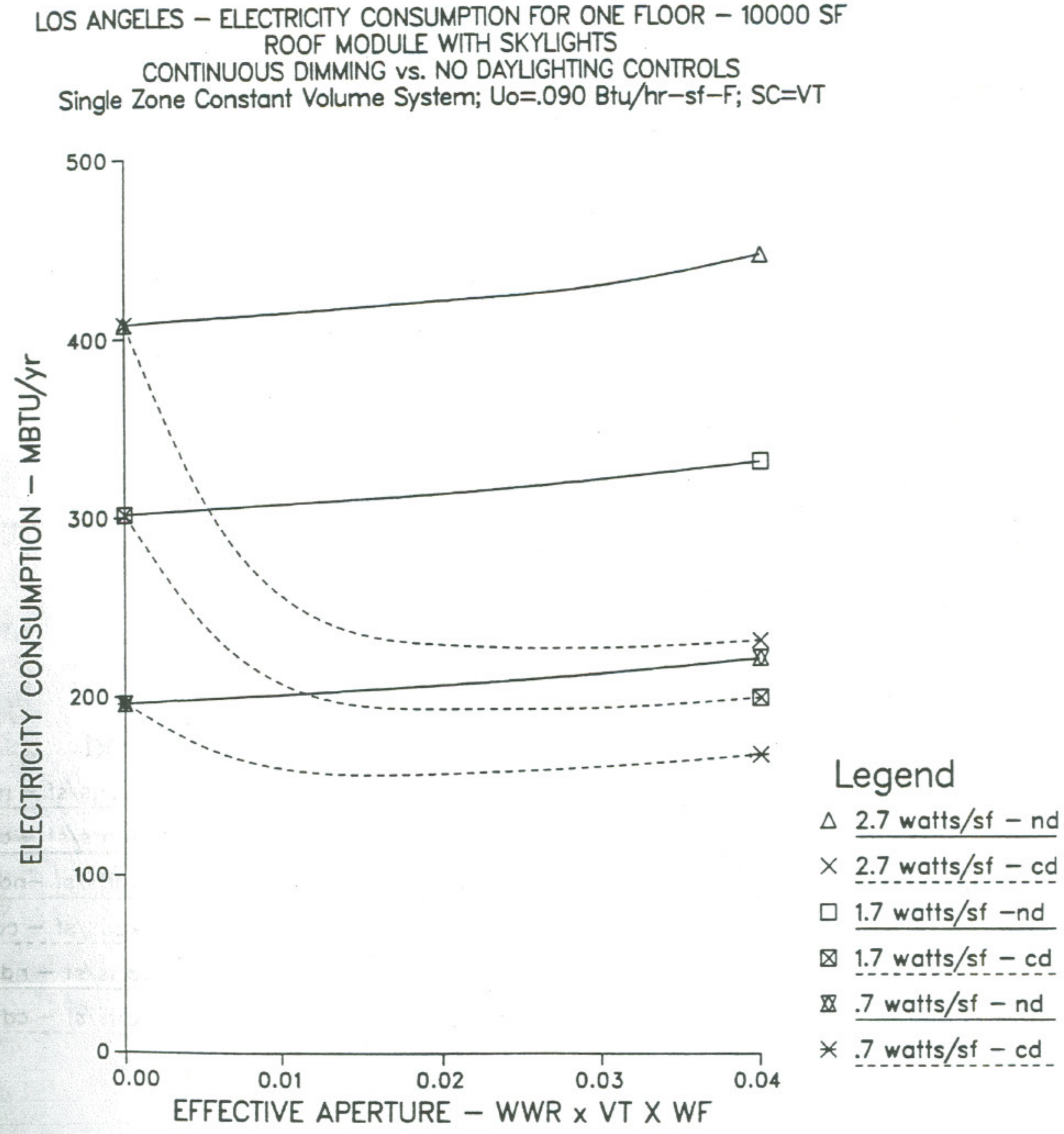


Figure 6-8. Net annual electricity consumption as a function of effective aperture at three electric lighting power densities, Skylighted zone, Los Angeles.

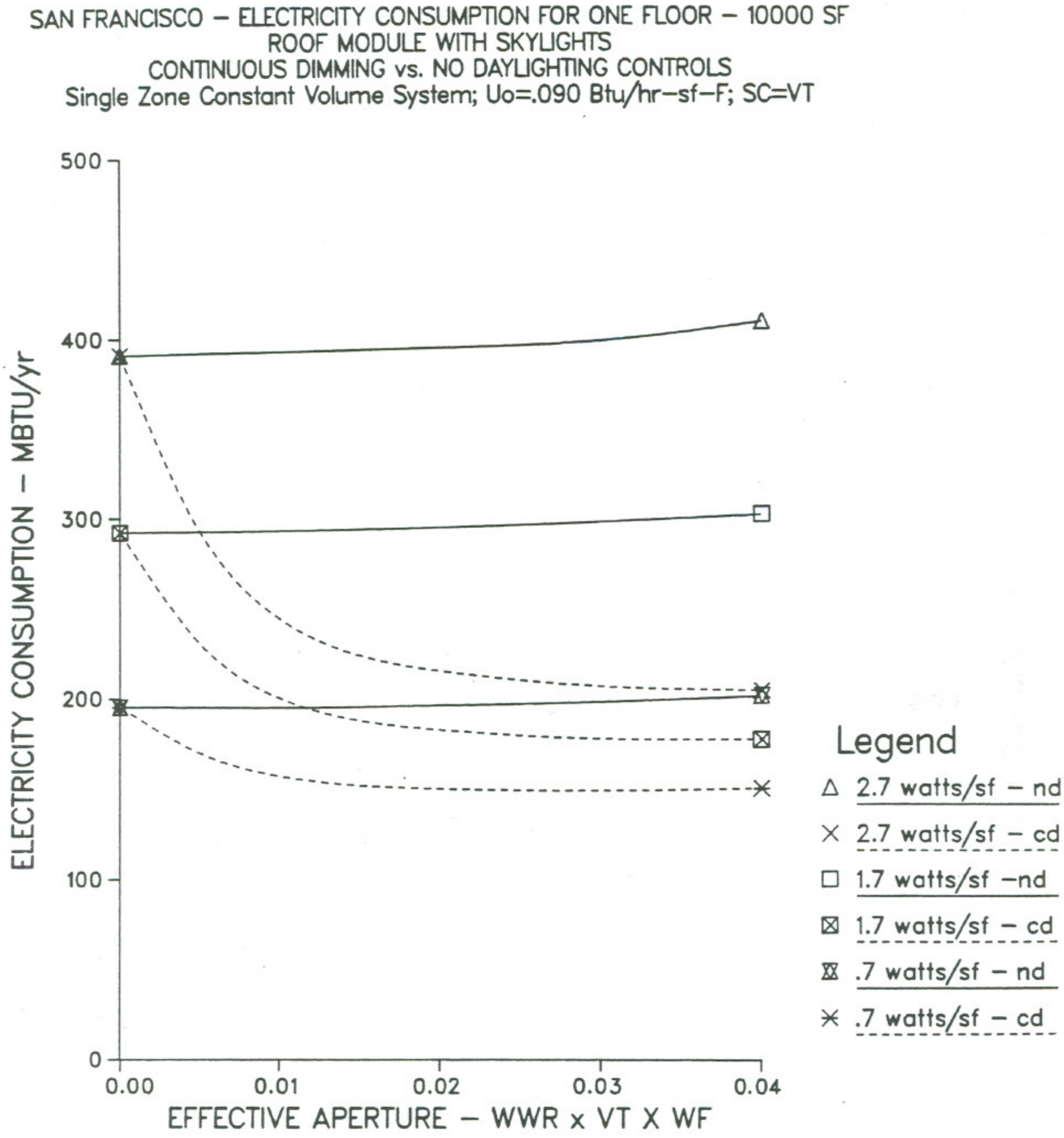


Figure 6-9. Net annual electricity consumption as a function of effective aperture at three electric lighting power densities, Skylighted zone, San Francisco.

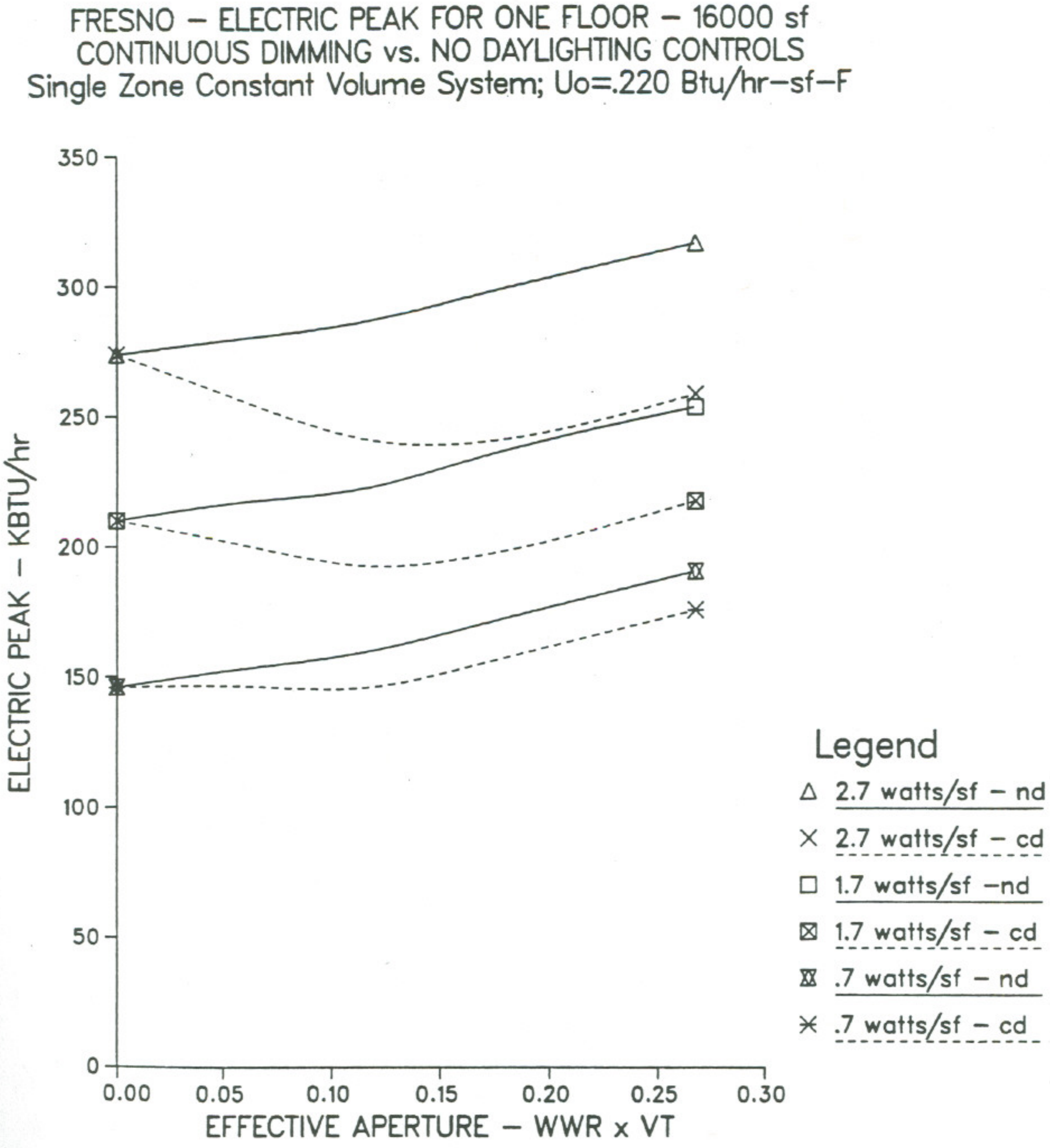


Figure 6-10. Annual electrical peak demand as a function of effective aperture at three electric lighting power densities. Total five zone module with vertical fenestration in perimeter zones, Fresno.

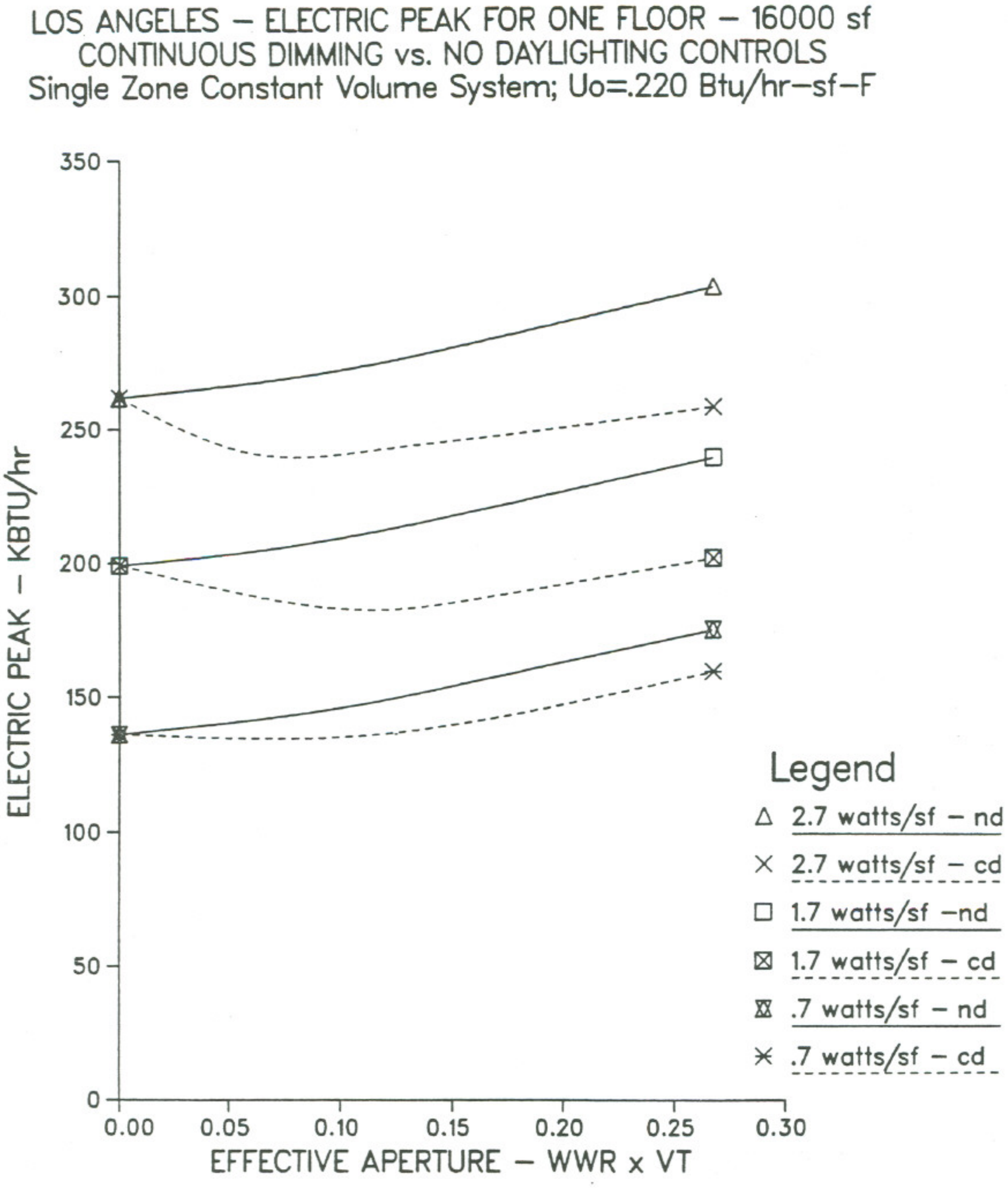


Figure 6-11. Annual electrical peak demand as a function of effective aperture at three electric lighting power densities. Total five zone module with vertical fenestration in perimeter zones. Los Angeles.

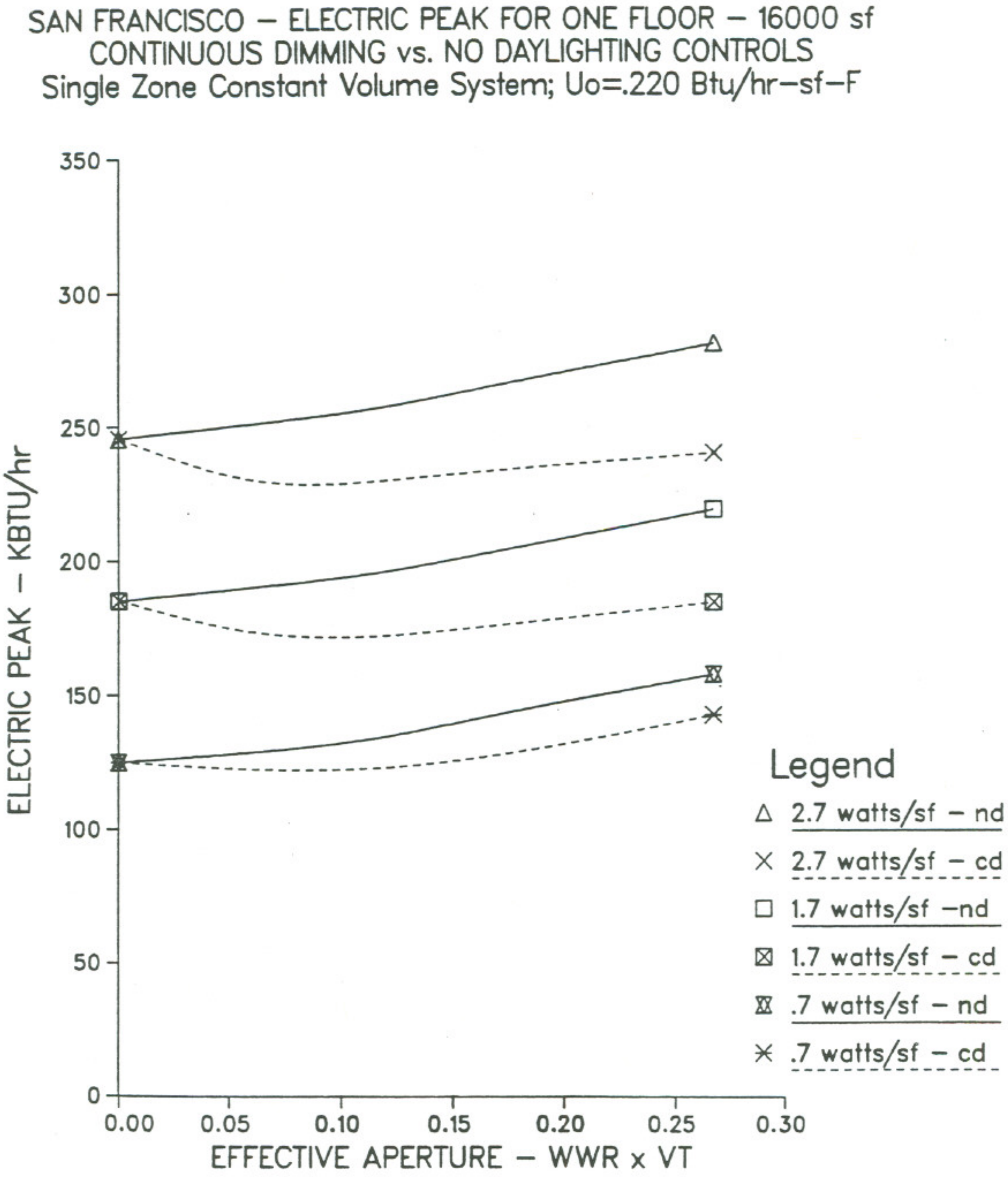


Figure 6-12. Annual electrical peak demand as a function of effective aperture at three electric lighting power densities. Total five zone module with vertical fenestration in perimeter zones, San Francisco.

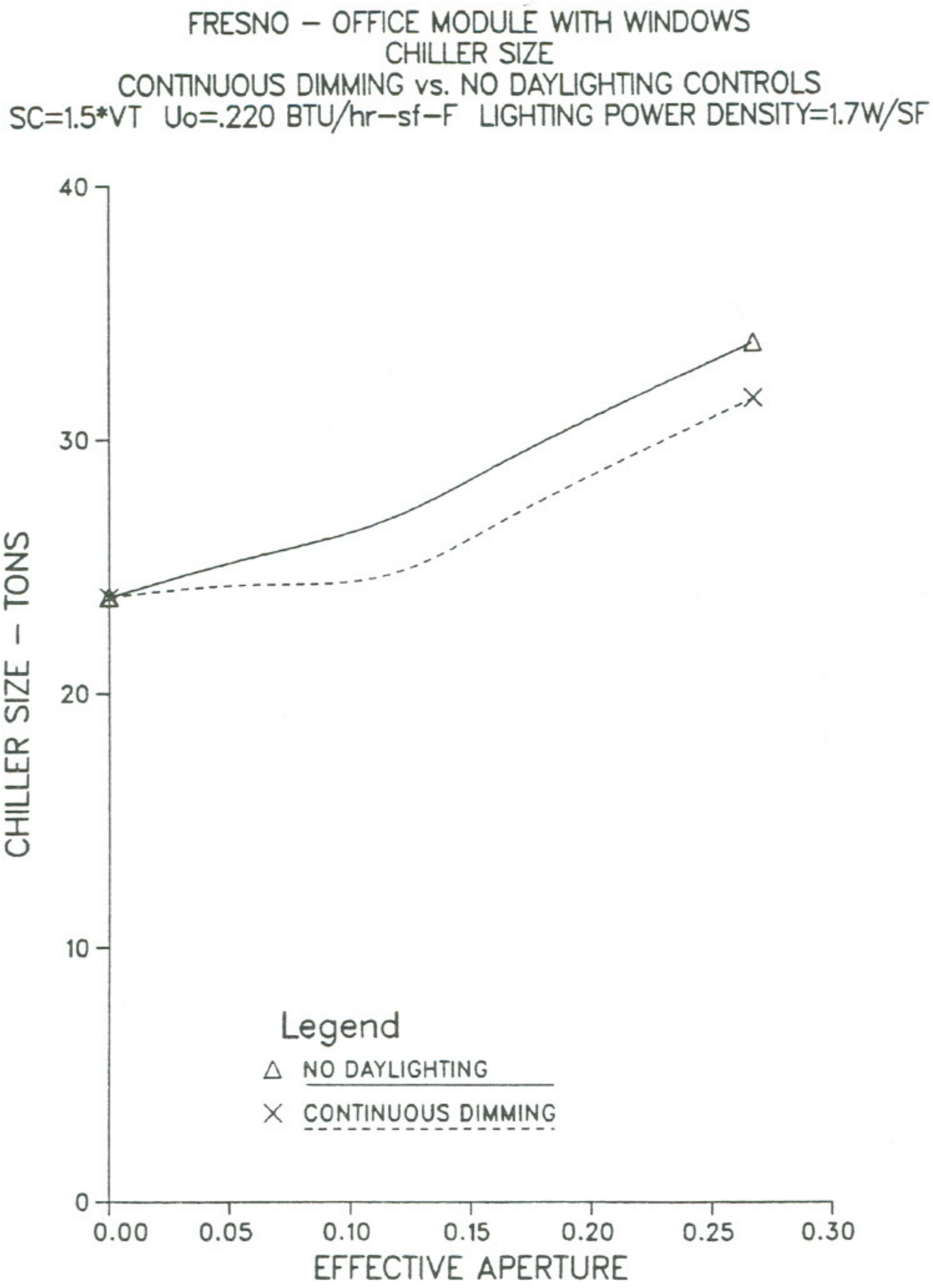


Figure 6-13. Chiller size as a function of effective aperture. Total five zone module with vertical fenestration in perimeter zones, Fresno.

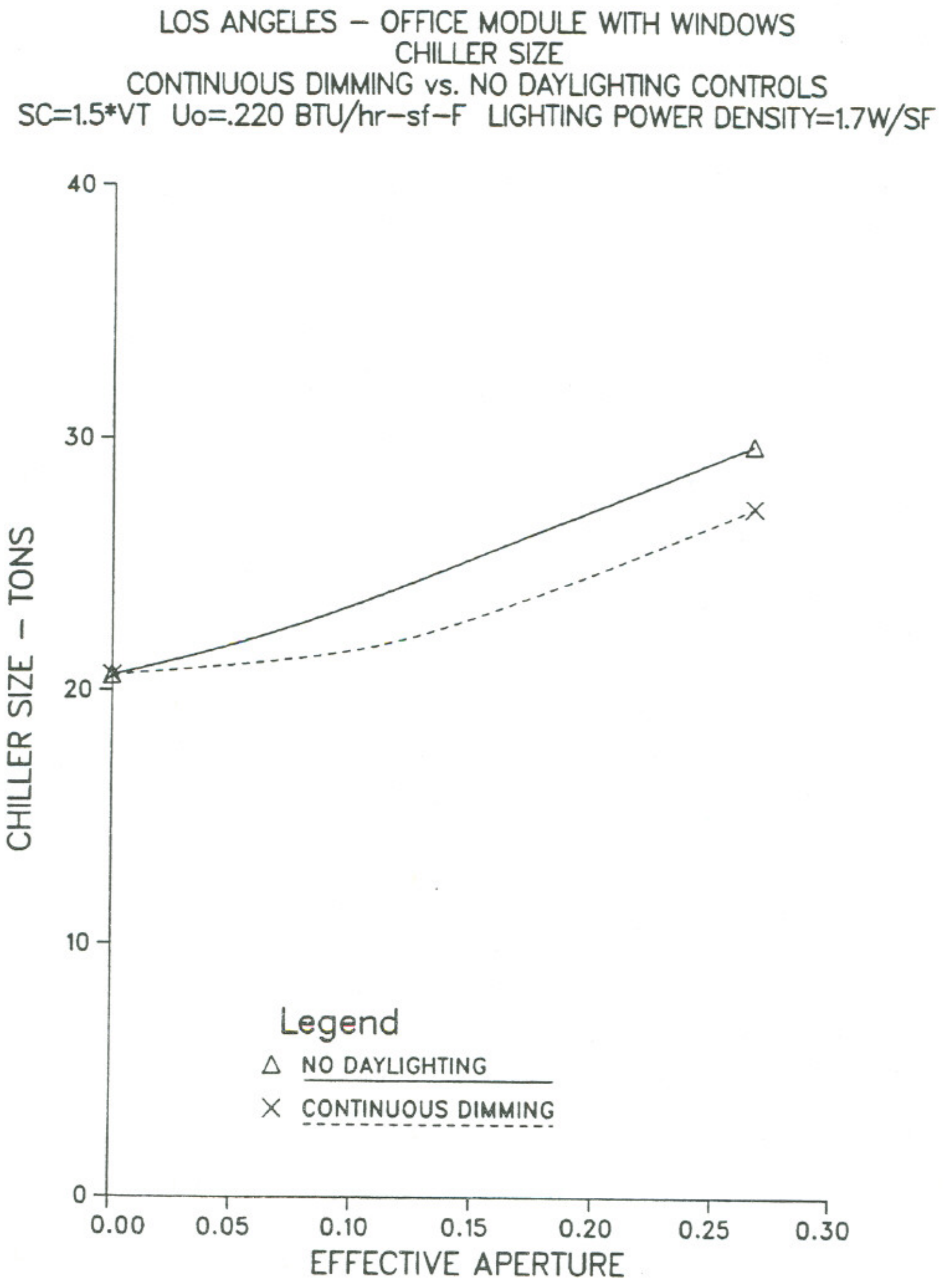


Figure 6-14. Chiller size as a function of effective aperture. Total five zone module with vertical fenestration in perimeter zones, Los Angeles.

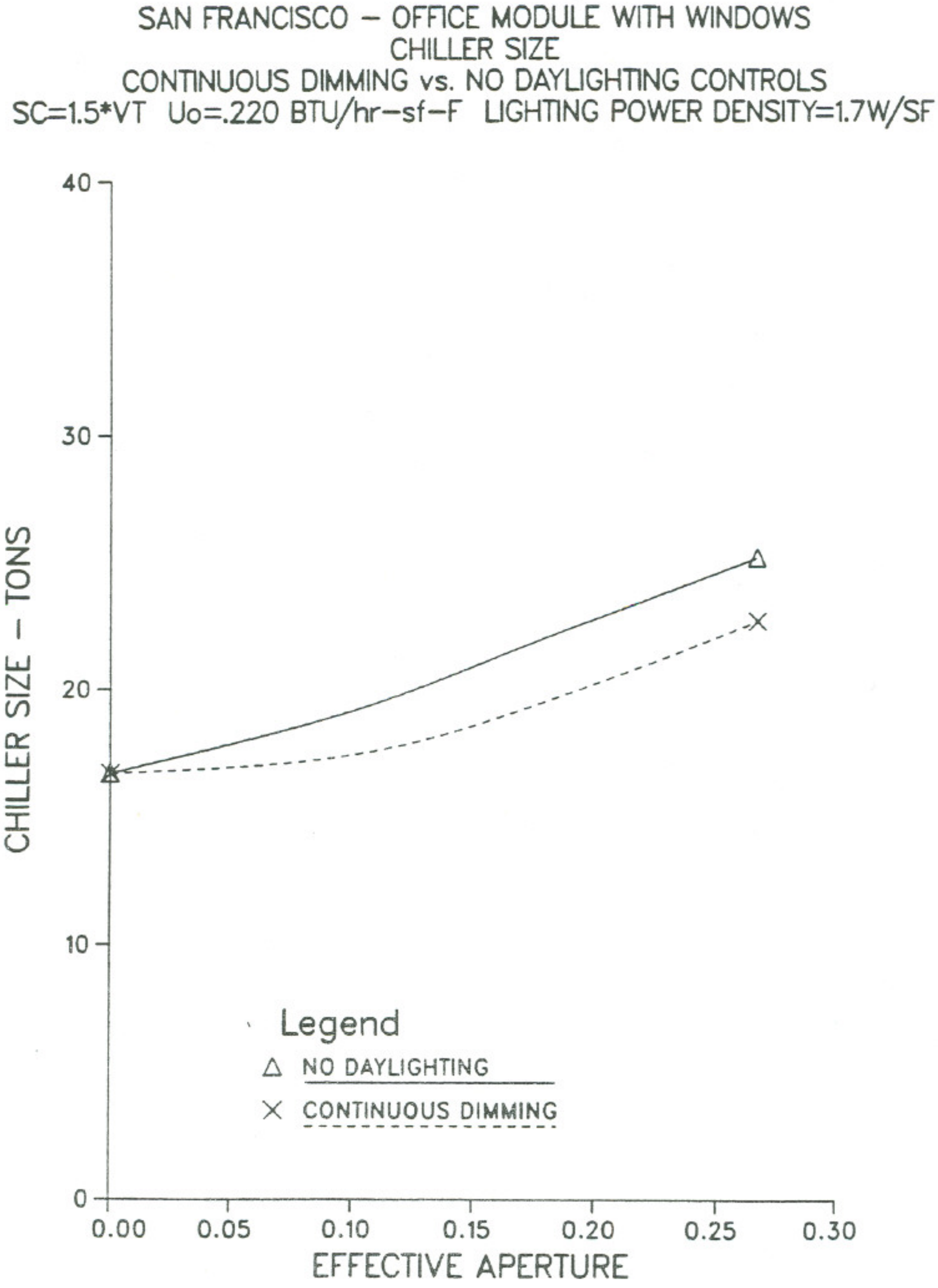


Figure 6-15. Chiller size as a function of effective aperture. Total five zone module with vertical fenestration in perimeter zones, San Francisco.

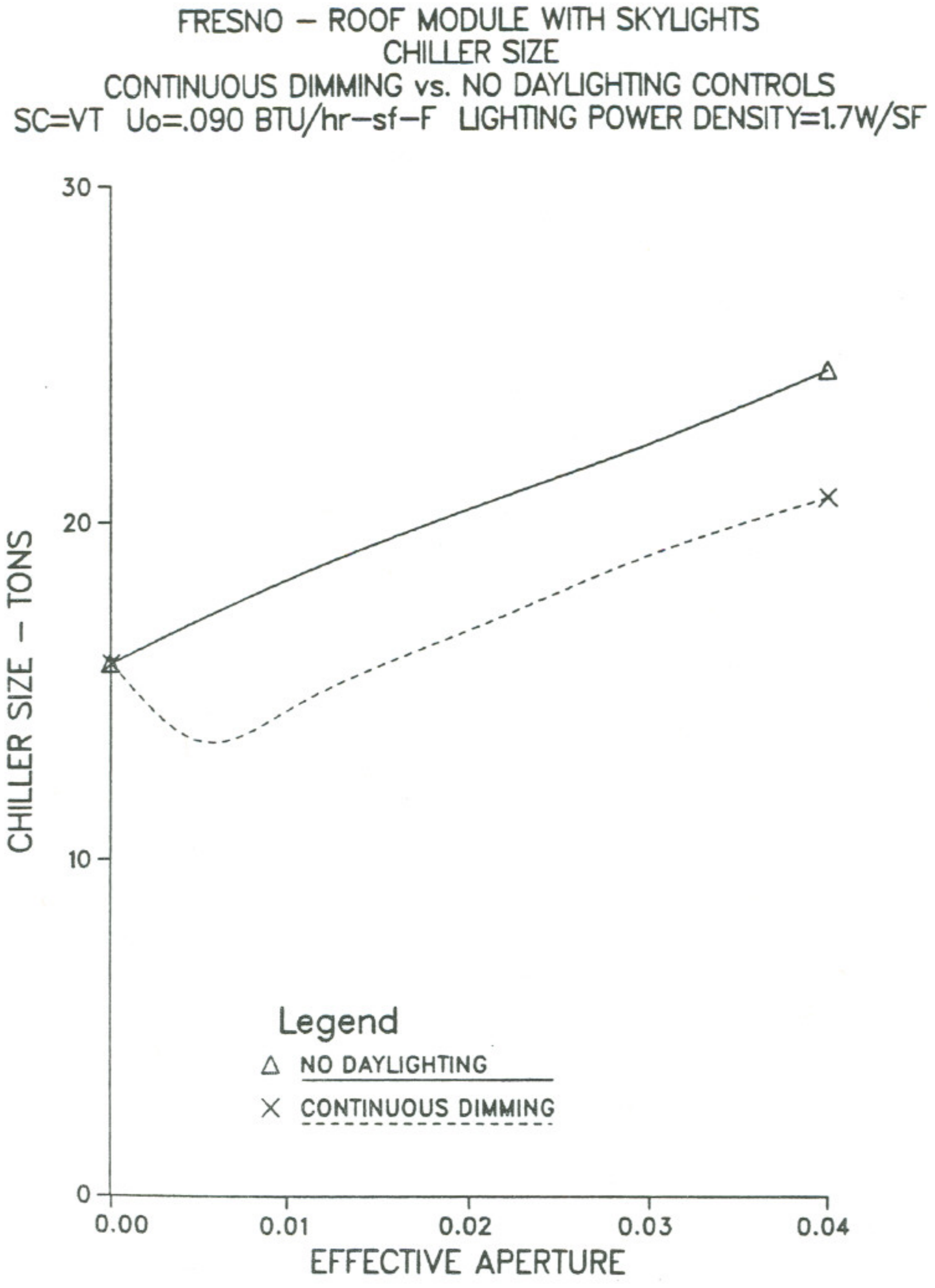


Figure 6-16. Chiller size as a function of effective aperture. Skylighted zone, Fresno.

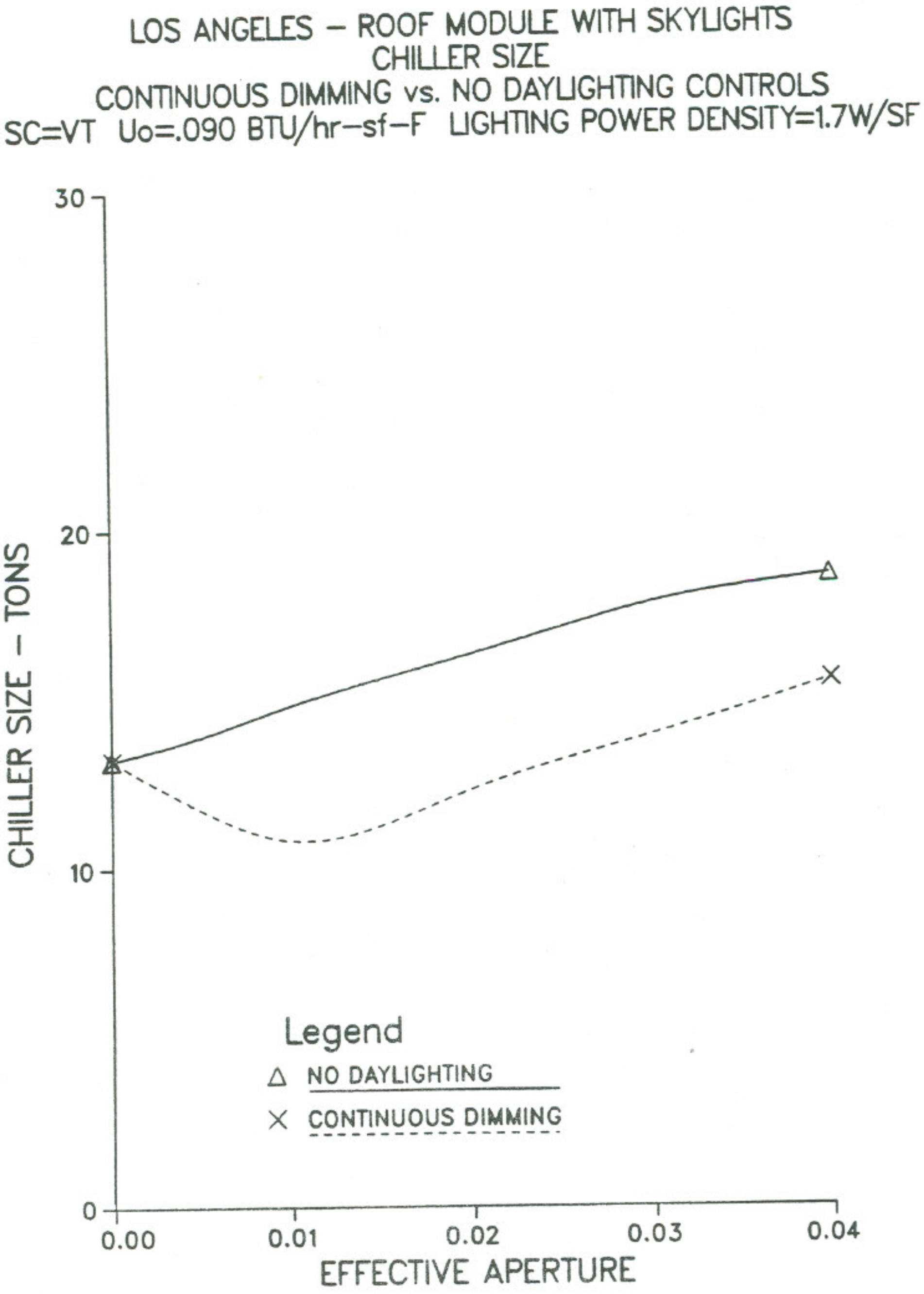


Figure 6-17. Chiller size as a function of effective aperture. Skylighted zone, Los Angeles.

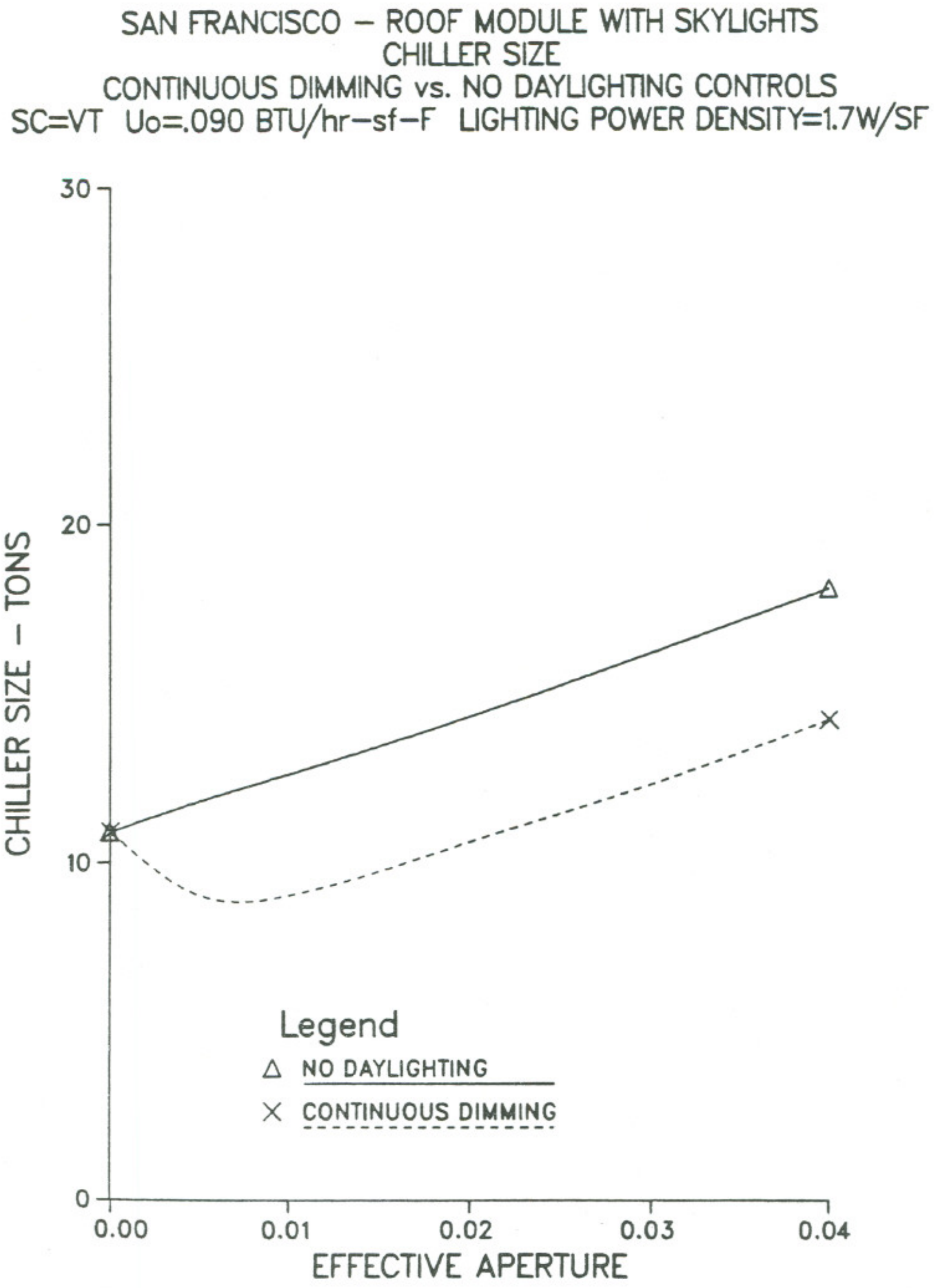


Figure 6-18. Chiller size as a function of effective aperture. Skylighted zone, San Francisco.

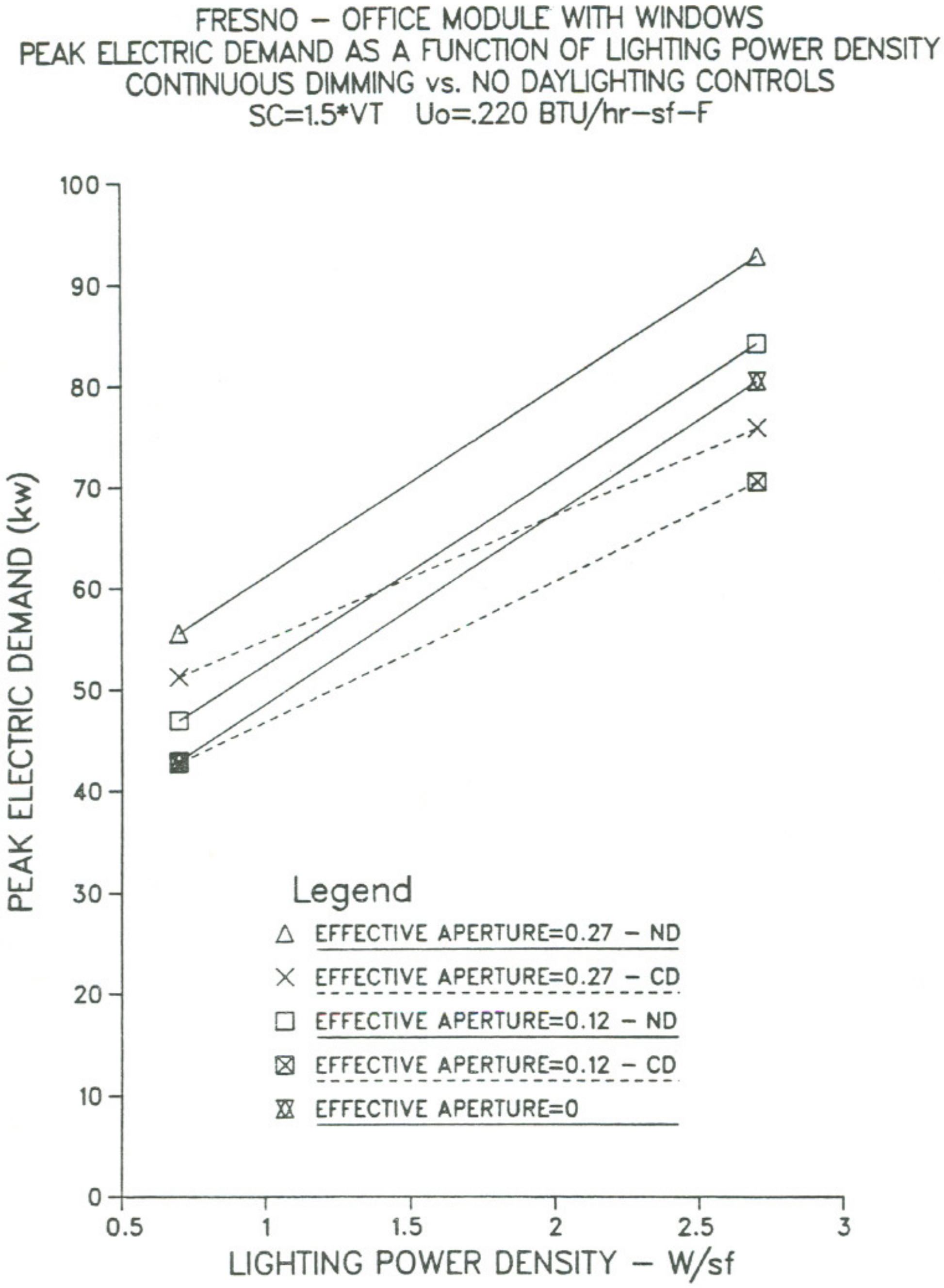


Figure 6-19. Electrical peak demand as a function of installed electric lighting power density at three effective apertures. Total five zone perimeter zones, Fresno.

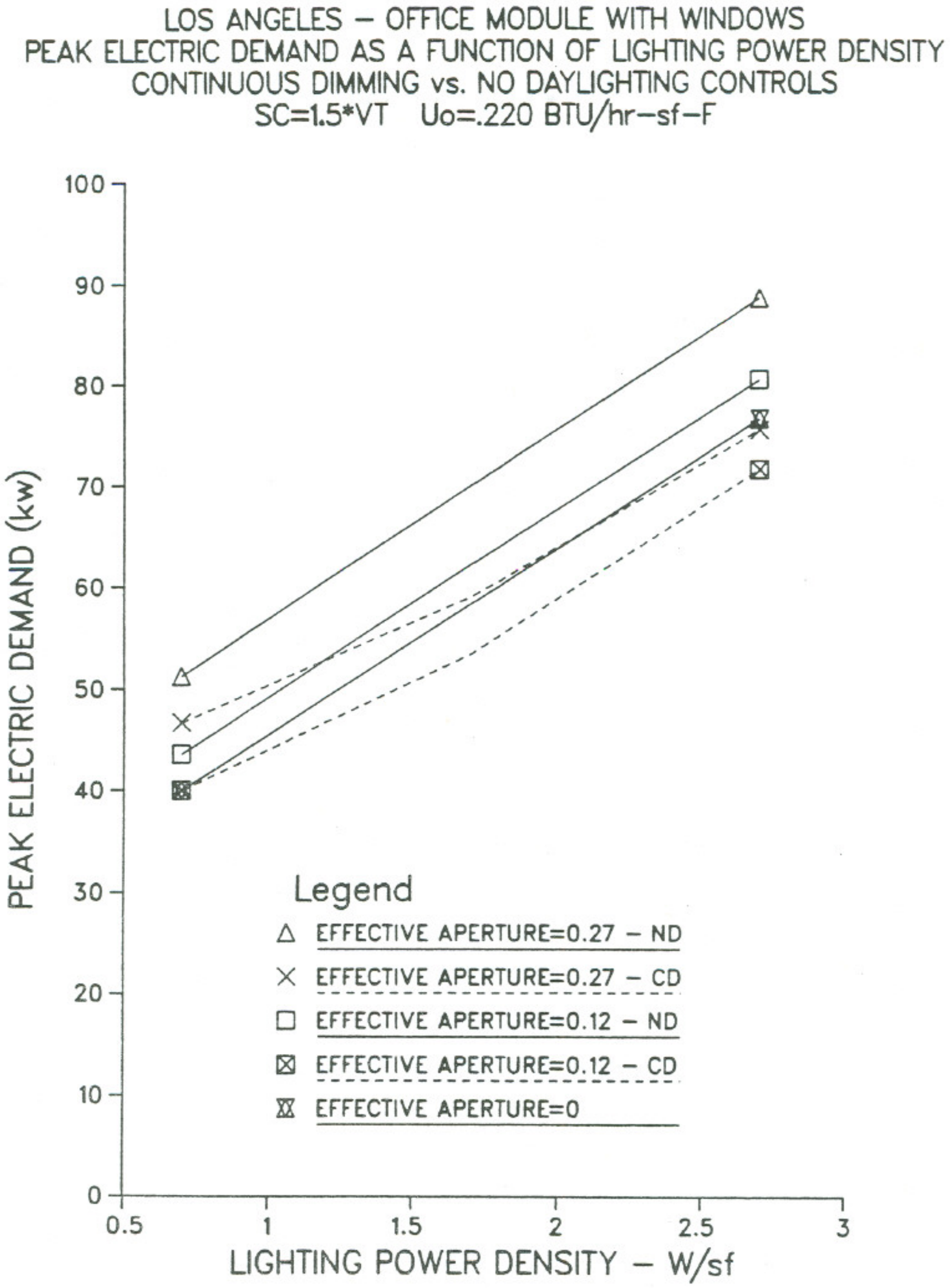


Figure 6-20. Electrical peak demand as a function of installed electric lighting power density at three effective apertures. Total five zone perimeter zones, Los Angeles.

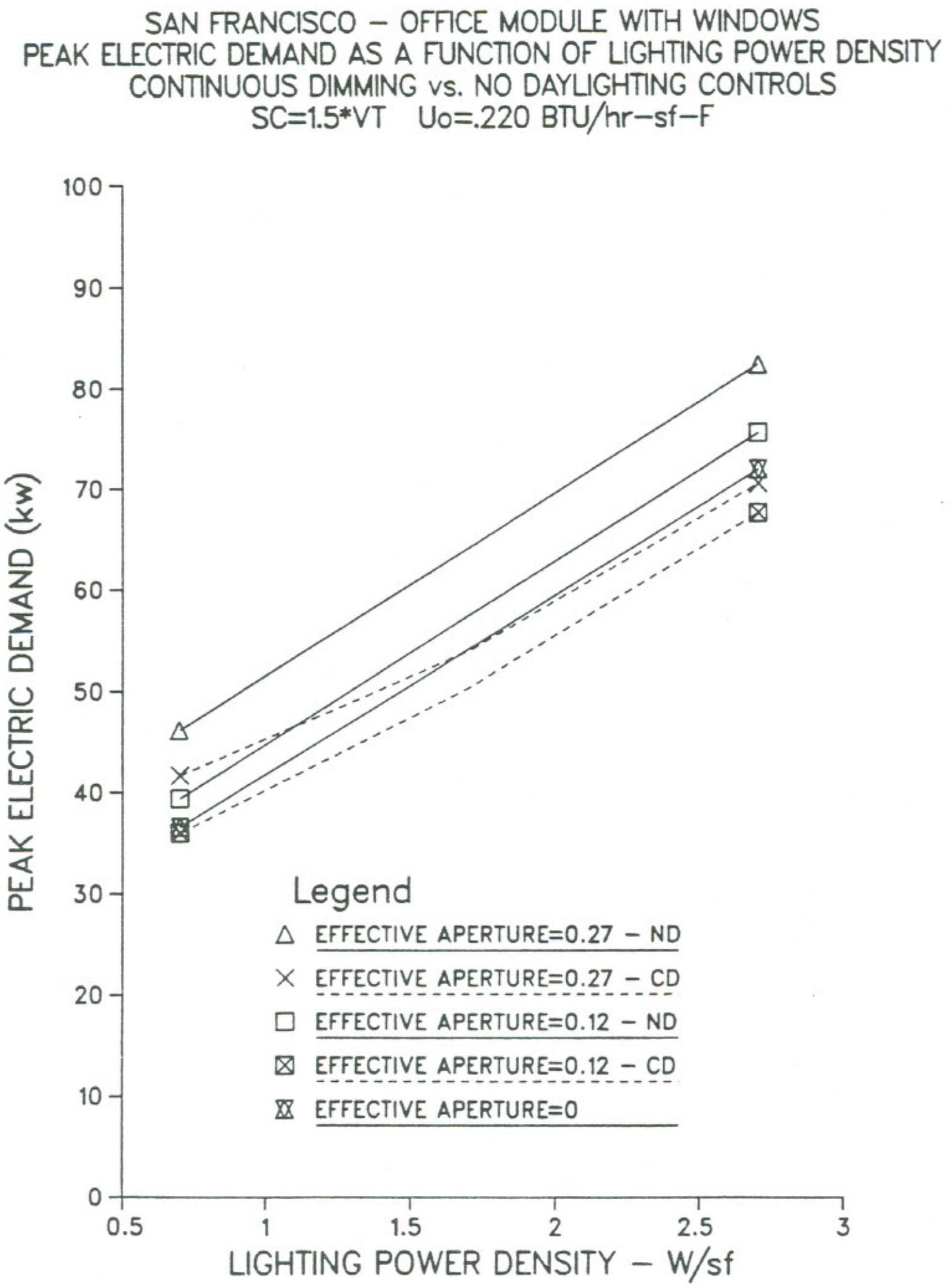


Figure 6-21. Electrical peak demand as a function of installed electric lighting power density at three effective apertures. Total five zone perimeter zones, San Francisco.

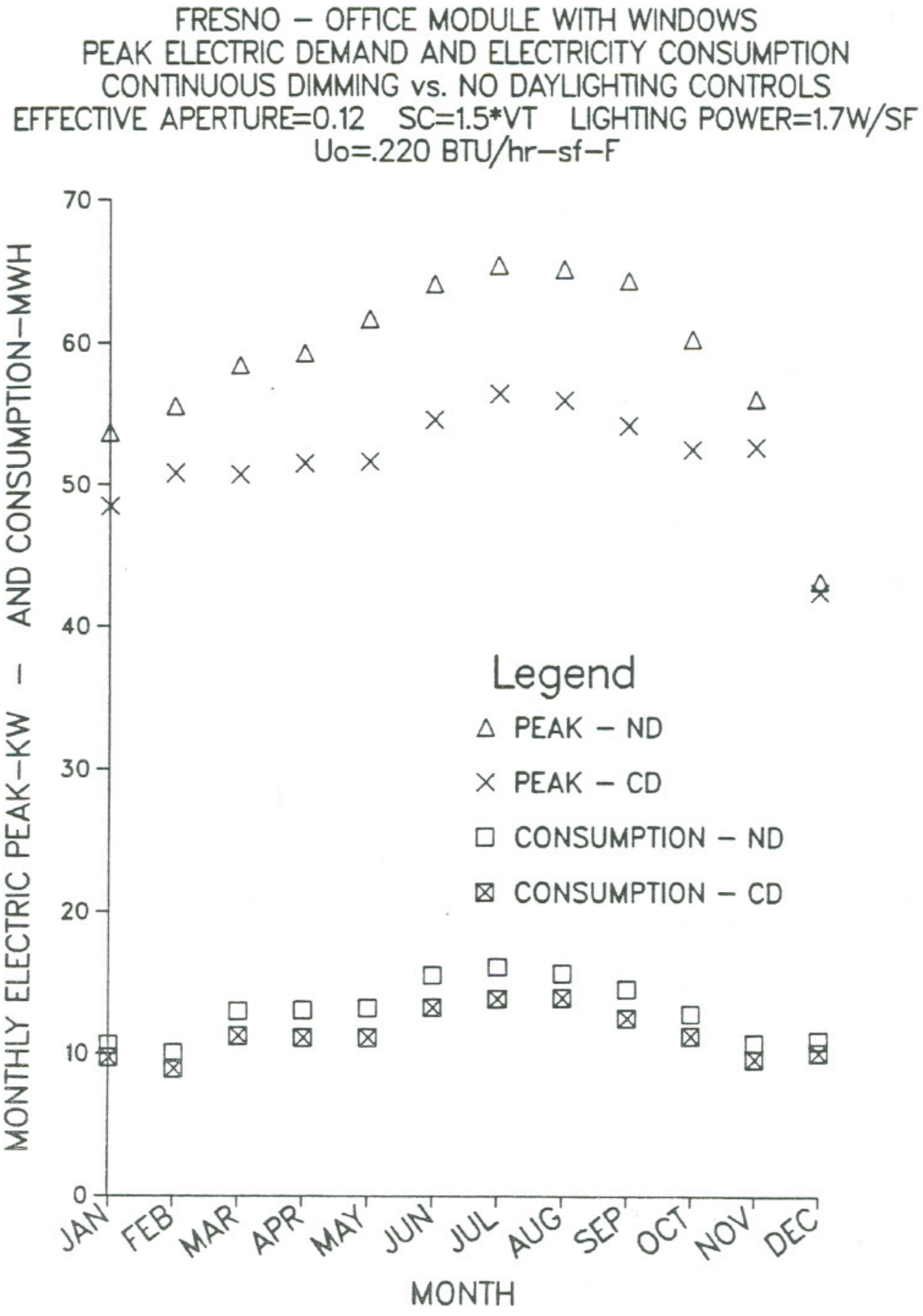


Figure 6-22. Monthly electricity consumption and peak demand for $A_e = 0.12$ and lighting power density of 1.7 W/ft^2. Total five zone module with vertical fenestration in perimeter zone. Fresno.

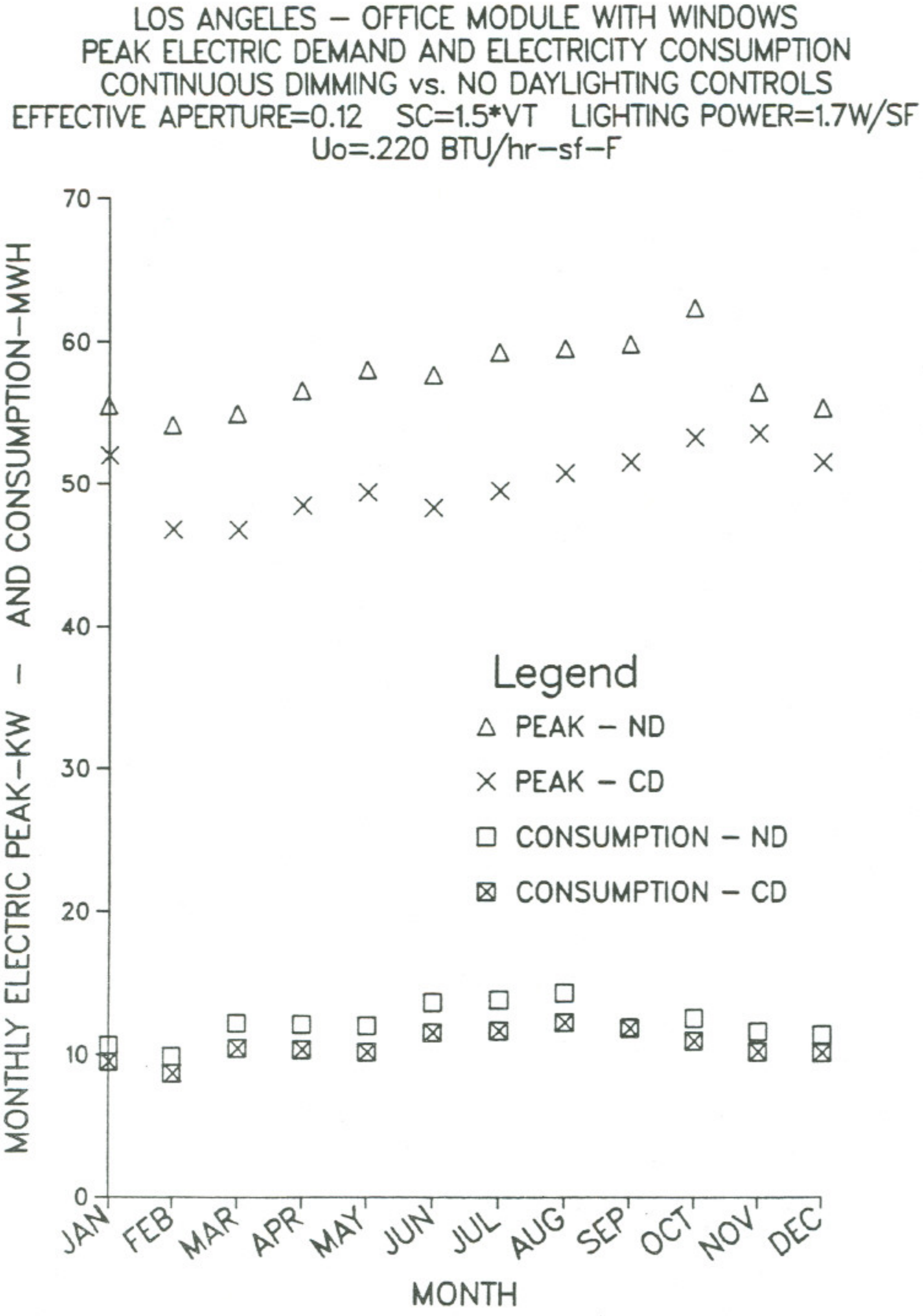


Figure 6-23. Monthly electricity consumption and peak demand for $A_e = 0.12$ and lighting power density of 1.7 W/ft^2. Total five zone module with vertical fenestration in perimeter zone. Los Angeles.

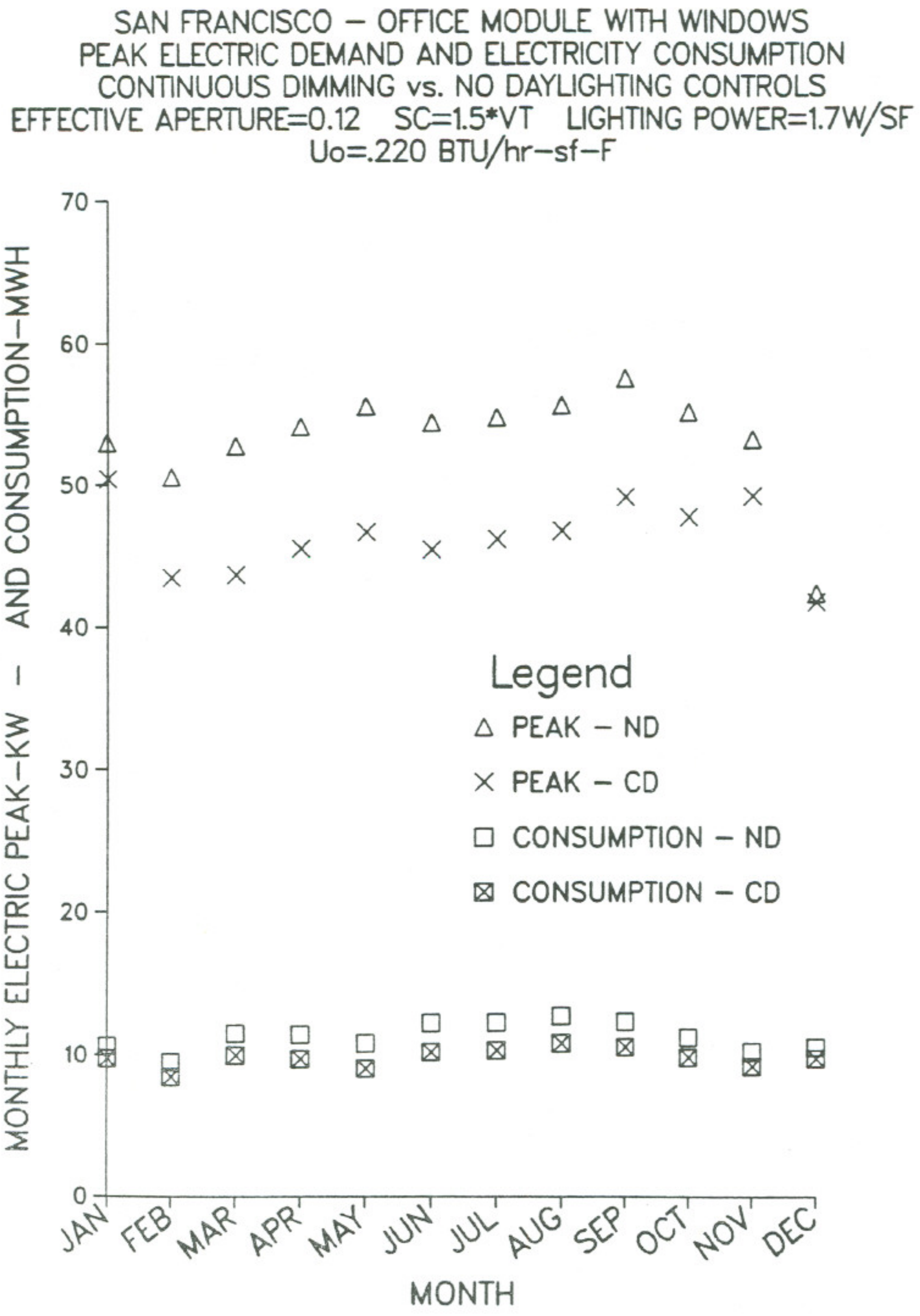


Figure 6-24. Monthly electricity consumption and peak demand for $A_e = 0.12$ and lighting power density of 1.7 W/ft^2. Total five zone module with vertical fenestration in perimeter zone. San Francisco.

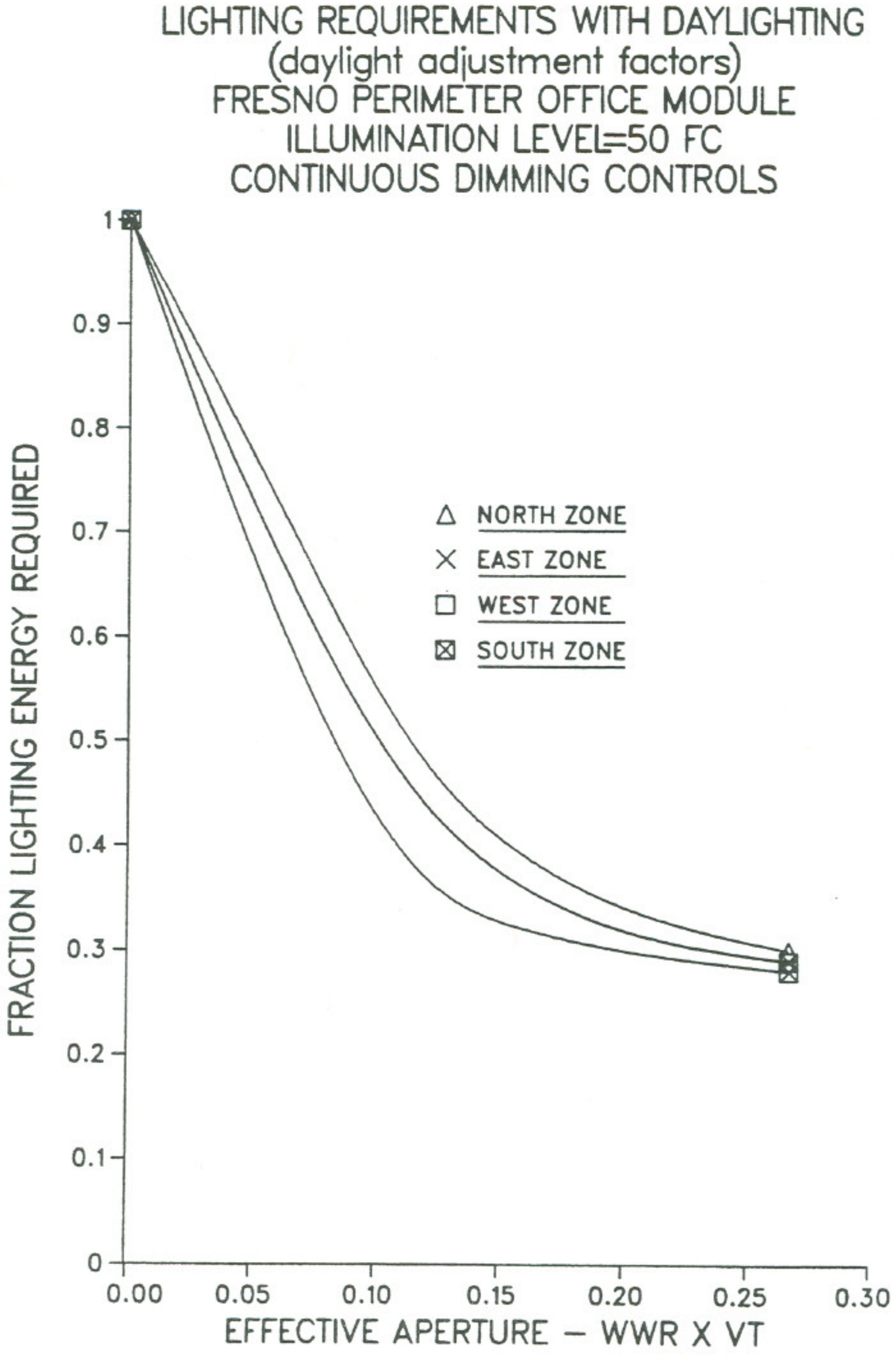


Figure 6-25. The fraction of annual electric lighting energy required when daylight is used, as a function of effective aperture. Fresno.

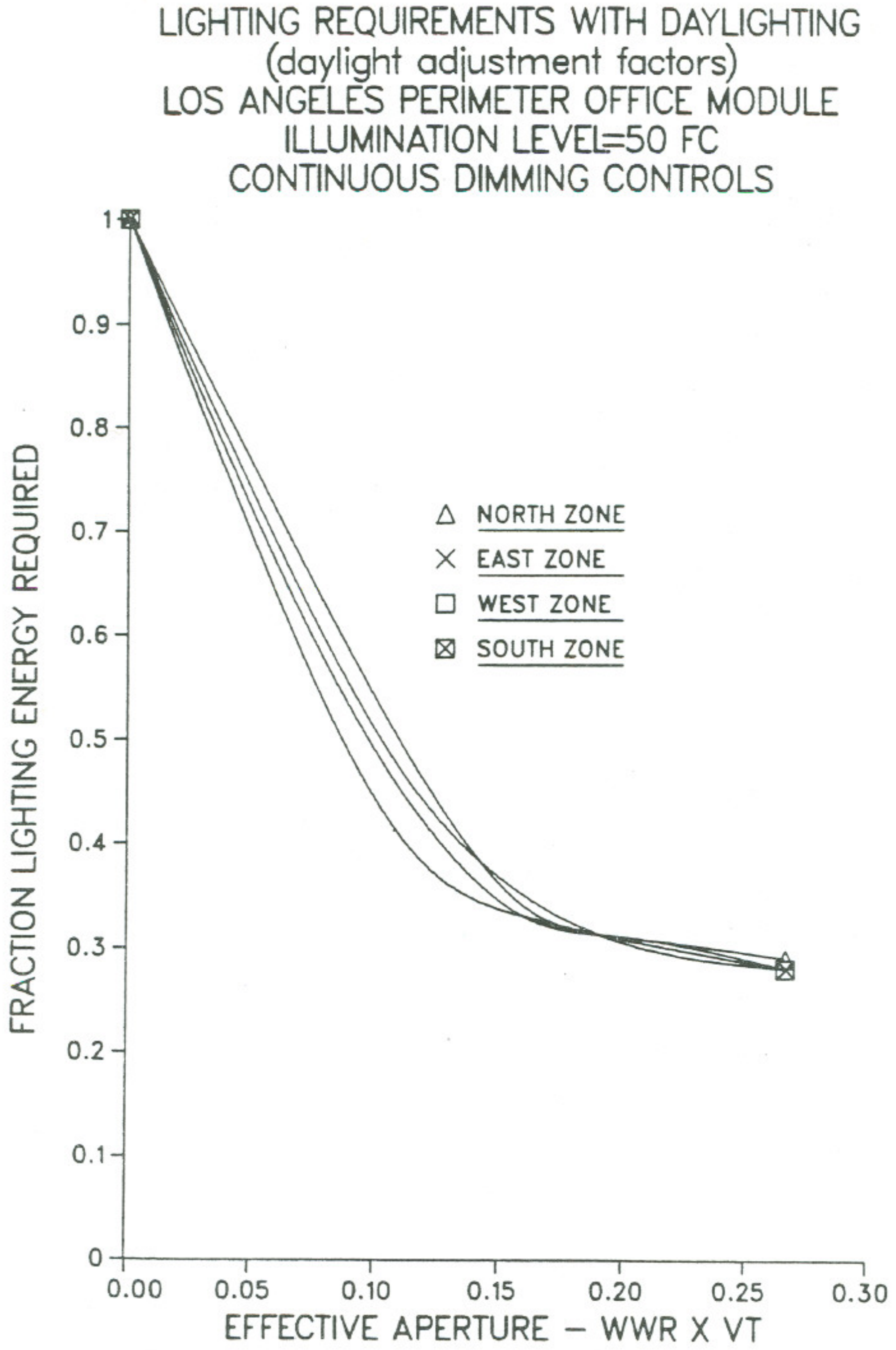


Figure 6-26. The fraction of annual electric lighting energy required when daylight is used, as a function of effective aperture, Los Angeles.

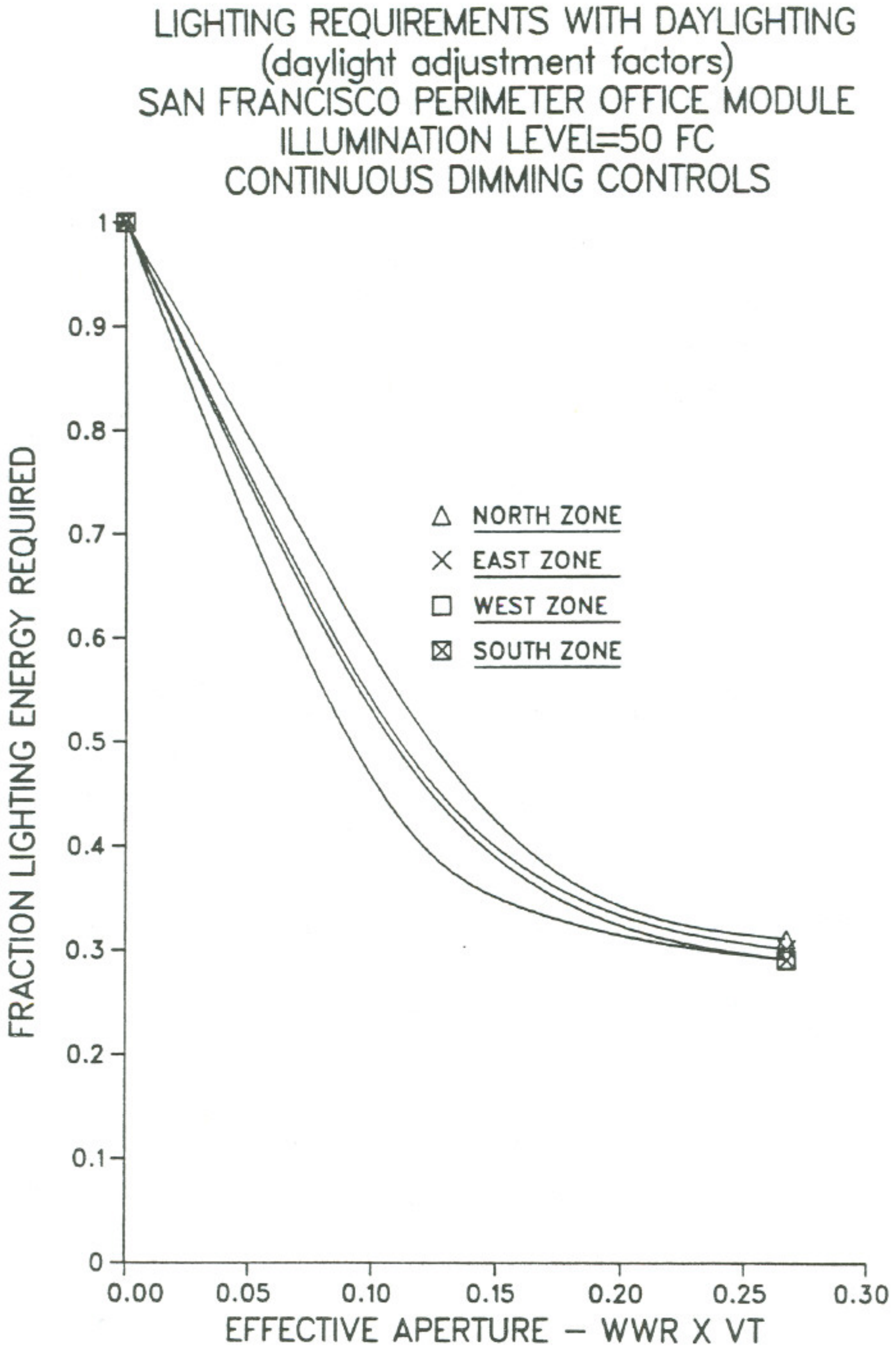


Figure 6-27. The fraction of annual electric lighting energy required when daylight is used, as a function of effective aperture by orientation, San Francisco.

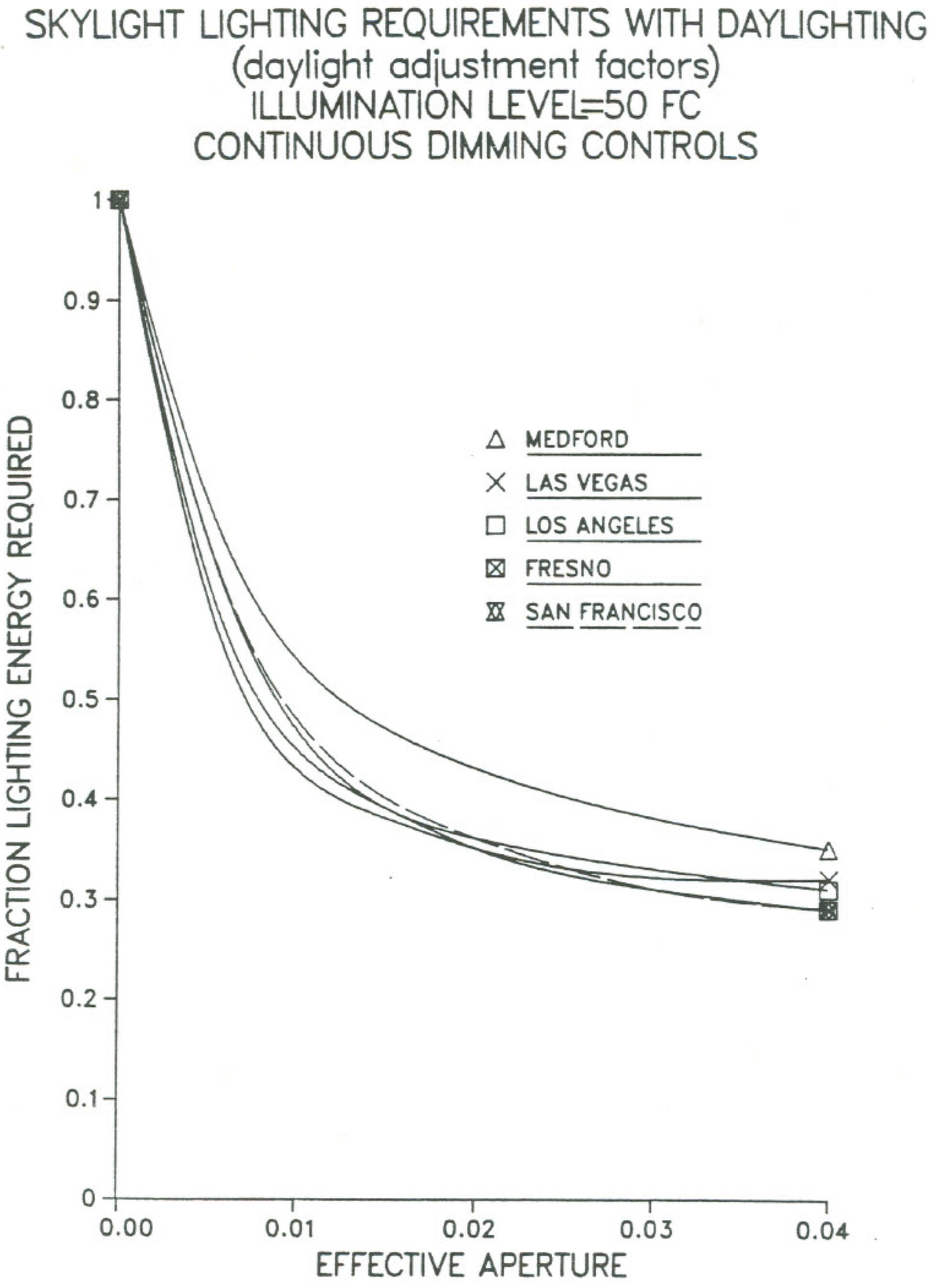


Figure 6-28. The fraction of annual electric lighting energy required when daylight is used, as a function of effective aperture for various climates.

Table 6.1 Regression Coefficients: Perimeter Zone with

Vertical Windows--Fresno

		Perimeter Zone (1500 ft^2) Coil Load			Perimeter Zone
		Cooling Peak	Cooling Energy	Heating Energy	Total Energy*
b_1	N	29.31	6.55	22.11	49.34
	S	59.28	33.06	10.49	44.30
	E	55.36	28.55	13.96	47.32
	W	74.70	29.40	14.54	53.63
b_2	N	44.84	70.88	-6.71	21.63
	S	86.57	122.11	-7.15	47.82
	E	91.78	125.14	-6.92	50.33
	W	92.20	134.04	-7.19	54.10
b_3	N	2.75	5.66	-1.02	9.59
	S	2.33	5.73	-0.53	10.43
	E	2.47	5.67	-0.65	10.15
	W	2.10	5.78	-0.69	10.10
b_4		9.38	4.68	1.57	9.45
Mean		52.46	52.97	3.17	62.70
r^2		0.960	0.984	0.934	0.976
σ		3.32	2.87	0.568	2.46

* Lighting + Equipment + Fans + Cooling Coil Load/3 + Heating Coil Load/0.6

Total energy based on assumed chiller COP of 3 and heating thermal conversion efficiency of 60%.

	Total Module (16000 ft^2) Plant Energy		
	Electric Peak Demand	Electric Consumption	Heating Fuel Consumption
b_1	14.96	33.55	34.43
b_2	22.39	65.14	-14.59
b_3	3.96	11.14	-0.70
b_4	5.26	9.55	1.45
Mean	228.06	549.47	29.28
r^2	0.997	0.996	0.926
σ	2.91	9.33	5.07

Table 6.2 Regression Coefficients: Perimeter Zone with Vertical Windows--Los Angeles

		Perimeter Zone (1500 ft^2) Coil Load			Perimeter Zone Total Energy*
		Cooling Peak	Cooling Energy	Heating Energy	
b_1	N	21.38	-19.76	7.83	7.40
	S	52.65	-4.63	3.63	6.68
	E	30.05	-11.02	4.15	3.63
	W	25.73	-14.85	5.92	2.73
b_2	N	31.35	65.12	-3.13	21.71
	S	88.35	125.84	-3.14	56.96
	E	97.50	110.64	-3.00	52.65
	W	94.18	122.20	-3.60	58.45
b_3	N	2.98	6.02	-0.40	10.88
	S	2.55	6.13	-0.22	11.22
	E	2.55	6.05	-0.24	11.10
	W	2.80	6.18	-0.31	11.13
b_4		8.35	3.57	0.65	1.82
Mean		45.37	40.57	1.01	52.66
r^2		0.972	0.986	0.880	0.983
σ		2.806	2.483	0.317	2.17

* Lighting + Equipment + Fans + Cooling Coil Load/3 + Heating Coil Load/0.6

	Total Module (16000 ft^2) Plant Energy		
	Electric Peak Demand	Electric Consumption	Heating Fuel Consumption
b_1	10.44	5.63	11.08
b_2	21.09	57.81	-6.51
b_3	3.95	11.16	-0.27
b_4	4.90	9.82	0.60
Mean	215.8	517.3	8.78
r^2	0.998	0.996	0.867
σ	2.25	10.01	2.69

Table 6.3 Regression Coefficients: Perimeter Zone with Vertical Windows--San Francisco

		Perimeter Zone (1500 ft^2) Coil Load			Perimeter Zone
		Cooling Peak	Cooling Energy	Heating Energy	Total Energy*
b_1	N	14.08	-10.54	22.02	38.46
	S	33.25	-3.58	12.08	22.95
	E	22.61	-5.30	13.84	25.68
	W	36.91	-7.55	16.43	29.42
b_2	N	31.30	33.23	-8.12	-2.41
	S	84.54	66.36	-9.93	13.34
	E	84.82	59.56	-8.95	12.52
	W	85.28	64.33	-9.84	12.92
b_3	N	3.21	3.15	-1.13	8.27
	S	2.98	3.26	-0.68	9.13
	E	3.09	3.18	-0.75	8.91
	W	2.76	3.25	-0.86	8.76
b_4		4.91	0.50	2.31	9.92
Mean		37.99	19.28	3.70	47.22
r^2		0.973	0.986	0.914	0.968
σ		2.45	1.34	0.76	2.07

* Lighting + Equipment + Fans + Cooling Coil Load/3 + Heating Coil Load/0.6

	Total Module (16000 ft^2) Plant Energy		
	Electric Peak Demand	Electric Consumption	Heating Fuel Consumption
b_1	8.00	9.89	35.30
b_2	18.01	34.83	-18.70
b_3	3.83	10.38	-0.84
b_4	4.42	9.17	2.28
Mean	199.25	470.21	36.00
r^2	0.998	0.997	0.904
σ	2.17	7.30	6.76

Table 6.4 Regression Coefficients: Rooftop Zone
(10,000 ft^2) with Skylights--Fresno

	Coil Loads			Total
	Cooling Peak	Cooling Energy	Heating Energy	Energy*
b_1	76.36	30.56	27.57	74.30
b_2	252.40	376.80	-26.37	116.70
b_3	2.95	5.18	-0.61	9.96
b_4	6.96	5.20	1.03	10.32
Mean	238.5	235.9	22.22	365.5
r^2	0.997	0.999	0.968	0.997
σ	2.54	2.57	1.86	4.64

* Lighting + Equipment + Fans + Cooling Coil Load/3 + Heating Coil Load/0.6

	Plant Energy		
	Electric Peak Demand	Electric Consumption	Heating Fuel Consumption
b_1	21.04	43.71	41.86
b_2	79.23	153.09	-39.97
b_3	3.91	11.02	-0.93
b_4	4.62	8.82	1.57
Mean	147.0	345.0	33.78
r^2	0.998	0.996	0.967
σ	1.44	5.77	2.90

Table 6.5 Regression Coefficients: Rooftop Zone (10,000 ft^2) with Skylights-Los Angeles

	Coil Loads			Total
	Cooling Peak	Cooling Energy	Heating Energy	Energy*
b_1	40.02	-8.87	10.58	16.78
b_2	186.40	286.50	-12.04	75.14
b_3	3.24	5.40	-0.27	10.50
b_4	6.37	5.16	0.33	10.33
Mean	190.4	184.7	6.94	311.31
r^2	0.998	0.998	0.952	0.998
σ	1.80	2.38	0.94	4.07

* Lighting + Equipment + Fans + Cooling Coil Load/3 + Heating Coil Load/0.6

	Plant Energy		
	Electric Peak Demand	Electric Consumption	Heating Fuel Consumption
b_1	9.63	11.44	16.20
b_2	47.24	76.55	-18.84
b_3	3.87	10.82	-0.41
b_4	4.93	10.62	0.49
Mean	132.8	314.6	10.52
r^2	0.999	0.999	0.948
σ	0.727	3.08	1.51

Table 6.6 Regression Coefficients: Rooftop Zone

($10{,}000\ ft^2$) with Skylights-San Francisco

	Coil Loads			Total
	Cooling Peak	Cooling Energy	Heating Energy	Energy*
b_1	31.20	-3.70	29.44	57.14
b_2	213.10	178.90	-30.46	-8.57
b_3	3.03	2.91	-0.70	8.66
b_4	4.36	2.14	1.31	10.47
Mean	167.7	98.6	24.60	306.3
r^2	0.999	0.999	0.977	0.996
σ	1.53	1.30	1.74	4.86

* Lighting + Equipment + Fans + Cooling Coil Load/3 + Heating Coil Load/0.6

	Plant Energy		
	Electric Peak Demand	Electric Consumption	Heating Fuel Consumption
b_1	7.62	17.44	-45.32
b_2	51.29	30.72	-47.77
b_3	3.78	10.01	-1.08
b_4	4.47	10.56	2.05
Mean	125.45	298.1	37.98
r^2	0.999	0.999	0.997
σ	0.86	2.66	2.64

6.4. STATE OF THE ART ASSESSMENT

6.4.1 *Introduction*

Through the long history of daylighting a large body of knowledge has been accumulated and applied to the design of buildings. Visual and thermal comfort have been major determinant in the shaping of traditional architectural form and urban planning. This traditional body of knowledge, having fallen into disuse in the twentieth century, is now being rediscovered and reexamined. New technologies are now available to expand and improve the comfort conditions and usefulness of buildings. These new technologies, being mostly energy intensive must now be considered as measures to improve the performance of traditional design approaches rather than merely supplant them. In this section we discuss the available technologies and in particular the importance of integrating daylighting design with electric lighting design. This complements the quantitative estimates on energy savings potential in Section 6.3. While Section 6.3 describes the magnitude of potential savings, this assessment section provides background for implementation. Supporting data for this section may be found in the references.

6.4.2 *Integrating Daylight and Electric Light*

6.4.2.1 *Introduction*

Integration of daylight and electric light in buildings during daytime hours is a key element in energy conservation and can be characterized as part of a holistic design process for the visual environment [7-10]. In this process the merits and deficiencies of both daylight and electric light are considered in order to arrive at the best design for a specific project. The solution depends on the type of building, activity patterns in it, and local environmental factors. The integration of daylight and electric light must be closely coordinated both during the design process and in the operation of the occupied building if the intended objectives are to be realized.

Early concepts of design integrations were introduced in the late forties when the recommended illuminance for school classrooms was 15 $\mathrm{lm/ft^2}$ (15 fc or about 160 lux) and for offices 20 $\mathrm{lm/ft^2}$ (20 fc or about 215 lux). At these low lighting levels in deep interiors there was often harsh contrast between interior background surfaces and the bright sky visible through the windows. As a result, the glare which was unavoidable when looking from the depth of the room at the windows produced both discomfort and a gloomy appearance in the space remote from the window. Higher design lighting levels prevalent today mitigate this problem but it remains a key consideration in any daylighted design.

In this portion we survey concepts of integrating daylight and electric light in view of present day requirements, trends in architecture, and the concern for energy conservation and suggest presently possible design approaches as well as areas where further investigation is necessary.

Proper understanding of the integration process is of critical importance for designers to achieve energy conserving results in the context of satisfying visual environments. Windowless buildings with no access to daylight or view have been proposed as energy conserving alternatives to the prevelant fashion of overglazed buildings with tremendous energy and glare problems. The results presented in the previous section clearly indicate that the most energy efficient solutions are those with fenestration carefully designed to optimize the balance between daylighting and thermal forces.

6.4.2.2 Design Objectives

The historical objectives of fenestration design to provide a source of natural light and a means of visual communication and relation with the outside world remain important issues that now must be considered in the context of the crucial importance of energy savings and cost-effectiveness.

Design integration, while using daylight to the maximum possible extent and using electric light minimally, must consider that human performance and well-being should be enhanced rather than sacrificed. Although well-being, energy savings, and lowest overall building cost do not necessarily achieve their optimums simultaneously, consideration of the relation between basic human needs and productivity are required for proper cost benefit analysis.

The dilemma between maximum energy savings and optimal overall costs is a serious one in daylight design. Oversized windows in some cases can minimize the use of electricity for lighting. Because of increased requirements for heating and cooling, however, the overall operating costs of building management may be higher than with a solution based on an integrated scheme. Design objectives should lead to a solution in which overall costs are minimized while energy savings, visual performance, and visual well-being are maximized. The logic behind this preference in design objectives is that buildings are built to last a long time, while energy costs are unpredictable it seems unlikely that electricity costs would fall substantially in the foreseeable future. It is possible that they could fall on a short term basis. The average rate of increase however is subject to large uncertainty. Furthermore, the value of occupant productivity currently exceeds the energy costs so that any solution that maximizes energy savings but reduces productivity will be counterproductive.

Current design objectives can be divided into the following major categories:

Human performance and well-being

This category primarily concerns the visual environment, including visual performance and visual well-being. Thermal and acoustical comfort should not be overlooked, however.

The quality of the visual environment depends generally on adequate illuminance for visual activity, limitation of glare, and subjective considerations such as avoiding a gloomy interior, achieving a color scheme, and providing an acceptable size and shape of windows to maintain contact with the outside world. Daylight admitted through windows is also considered essential for photobiological processes, such as controlling the biorhythms in the body and stimulating metabolic functions.

Effective energy management

The total energy balance should be examined in light of optimal energy efficiency. Regarding daylight admission, the energy balance of heat gains and losses due to solar radiation, conduction, and air change should be evaluated. For electric light, the overall system efficacy, not only lamp efficacy, should be taken into consideration. Designs which minimize peak electric loads as well as total annual energy consumption generally produce maximum cost savings to building operators.

Cost-effectiveness

The overall cost mentioned above should include depreciation and interest on the investment as well as the operating costs for fenestration, shading, and the electric lighting system. The value of occupant productivity may also be included in this analysis.

Dynamic controls

Fixed or static shading systems are generally less energy-efficient than operable systems. For example, fixed shading devices may unnecessarily reduce the amount of daylight indoors even when the sun is not shining on them. If this is the case more electric light will have to be used than with adjustable or operable shades. Similarly, any large electric light system that is controlled by a single master switch will tend to use more energy than justified by functional needs. In general, the higher the level of control in the system, the higher the energy-saving potential. Properly designed simple solutions, however, may be low in cost, and benefits, while not maximum, may be quite high.

6.4.2.3 Depth of Daylight Penetration and Relationship to Electric Light

In sidelighted interior spaces in which daylight comes through the windows on only one wall, illuminance near the windows is relatively high and falls off very rapidly with distance from the windows. Daylight illuminance levels depend on the available daylight outdoors, external obstructions, and internal reflectances. The depth to which daylight can provide the required illuminance will depend on both these architectural features and the visual difficulty of the tasks performed. The depth of this perimeter zone can be determined with the aid of various design tools including nomograms and calculations.

Switching off the electric lighting in the area close to windows can be performed by the simplest manual on-off control. More recently, other solutions have been introduced. On-off switching of groups of luminaires can be connected to photoelectric sensors that automatically control the switching according to the distance from windows. The most sophisticated system involves the automatic dimming of the electric lighting in all the parts of a building that can utilize daylight. Control strategies are discussed elsewhere in this chapter.

Obviously, the more sophisticated the lighting system, the more expensive it becomes. As mentioned before, the economical feasibility and pay-back time should be examined in addition to energy savings. In many cases the simpler solutions of automatic on-off switching may provide quite high savings.

It is worth mentioning that for maximum energy saving the most efficient lamps and ballasts should be used, and regular cleaning, maintenance, and relamping should be carried out at predetermined intervals.

6.4.2.4 Daylight Glare

Visual comfort, one of the most important criteria in lighting design, cannot be achieved in the presence of glare. Light sources, if in the field of view will be the brightest surfaces, creating glare sources. Generally speaking, the degree of glare depends on the ratio of the luminance of the source to the background, on the size of the source, and on its location in relation to the direction of view.

The sources of daylight glare are direct sunlight, sky, and reflection from outside surfaces, as seen through daylight-admitting openings. Direct sunlight must always be controlled to avoid intolerable glare. On bright days the sky may cause quite severe glare discomfort. In particular, if light is admitted through windows that are located at eye level, these windows are likely to be in the occupants' major directions of view. Furthermore, windows are larger than luminaires so that the distinction between the glare source and its background as perceived by the retina of the eye is not clearly definable. As a result, daylight glare cannot be evaluated by the same calculation procedures as the glare from electric luminaires.

It is recommended that designers provide means to reduce the glare discomfort from daylight by locating work stations so that occupants' main directions of view do not include the sky or other bright sources, to reduce window luminance by using suitable shading devices, and using light-colored surfaces around windows.

The addition of electric light away from the windows merely to reduce contrasts, and thus reduce glare discomfort, is not recommended because of energy considerations. However, in integrated systems, electric light is needed anyway. So if it is properly designed, it can become a successful means of controlling daylight glare.

In summary, an integrated design involving daylight admission, controllable shading devices, and proper use of electric light can limit discomfort glare and keep it below annoyance levels.

6.4.2.5 Spectral Characteristics

Daylight is continuously variable in intensity, direction, and spectral characteristics. In special cases where the visual task involves accurate color judgements, reference should be made to the particular spectral distributions concerned [7,11].

Electric light sources have fixed spectral distributions that can be defined precisely. Data can be obtained from manufacturers' literature and guides on lighting [12, 13].

For most work activities, however, there are no strict demands for accurate color discrimination, and a wide range of lamps can be selected for integrating with daylight according to criteria that relate to the qualitative aspects of the total visual environment. Nevertheless, the electric lighting should have a color appearance and color-rendering characteristics compatible with those of the daylight. It should also be compatible with the interior color finishes.

Effective integration calls for lamps that make the occupants unaware, or at least unconcerned, that part of the interior is lit by daylight and the remainder by electric light.

The efficient types of fluorescent lamps are the favorite sources for general-purpose integration. For accurate color judgement, the less efficient "de-Luxe" types, having superior color-rendering properties, should be used. The new generation of so-called "Tri-phosphor" lamps, which are more efficient than the de-Luxe lamps, should be used with caution.

6.4.2.6 The Direction of the Flow of Light

The directional properties of daylight, which comes in the majority of cases through vertical side windows, differ from those of the general electric lighting, which usually comes from above. However, it should be borne in mind that the resultant flow of light is not highly directional from either diffused daylight or electric light inside interiors having interreflections from all surfaces. The exception is direct sunlight, which is generally limited in its penetration or excluded altogether.

The importance of the directional properties of lighting in a working space depends greatly on the activity pattern. Just as people usually pay little attention to the spectral properties of integrated lighting, in most cases they tend to ignore the differences in the directions from which light reaches their working surfaces. This does not mean that directional characteristics are unimportant, but that they are satisfactory for the majority of visual activities. However, in some visual tasks, such as detection of fine details in texture or enhancement of form and shape, directional properties can markedly influence visibility.

6.4.2.7 Integration, Climate, and Energy

The preferred type of integration is naturally related to local factors such as climate, daylight availability, cost of electric power, peak demand, etc. When substantial air conditioning is required in summer, daylight should be utilized as much as possible without incurring cooling penalties. As discussed elsewhere in this chapter, daylight must be effectively utilized in order to achieve these potential savings.

It should be mentioned that from energy considerations alone, the more efficient the electric lighting becomes, the less advantageous is the utilization of daylight. As mentioned before, however, there are other considerations that make daylight the preferred source for interior lighting. Furthermore, the integration of daylight and electric light can utilize both sources optimally.

6.4.2.8 Dynamic Integration of Daylight and Electric Light

The ultimate control system to integrate daylight and electric light should include all environmental factors, i.e., thermal, visual, and, to some extent, acoustical. However, at this stage we are concerned primarily with the visual environment where electric lighting and shading devices are involved.

Manual switching of sections of the electric lighting system already provides the simplest dynamic option. Regretfully, many buildings lack convenient access to manual lighting controls preventing effective use. While manual switching can readily be designed into new building construction, it is likely that automatic controls while more reliably and consistently switch for maximum energy benefits.

We can currently utilize high-technology automatic devices, which provide us with a wide variety of control options. A few examples are reported in studies at the Lawrence Berkeley Laboratory [14]. There is still little documented data on actual building performance--this remains a very high priority need.

We currently have much knowledge on the technical aspects of lighting controls, while the human acceptance of such controls has not been investigated thoroughly enough. Occupant response to high-technology control is now being studied at the Lawrence Berkeley Laboratory [15].

In conclusion, we suggest that design integration should aim at the maximum utilization of daylight and the minimum possible use of electric light to create an efficient and pleasant visual environment. Lighting energy consumption should be analyzed as part of the total energy use of the building. The proper design strategy is overall minimal cost of the lighting environment and not maximal energy saving.

Special care should be given to visual well-being by providing an acceptable view through windows and by avoiding excess glare from windows and luminaires.

6.4.3 *Review of Daylighting Design Strategies*

In this section we review the major design approaches that incorporate daylighting into building designs. Existing and proven techniques that have provided effective daylighted spaces are emphasized. Some of the more innovative but speculative approaches which have not yet been convincingly demonstrated are also discussed. Of the design approaches discussed, some emphasize energy savings, while others emphasize less quantifiable benefits of improved ambience with energy savings not the major concern. This section is divided into sidelighting and toplighting approaches.

6.4.3.1 Sidelighting

Sidelighting is typically the most widely applicable daylighting strategy, simply because of the preponderance of buildings having perimeter zones with vertical glazing. Approaches can be divided into two major categories: 1) sidelighted perimeter zones and 2) interior zones in which perimeter zone sidelighting can be distributed. The rule of thumb developed many years ago is that useful daylight penetration rarely exceeds 2 to 3 times the height of the window into a space. Using this guideline, perimeter zone daylighting is limited to 20 to 25 feet depths in a typical office space with 9 to 10 feet ceiling heights. Daylighting can largely be accomplished using relatively conventional window designs, relying primarily on the diffuse component of daylight as the major source and shading direct beam solar radiation. In these circumstances control of direct sunlight to prevent overheating and glare is a more important issue than utilizing the direct sunlight to enhance daylight in the space. Daylight penetration deeper than 20-25 feet, however, typically uses direct beam sunlight requiring sophisticated control of direct sunlight penetration into the building. There are approaches to this enhanced daylight penetration using simple architectural elements as well as sophisticated optical systems. As the deep penetration approach typically relies on the use of direct sunlight, the hours of useful operation are climate and orientation dependent.

6.4.3.1.1 Sidelighting in Perimeter Zones

The greatest opportunity for daylighting exists in perimeter zones, in existing buildings where glazing is already present and in new buildings where glazing can be included. Defining the perimeter zone as limited to a depth of 15 to 20 feet corresponds with the depth of typical individual offices at the perimeter and is a useful boundary for a daylighted portion of an open office landscape. In a zone less than 20 feet deep in a building, it should be possible to provide daylighting for 70 to 90 percent of the daytime operating hours in the year, depending upon details of climate and orientation. It is even relatively easy to provide daylight levels substantially in excess of the nominal 50 footcandles levels typical of much current office lighting design. Excessive daylight levels, however, frequently introduce unnecessary cooling loads requiring careful selection of glazing area, glazing transmittance, and shading system to control the variability of available daylight and solar thermal gains.

While daylighting the perimeter zone should be accomplished without difficulty, examination of the vast majority of buildings demonstrates that this has not been the case. At a minimum, energy savings with daylighting require suitable electric lighting controls. Fenestration control is necessary if the thermal loads and glare are to be effectively controlled. An ideal system might integrate the control of fenestration and electric lighting. Such a system would probably be moderately costly but it is feasible with state-of-the-art control technology.

The complexity and cost of these systems will also be a function of the expectations regarding occupant interaction with fenestration and lighting control. It is reasonable to expect that an office occupant will take some simple actions in response to their office environment requirements. It is equally reasonable to expect that occupants will not spend a large amount of time and concern with the systems. Because American office workers have not historically worked in environments in which occupant control has been available, it seems likely that strategies based primarily on occupant control of fenestration and lighting will require a new level of understanding and responsibility. This leads one to the conclusion that, in the near term, the control function should be automated for maximum effectiveness.

Fenestration design considerations will be orientation sensitive and suggest that the site and envelope design of a building would differ depending upon orientation.

6.4.3.1.2 Enhanced Sidelight Penetration

To introduce daylight beyond the 20-foot boundary in most sidelighted offices requires designs that differ from these for the perimeter zones. Several additional issues must be considered. First, the aperture that allows deep daylight penetration might be larger than that providing daylight for the perimeter zone only. Secondly, even with an enlarged aperture the available daylight levels in the deep space may be insufficient. This suggests the use of direct sunlight as the daylight source to provide necessary light levels. The difficulty with utilization of direct sunlight is primarily one of directing and controlling distribution into the deeper zone as well as controlling thermal gain and glare. There are two primary approaches to admitting additional sunlight and daylight. The first represents a combination of increased glazing area, primarily obtained by increasing the ceiling height. Adding glazing area in the first thirty inches above the floor contributes almost nothing to horizontal illuminance levels deep in the space. Raising the ceiling from a typical 9 feet to 10 or 11 feet provides some improvement in penetration deep in the space due to both the increased glazing area and the higher daylight source location.

If raised ceiling heights or clear glazing strips above a tinted vision strip are used it is important to control the light admitted near the top of the window. Occupants sitting close to the window need to be protected from direct sunlight. The available daylight probably exceeds needs in the immediate vicinity of the window. It would be useful to "push" the light flux needed deeper in the space without losing it to the area near the window. One architectural approach that can accomplish both objectives is to incorporate a light reflecting/shading element within the upper portion of the glazing. One such design solution is the use of a horizontal reflective light shelf, typically located 6 to 7 feet above the floor with several feet of clear glazing above it. The shelf acts as an overhang to provide control of direct light penetration (at least for some orientations) while using a light colored diffuse or specular upper surface to bounce the intercepted light deeper into the space. Solutions of this type have gained some degree of popularity in part due to their apparent simplicity. However, there is very little data to define the real performance of light shelves. Under conditions in which the direct sun is not striking the light shelf daylighted penetration will be less than with an unshaded window. An alternative approach using an operable device such as a venetian blind or louver system provides similar protection and light distribution. There appears to be insufficient technical information at the moment to determine the real strengths and weakness of such systems and their energy-saving potential.

Deeper penetration of daylight can also be improved by modifying ceiling characteristics. Although experience is limited at the present time several options might be considered. The first would be to slope the ceiling from a high level near the perimeter to a lower more conventional ceiling height as one moves deeper into the space. One advantage to this is the improved reflecting surface presented by the ceiling to the light admitted at the aperture. In addition, this allows the advantage of the higher ceiling at the perimeter without a substantial increase in floor-to-floor height. This approach would require additional attention to the location and placement of ductwork, utilities, and other elements in the plenum space if it is to be obtained without an increase in overall floor-to-floor height. Another approach is to modify the ceiling characteristics by changing ceiling texture and local ceiling geometry to provide enhanced daylight distribution deeper within the space. This might be done by the use of a more specular surface near the outer edge of the room to push light at grazing angles deeper into the space. A series of tilted ceiling panels deep within the space would be utilized to catch the light reflected off at grazing angles and distribute it diffusely into the area below. Design schemes of this type would require additional development to test their effectiveness. While there is room for innovation and improved effectiveness in these approaches, high ceilings continue to be the reliable solution for deeper daylight penetration.

Daylighting in the deeper interior zones also requires different lighting design strategies. In these instances it is typically unreasonable to expect daylighting alone to produce adequate task illuminance levels, therefore daylight is seen primarily as an ambient light source.

6.4.3.2 Toplighting

Toplighting refers to those designs where daylight is admitted through roof apertures rather than from vertical windows in walls. Glazing over large atria is treated separately. Toplighting is thus generally applicable to the interior zones of single story buildings and the top floor of multistory buildings where most or all of the floor area can be lighted through the roof. Occasionally it will be used to light more than a single floor if appropriate holes are cut in the intermediate floors. Systems that collect light at the roof and then funnel that light through lightpipes or conduits have been devised but are presently expensive. Some of these approaches are discussed in section 6.4.6, Advanced Optical Systems.

Unlike sidelighting where the spatial relationship between the light admitting source and the space to be lit dictates a limitation on the useful penetration of daylight, a toplighted space in principle can be entirely daylighted if apertures are appropriately sized and spaced over the floor area. We consider here two major types of toplighting; those in which simple flat glazing or bubble glazing is used over a simple opening in a horizontal or sloped roof plane and those situations where roof monitors incorporating vertical, sloped, or horizontal glazing elements admit and distribute light to the space. An examination of older warehouses and industrial buildings in virtually any locality should reveal a striking diversity of roof monitor systems. In older buildings of this type with high ceilings these systems allowed good control of incident daylight and sunlight as well as providing openings for natural ventilation. They are, however, more complicated to construct than cutting a hole in a roof plane. In the last several decades simple glazed openings in flat or sloped roofs predominant as the form of toplighting apertures. The fundamental difficulty with horizontal or approximately horizontal glazing is that solar transmission peaks in the summer, increasing cooling loads, and diminishes in the winter, exactly the opposite of what is required for good annual energy performance in most climates. Bubble or domed skylights were designed primarily for structural and drainage reasons. Nonetheless, they do intercept some additional low altitude sun if the glazing is diffusing.

Conventional commercially produced skylights are available in a wide variety of forms. The most common are rectilinear with one or more sheets of plastic vacuum-formed into a bubble shape to provide structural integrity. Typical construction utilizes an aluminum frame made from extrusions which hold glazing in an appropriate gasketing system. Skylights are now commonly available as double glazed units and in some areas as triple glazing. In the last few years more attention has been paid to improving the insulating qualities of the metal frame and reducing the air leakage characteristics of skylights. Multiple glazing and insulated metal frames help reduce the likelihood of condensation on the underside of skylights which can be annoying if it drips into the space. Gutter systems are frequently provided in the aluminum extrusions to catch any water that might form on the surface.

Glazing options for either vacuum-formed plastic or flat glass skylights are numerous. Clear, tinted, and white diffusing plastics are the most commonly used. The diffusing plastics play an important role in spreading the light from a relatively small opening over a large floor area. This is particularly important when ceiling heights are low. However, good diffusion is achieved with some loss in transmissivity. Some newer skylights employ a double layer of acrylic lens material which will diffuse the transmitted light without a substantial loss in transmission. Flat glass skylights are available in a full array of glass types including reflective coated glass.

The use of overhead glass in any installation must address safety in the event of breakage. Tempered glass, laminated glass, and wired glass will then appropriate choices in specific circumstances.

In addition to optical losses through glazing materials additional losses may be incurred as the light is transmitted through the thickness of a roof or plenum. In the simplest case this depth may be well under one foot, which for a large sky light, will have very little effect. However, in a space with a hung ceiling, the plenum depth may be several feet. The light traveling through the skylight will then have to pass through a lightwell whose depth is several feet or more. This introduces light losses that are a function of the light well geometry, color and surface texture. In cases where nondiffusing glazing is used the lightwell can be designed as a light diffusing and distributing element.

In the energy analysis section of this report, we show that the potential savings through skylighted spaces are very large. Despite this fact the skylights are not used nearly as frequently as they might be to provide natural light. One reason that is repeated frequently by building owners is the fear of water leakage. For a well designed and carefully installed skylight system, this should not be a problem. However, it appears to be a major concern based perhaps on prior historical information for many building owners.

6.4.4 *Solar Control Solutions For Buildings*

The majority of buildings erected in the last twenty years have been designed with limited and generally ineffective approaches to sun control. As occupants have been uncomfortable and energy costs have increased a market for retrofit solar control films has emerged. Building design should be responsive to the varying solar conditions on each of the orientations and the varying requirements to achieve human comfort and energy efficiency. A cursory view of existing building stock suggests that the vast majority of building designs have not been responsive to these requirements. Conventional approaches to solar control have tended to rely largely on deep tinted solar control glass and more recently on reflective glass in combination with interior shading devices. These solutions are reviewed in the sections that follow.

6.4.4.1 Architectural Solutions

Architectural solutions include elements of the architectural design of the building rather than devices attached to the windows and skylights.

One solar control approach in this category is designing window setbacks such that the building envelope itself is a shading element. In most new construction this shading approach is limited since the overall wall thickness is typically held to a minimum to maximize interior space. Lease agreements typically specify floor area calculated to the glass line so that there is a strong economic incentive to place the glazing at the outermost edge of the building.

Fins and overhangs have long been an important elements of architectural design, but run counter to recent emphasis on slick, smooth surfaced buildings. With energy control reappearing as an important design consideration, new interest is being expressed in the use of overhangs and fins.

6.4.4.2 Exterior Sun Control Devices

This category includes a variety of devices that are attached to the exterior of windows or skylights. They include plastic films, woven fabric, woven metal, punched and perforated screens and various types of blinds and louver systems. These devices may be fixed or operable. Operable devices can be manual or automatic. The devices vary widely in cost, durability, appearance, and performance. Some products, such as the woven fabrics, provide a general attenuation of the incident light but do not distinguish between direct sunlight, sky diffuse, or ground reflected light. By controlling the density of the weave and the color of the material the transmittance is controlled. Darker materials will control solar gain by absorption whereas lighter ones will reflect a greater percentage but will also generally transmit slightly more. For an exterior device the vast majority of the absorbed energy remains out-of-doors so that the distinction between absorption and reflection is not critical. Shading coefficients for these systems fall in the range of 0.1 to 0.5. Metal screens are available in two different varieties: punched and woven. The punched screens are generally fabricated from aluminum and have small louvers which provide angular control of incident sun light. The woven metal screens similarly consist of small louvers, the louvers are woven into place at a fixed angle. For both of these products ground reflected light will enter somewhat more easily than sky diffuse and both will have a shading coefficient that varies with angle of incidence. Altering the color of these devices will affect the transmitted energy because of their louver-like construction. In general, the darker devices perform better as exterior shading systems.

6.4.4.3 Glazing Controls

A wide variety of glazing materials is available for control of solar gain. In addition to clear glazing there are two general classes of glazing that provide solar control. Tinted glass utilizes absorbing materials dispersed throughout the glass itself. Reflective glazings utilize a surface coating which may be deposited a number of different ways to reflect and absorb incident energy. Each of these two types of glass can be combined into multiple glazed units and the reflective coatings can also be deposited directly on the tinted or heat absorbing glass. Heat absorbing glass is available in three major varieties: grey, bronze and blue-green. The total absorptance is a function of the thickness of the glass with thicker glass providing greater absorption and less transmission. Grey glass will transmit approximately the same percentage of visible light as solar thermal radiation. Bronze glass because it uses different absorbing materials will generally transmit more solar radiation than visible light. Blue-green glass acts in the opposite way with a much higher visible light transmittance than solar thermal transmittance.

Reflective coatings can be deposited on either clear or tinted glass or on plastic films. Their properties are highly dependent upon the materials used for the coatings and the process by which they are deposited. They vary widely depending upon whether the coating must survive in an exposed environment or whether it will be protected in the air space of a double or triple glazed unit. The higher performance coatings generally are metallic films and require some protection within a sealed glass unit. It is possible to deposit these coatings to make a multilayer structure which has a selective transmittance property. Several glazings are commercially available in

Europe with high daylight transmittance relative to overall solar transmittance. In general these selective coatings are more desirable than the non-selective coatings, but are generally less durable and more expensive.

Clear glass can be converted to tinted or reflective glass by gluing plastic solar control films to the glass. This is primarily a retrofit strategy. Plastic solar control films come in tinted as well as reflective varieties. They are applied to the inner surface of the window in existing construction. Newer versions of these films are also selective in their transmittance and provide higher daylight transmittance relative to total solar transmittance. In addition some of the films also have a low emittance surface which reduces radiative heat loss.

Sun control may also be provided using glazing materials other than glass. For skylight applications various sorts of rigid plastic are traditional alternatives. Double walled ribbed plastics are available in tinted as well as clear versions. Transcluent fiberglass panels are also used and have tinted versions which provide some sun control. Glass blocks enjoyed widespread use in an earlier era and are now making somewhat of a comeback. They generally have a diffusing middle layer or ribbed surfaces which can provide a general light diffusion or can redirect the light in a specific direction.

6.4.4.4 Interior Shading Systems

Interior shading systems include the familiar array of blinds, shades, drapes, and well as a few newer window management products. These devices are generally operable and are designed to provide privacy, as well as control of light and solar gain transmission. In addition, since they are viewed by the office occupants appearance is normally a major factor in their selection.

Two trends are emerging in the newer products in these categories. First, products utilizing more highly reflective surfaces are becoming available, thus reducing the minimum attainable shading coefficients. Unlike exterior devices, most of the energy absorbed in the interior devices remains in the space so reflectivity is a desirable feature. Pleated blinds, venetian blinds, roller shades, vertical blinds, and draperies with various reflecting surfaces have become commercially available over the last few years. A second trend is the increased interest in automatic controls for window shading systems. These may be used to store or deploy a simple device, or to adjust a device (e.g., venetian blind) to provide better solar control. Once one has an automatically controlled system, it should be possible to link fenestration control, lighting control and other building functions to a microprocessor that determines the optimal operation of each controlled building element.

6.4.5 *Lighting Controls*

6.4.5.1 Introduction

All buildings with windows or skylights are daylighted but only those that have an effective means to control electric light will save energy and moderate peak load. Lighting controls are necessary to ensure that potential electric savings are realized. As in other aspects of daylighting design, controls appear to be a simple and straightforward issue. However, the design of cost-effective control systems that maximize the use of daylighting potential consistent with occupant comfort is not well developed. In this section we discuss the state-of-the-art in the use of lighting controls in daylighted buildings and conclude with recommendations and suggestions for further research.

Lighting controls serve multiple functions in most buildings, with daylighting not the only issue in control selection. In pre-energy crisis days it was common practice to minimize first cost by placing all lighting controls in a central circuit breaker panel. The entire floor area, covered by a single lighting circuit, would be switched at one time. The zoning of these circuits was based on the desire to minimize installation costs. Most buildings were lit to a single uniform level and that level represented the high-end of the spectrum of visual needs. Lights would be switched on in the morning prior to the arrival of the first worker and switched off late at night after cleaning crews had departed. In some buildings nighttime heating was provided by keeping the lights burning all night long. In the days when building owners were paying under one cent per kWh it was widely believed that operating lights 24 hours per day was the most cost effective strategy.

The increased costs of electricity has led to more care and thought being given to visual performance requirements and the lighting solutions to meet them. Switching and control strategies play an increasingly important role. These includes strategies for 1) occupancy scheduling, 2) lumen maintenance, 3) fine-tuning and 4) load shedding. Each has a set of different but overlapping hardware requirements which suggests that a hardware investment may be paid back by more than one strategy. For this reason we describe each of these briefly before beginning the major description of lighting controls for daylighting purposes.

6.4.5.2 Switching and control strategies

Occupancy scheduling: In this strategy lights are turned off or dimmed to lower levels during periods when the spaces are occupied with visually non-critical tasks or are unoccupied. A number of different types of hardware systems are available. Control hardware can be classified in four distinct categories:

- Manual wall switches
- Mechanical or electronic time clocks
- Microprocessor based systems
- Personnel sensors

Wall switches are inexpensive but experience suggests that in areas occupied by more than one individual, manual switching is not often used except at the beginning and end of the day.

Mechanical time clocks are frequently noisy and unless a stop is installed on the switch, lighting hours may be excessive. Recently, programmable timeclocks have become available with costs of ~ $100/control point. These are appropriate for smaller buildings.

The operation of different blocks of lights in a larger building can be automatically scheduled using a microprocessor-based system. These systems are appropriate in buildings where the arrival and especially departure times of the building personnel are relatively predictable. Microprocessor based systems are advantageous compared to manual wall switches or mechanical time clocks due to the ability to control appropriate blocks of lights according to different schedules. As with any system that controls lighting according to a pre-programmed time schedule, override facilities must be provided and must be accessible to the occupants so that workers who need to work during a preprogrammed "off" time can obtain lighting in their local area as necessary. Virtually all commercially available microprocessor-based systems are relay-based switching systems, where each relay controls some large block of lighting. Exactly how many lights are controlled by each relay is a design consideration which is dependent on the anticipated needs in the space. The potential for saving energy by scheduling increases with decreasing switching zone size. However, the cost of the controls increases linearly with the number of control points suggesting that there is an optimum switching zone size which can be calculated if the occupant probability distribution can be calculated or estimated.

The most economical way of scheduling the lighting using a microprocessor-based switching system is to program only the "off" times and permit the occupants to switch their lights on using the overrides as they arrive.

Personnel sensors are the obvious choice in situations where tight scheduling of the lighting is desirable and where the occupant distribution patterns cannot be determined ahead of time. Appropriate locations would be one and two person enclosed offices, conference rooms, retail store supply rooms and infrequently used areas in industrial settings. Areas occupied frequently by more than two people cannot usually be economically controlled by a personnel sensor since the overlapping patterns will greatly reduce the potential energy savings.

Lumen Maintenance: The light levels in a newly installed lighting system are typically 20 to 40% higher than the design level since the light output of lamps, fixtures, and associated lighting hardware tends to decrease with age. Thus when the systems are new they put out approximately 30% more light than was called for in the design and just before cleaning or replacement the nominal illuminance level would drop to the design level. Lumen maintenance systems are designed to sense the actual illuminance level in the space and reduce lighting system output so that only the desired footcandle level is maintained. When the systems are new this would result in savings on the order of 30% and when the systems have aged the savings will drop down to 0%. On the average the savings from lumen maintenance systems can be estimated on an annual average basis as being 30-50% of the initial savings since the light output drops more rapidly in the first hours of operation. The real savings from these systems depend strongly on lighting maintenance procedures and decisions regarding group relamping or cleaning. In general, these systems would not expected to save more than about 15% per year and thus make more sense in combination with other strategies. A lumen-maintenance system coupled with an energy monitor would provide a powerful economic inventive to relamp when appropriate, since energy use will be at a maximum when the lamps are old. Lumen maintenance can only be implemented with dimming hardware.

Fine-tuning: This strategy refers to the ability to tailor the illuminance level to the specific requirements at that location. In speculative office buildings it is common to design the complete lighting system without ever knowing the visual needs of the ultimate occupants of the space. Even in buildings in which lighting design has been matched to occupant needs, frequent changes in occupancy or in visual tasks may necessitate changes in lighting system output which can be expensive if not planned for properly. The common response would be to design for the worst case so as not to incur these costly changes later. The ability to carefully control the output on a fixture by fixture basis, either with multilevel switching or dimming capabilities, allows one to install a lighting system capable of providing worst case illuminance but then adjusting the system so that its output in each location matches the needs. A number of the newer dimmable systems come equipped with adjustments in the ballast allowing the output of each set of lamps to be raised up or lowered in response to local needs. In a more sophisticated system these changes could be made electronically based upon input to a central controller. The resolution of such a system could vary from an individual fixture to a grouping of fixtures to an entire lighting zone. Depending upon the range of needs, fine tuning strategies could range from continuous dimming systems to on/off systems.

Load Shedding: Since commercial customers pay for peak demand as well as for electricity consumed strategies which moderate or control peak load will have economic value. Since lighting loads can represent 30% to 60% of the electric load at any given time they are likely to represent approximately the same fraction of the peak load. The ability to shed load may be beneficial to large customers who have special rate agreements with the utilities. Load-shedding may also benefit all customers financially since peak demand charges may be reduced. In some cities experiments have been undertaken where building owners "sell back" peak demand to the utility under critical load conditions. Ideally, some load shedding can be done in a manner that does not adversely affect occupant productivity or visual perception. In other cases switching systems may be acceptable. Specific solutions in any given building will depend upon the details of design and operation.

6.4.5.3 Electric Lighting Controls for Daylighting

In order to save electricity or moderate peak load, daylighting strategies require effective lighting control strategies. As can be seen from the brief discussion above, a number of the systems will also work as daylighting controls.

Proper lighting controls are essential components of any successful daylighting design. The design and specification of a lighting control system must meet three stringent criteria. First, the operation of the controls must be consistent with the visual performance requirements and the perceived needs of the building occupants. Controls which regulate illuminance without concern for the response of office occupants will rarely be successful. Second, the control system design and specification must be appropriate for the lighting hardware and for the overall lighting strategy. On/off controls used with HID lamps that require five to ten minutes before they can be restruck clearly does not make much sense in most building applications. The relationship between task illuminance and ambient lighting systems discussed in the lighting integration section must be addressed by the lighting control systems as well. Finally, the lighting control systems must save energy in a cost-effective manner. An additional desired feature is that they provide the flexibility for some load management control when daylight is available. Cost-effectiveness is an implicit requirement since the systems will never be specified if they don't meet some minimum cost recovery criteria.

Before discussing typical lighting control systems for various lighting strategies, we discuss generic issues related to the operation of all photoelectrically lighting control systems.

Control Systems Components

Control systems have a minimum of three interrelated elements. The first is a light sensor or detector to sense ambient light levels in the space. The second is a control logic which compares the instantaneous measured value to some preset desired criteria. The third is a control device such as an electronics package or relay which takes the action to control light output based upon signals from the control unit. In any given system one or more of these elements may be combined, but the functional requirements will be present in all systems. In the case of an office occupant turning a light switch off when there is sufficient daylight, the sensing and control functions occur in the eye and the brain of the individual.

Spatial Control

Control systems can be configured in a variety of ways to cover anywhere from a single task area or room to an entire building. In some cases the systems are modular and additive; in other cases the three key elements described previously are linked throughout the building. In the first case, a dimmable ballast with built-in sensor controlling a single fixture is a unit that can be repeated throughout a room, a building zone, or the entire building. At the other extreme are centralized systems using a central control system, distributed sensors, and on/off or dimmable controls located throughout a number of rooms and zones in the buildings all of which are linked back to the central control unit. Because the daylight contribution from most windows and skylights has a strong spatial dependence, zoning decisions have an important impact both on the acceptability of the final system as well as the cost and effectiveness. In cases where a group of fixtures or lamps are controlled by a single sensor, it is essential that different regions in the zone be illuminated in a similar way. For example, a 15 ft deep, 50 ft wide zone, with identical window treatment across the width of the zone, will have an illuminance gradient moving from window to the interior depth but should not have much variation longitudinally along the 50 foot dimension. In this instance a single sensor properly located with respect to zone depth should provide adequate control over the entire 50 ft wide zone. However, if the same zone was divided into five, ten-foot offices, each with their own operable shades or blinds, a single sensor located in one of the five offices might produce very misleading control signals. Imagine a case where the drapes in the office containing the sensor remained open on a sunny day because the occupant had left whereas the other four occupied offices had closed drapes or shades. Use of multiple sensors in a zone to average a signal from several offices provides some improvement, but still leaves open the possibility that the automatic lighting control system would respond inappropriately under some conditions. These examples also assume that the visual task requirements are uniform across the zone. If some tasks require more illumination than others the appropriate solution would be to provide additional task illuminance. However, if this is not possible or desirable for other reasons, then the entire zone would have to be controlled in a way that satisfied the most demanding task. An advantage of fixture by fixture controls in this situation is that each fixture can be responsive to the visual requirements in that particular sub-area in the zone.

The appropriate location of a sensor controlling a single zone is the subject of continuing research investigations. One option is to place the sensor outside the zone entirely, for example, on a vertical or horizontal surface outside the building and develop a relationship between interior levels and simultaneous exterior levels. This approach has been used with some success but it seems unlikely to be a consistently good solution since the relationship between interior illuminance levels and outdoor illuminance levels is not necessarily constant. If signals from a number of outdoor sensors were read and integrated into the control logic it might be possible to obtain better correlations. However, correlations based upon single sensor readings are unlikely to produce very satisfactory results. Sensors placed inside a room could be placed on a variety of different surfaces. A sensor could be placed at the task location and read illuminance on the task on a dynamic basis. Sensors could also be mounted on the walls or ceiling in which case the signal they see in the room is a function of the field of view of the active element in the sensor. A ceiling-mounted sensor for example mounted over a task location would effectively read the luminance of the task area with a narrow field of view or could read the luminance of a much larger piece of the room including walls and window if its field of view was sufficiently large. Results to date suggest that a limited field of view which avoids direct view of the window is the preferred design. However, task locations move in offices so some reasonable breadth of sensor view is useful so that relatively minor changes can be made in an office layout without substantially affecting the relationship between the sensor location and the control system logic. In practice the sensor acts as somewhat of an integrator by looking at a moderate to large section of the floor of a room.

A further possibility is to locate a sensor in a small scale model of the room that is being controlled. The sensor location in the scale model would approximate the task location and the model would be mounted just behind the office glazing, interior to any operable shading system. This appears to provide solutions to several of the problems mentioned above but remains to be tested to determine its practicality and effectiveness.

The time response of the sensor is also a matter of some concern. A system with an instantaneous response may result in a hunting behavior between two adjacent sensors whose field of view may overlap. At the other extreme a very long time response may not produce acceptable performance on a partly cloudy day where the interior daylight level can change over a broad range in a relatively short time. In practice a time response on the order of 30 seconds seems to be sufficiently long to damp out any feedback problem between adjacent sensors while at the same time sufficiently short to respond to most of the time variation in daylight levels. An assymmetric response is best--fast response in reductions to available light with a slow response to increasing daylight.

Most existing systems that are ceiling-mounted respond indirectly to the change in horizontal illuminance in the space. However, an occupant's perception of the illumination quality and quantity in the space is based upon wall luminance and the perceived brightness of other objects in the space. This can result in a situation where the desired illuminance value is maintained on a horizontal work plane while at the same time producing relatively large changes in the illuminance distribution around the space. Furthermore, horizontal illuminance is known to be a poor metric relating to visual performance. The spatial distribution of that illuminance and the resulting task contrast as perceived by the occupant are also important issues. In principle it should be possible to develop sophisticated sensor systems which drive electric lighting systems so that equivalent visibility is maintained at all times. Such systems have not been demonstrated yet and it is not clear that the improved performance might justify the increase in cost and complexity.

As mentioned earlier, the human eye and brain can be considered to be a sensor-logic system for manually operated lighting. The advantage of using manual operation is that the lights can be switched or dimmed at precisely the time that the desired visual performance requirements are met. On the other hand, humans are fallible and most will not spend their time in a working environment worrying about whether lights should be turned on or off. Thus it seems likely that savings from manually operated systems would be less than those from automatically operated systems. A major advantage of manual systems is that there is no additional hardware cost beyond a switch or dimmer that would already have been provided. However, the uncertainty in manual operation makes it unclear what kind of credits might be taken on the load portion of energy analysis calculations. In general, manually operated systems are likely candidates for one or two person offices where the lighting to be controlled is for a personal task area. In the case of a larger open landscape office manually operated controls are not likely to work well since they may be under the influence of a large number of people with differing illuminance needs and perceptions. However, it is important to realize that human satisfaction with the lighting system must be met. Even automatically controlled systems will end up being manually operated, that is circumvented, if their operation is not consistent with occupant needs in the space. It is relatively simple to tape an opaque element over a ceiling mounted sensor so that the lights are fully on at all times.

Logic in Control Systems

The signals from lighting sensors must be interpreted and processed prior to actuating a lighting control. These fall into two major categories: distributed and centralized control. In the case of distributed controls the signal received from the lighting sensor is generally compared to a preset value representing the desired level. One sensor can be linked to one logic unit or the output of a single sensor can be sent to a series of logic units in different fixtures. In the latter case all the fixtures might be driven uniformly or they could be driven differentially if the set point for comparison varied among the fixtures. This latter situation might be desirable in the case of fixtures that step back from the window, but link to a single sensor at one location in the space. It would be possible to develop an approximate correlation between each fixture and the single sensor and use that correlation as the basis to drive the output of each individual fixture. The signals between sensors and logic units are typically low voltage, primarily to reduce installation costs.

The simplest logic systems compare an input signal to a single preset desired level and send an on/off control signal to the lighting hardware. The most obvious choice of photosensor is a photo-relay facing outside the building. Since photo-relays are typically thermal relays, thermal inertia tends to reduce the frequency of hunting or cycling when the daylight level is near the switching set point. In addition, one can introduce a "dead-band" so that the lighting will be switched off when the daylight illuminance on the photosensor exceeds 300 lux but will not restore the lighting until the daylight drops below 1500 lux. This suggests the incorporation of both an adjustable deadband and an adjustable time response in one electronic package. At present there are very few manufacturers of such hardware.

In principle, a lighting system could be switched by a photosensor located inside the controlled space and sensitive to the light from the controlled luminaires. This is rarely done since, in addition to the above problems, the lighting system will almost inevitably cycle on and off due to the sensitivity of the photosensor to the light from the fixtures it switches.

The second type of requirement is in a dimming or multi-step control system where the sensor input is used to actuate more than one control or to choose an intermediate position over a variable range of light output. For example, it is becoming more common to find two three-lamp fixtures wired in tandem so that three light levels are possible. Based upon an input from a sensor a simple logic device might then determine whether 3, 2, or 1 ballast lamp sets would be actuated. In the case of a dimming system the sensor would drive some form of proportional controller to produce the desired output. In the case of the new electronic ballasts these control logic functions are integrated into the power control circuitry of the ballast. In some cases the ballasts and lamps dim to 20 or 30% of output but do not go below those values in order to maintain lamp life. Additional logic could be provided so that the systems turned off completely if daylight levels continued to increase beyond those required to drop the system to its minimum set-point. One of the difficulties with this approach is that when the system turns back on again it would move back up the curve beginning at 20 or 30% light output and eventually reach 100% light output in a dark room. However, for electronic and lamp life reasons a number of these systems turn on to full power and then dim down to the required level in a span of 30-60 seconds. This might prove to be annoying to office occupants.

There are several hardware-dependent reasons for not allowing lamps to dim below a certain level. For example, current limiters installed on an entire branch circuit which can dim even standard ballasts do not dim below ¯ 50% for two reasons: 1) below 50% light output the differences in manufacturing tolerances between lighting system components results in non-uniform dimming and 2) lamp life may be severely shortened due to reduced cathode heating voltage. Dimming systems using dimming ballasts can dim to almost 0% light output but become extremely inefficient at the low end due to the necessity of providing constant filament power.

Central control systems receive input signals from a variety of sensors and can control lighting within a zone and among all zones in a particular building. In principle these systems have great flexibility and their response can be fine-tuned or reprogrammed to meet changing building requirements. At the same time it is important to provide local control and overrides so that the systems are sufficiently responsive on a case by case basis. An advantage of these systems is that many can be driven by a number of different sensor inputs, for example daylighting, occupancy, and or a time clock. Thus if a space were only partially daylighted but unoccupied the lights could be turned fully off rather than just dimmed in response to the daylight.

These systems require that all sensors be linked back to a central controller and that the central controller in turn be linked to all of the lighting hardware. This is generally done in one of two ways; either using low voltage control wiring or using high frequency signals carried over power lines. The relative merit of each of these approaches tends to depend on the specific case under study.

Lighting Control Hardware

The hardware devices that control power to lamps and ballasts can be divided into three general categories. The first is relay systems which simply turn ballasts or circuits on and off. Proper wiring of conventional relays to a series of ballasts and fixtures can provide a good degree of multilevel control with state-of-the-art hardware. At the other end of the spectrum are lighting control circuits built into the new generation of electronic ballasts. In this case the circuitry that controls the power output from ballast to lamp is integrated with the control logic that interprets signals received from the sensors. Or equivalent low voltage signals received from the central control system. The distinguishing characteristic here is that the actuating device and the ballast or lamp control are part of the same device. The third category consists of auxilliary devices that are added to the existing lamp ballast systems to provide additional control. A number of fluorescent ballast dimming systems originally designed as retrofit devices fall into this category. These can be wired into a system in front of the existing or new ballasts to provide the desired dimming control. In some cases devices are not as efficient as integral dimming controls, although in others they are since the parasitic losses are distributed over a large area. Their specific impact on the ballast and lamp system is highly dependent upon the means by which they provide the dimming control.

A number of the logic and control systems described in the preceding section either require power to operate or reduce the inherent efficiency of the full light output from the lighting system. These parasitic power losses and inefficiencies can reduce the real savings from a system compared to the system that runs more efficiently at full light output, in particular if the specifics of the daylighting design are such that the savings are small. For example a daylighting system that saved 30% of net energy but whose parasitic power losses were 15% higher than a non-dimming system would in fact provide a net savings of only 15%, which might not justify the investment in the equipment.

Energy Savings

Part of the decision to invest in lighting controls is based upon an energy savings return. It is thus important to be able to estimate the probable and realistic savings achievable using various control systems and strategies for daylighting in buildings. As always it would be best to base these conclusions on extensive measured data from buildings. However, the existing database in this area is extremely limited and it is difficult to draw detailed conclusions at this point. In section 6.3 we have shown results from a series of computer modeling studies where daylight savings have been estimated for several lighting configurations. We also have discussed the effect of lighting controls on peak electrical demands.

6.4.5.4 Conclusions

Effective lighting controls are essential to realizing daylighting savings. The options are diverse and there is little accumulated experience to guide decision-making. Dimming is more expensive than switching. Some strategies require dimming capability, especially lumen maintenance and, to a lesser extent, daylighting, load shedding, and tuning. Scheduling can be easily accomplished with only switching hardware. In presently-available hardware there is a fairly clear distinction between centralized microprocessor-based systems for scheduling and distributed lighting control hardware for the other strategies. With present technology a hybrid approach where all the lighting is scheduled by a microprocessor but daylighting, tuning and lumen maintenance are implemented with dimming hardware in selected zones may be the most cost-effective.

6.4.6 Advanced Optical Systems

6.4.6.1 Introduction

Much of the discussion in this chapter has centered on the possibilities for daylight utilization based upon improved solutions in architectural design. Our review of the opportunities in this area suggest that while significant improvements can be made relative to most fenestration systems in current use there are limited additional opportunities to squeeze even higher levels of performance from refinements in architectural design alone. It may be possible, however, to produce significant advances with new optical materials whose light control properties differ significantly from those materials now in common use. The use of innovative optical systems to improve daylighting performance is not a new concept. An investigation of the patent literature going as far back as the late 1800s reveals numerous examples of the use of clever optical systems to enhance daylight performance in buildings. At the present time, we can take advantage not only of the well established reflective and refractive optic systems that have been known for more than a century, but we can also investigate more recent innovations based upon fiber optic systems or holographic coatings. In addition we must examine the use of optical systems whose basic performance has been understood for some time, but which could not have been produced economically in previous years. For example, new advances in large-area, thin-film deposition and other low-cost, high volume production techniques may now make optical systems practical and economical that might not have been considered feasible some years ago.

In this section, we outline several technical approaches for introducing daylight and sunlight into deep interior spaces. In previous sections we have discussed the possibility of using new optical techniques such as light shelves to introduce light more deeply into perimeter zones. We now consider situations where light transmission is desired over even longer distances and where it may be desirable to penetrate in any direction through the interior of a building. Such optical systems typically require three major elements. First, a collection system is required to gather the available light flux and, in many cases, to concentrate it. Second, the light flux must be transmitted to the point of use in a building. Third, the light flux must be distributed in a way consistent with the end use of lighting in that portion of the building. While the latter function represents a number of practical concerns, not the least of which is spatial control and integration with electric lighting, the problems are less of a fundamental optical nature than engineering design issues, and will not be considered further here. The collection/concentration problem and the transmission problem are closely related in that each may constraint the performance of the other. A number of these technologies have been investigated to varying degrees by researchers. However, there are not yet definitive research results or any practical operating systems; this area remains ripe for significant research advances.

6.4.6.2 Collection/Concentration Systems

We discuss briefly below several systems of various types for collecting and concentrating sunlight. A fundamental limitation of most of these systems is that they are designed to collect direct sunlight and introduces it into the building and, therefore, require a tracking system. Tracking systems include double-axis polar trackers which can introduce a beam of light with approximately constant cross section into an opening on the roof of a building for almost all sun and sky conditions. A simpler system would utilize an altitude-azimuth tracker where the primary mirror rotates in azimuth, and changes in altitude, to constantly direct sunlight down a shaft. Such a system is less efficient in intercepting light flux, but is simpler in that it uses only a single mirror. Skylights with these types of tracking systems are commercially available in the United States, although there is little or no definitive performance data at this time. Prototypes of the more complex double-axis polar trackers have been built and operated but once again, have only limited operating data. In principle, concentrating lens systems can be placed at the output of each mirror system to condense the cross section of the solar beam. In the limiting case, where a solid fiber optic guide is used as a transmission system such concentration would be essential. In a case where an open shaft is used, the concentration issue is largely dependent upon the economics of the shaft space used in the building. These issues are discussed in the transmission section. Any system designed to track the sun will suffer from great reductions in flux output when clouds or haze obscure the sun's disc. The flux intensity can change by several orders of magnitude in a matter of seconds as a cloud moves in front of the sun. Accordingly, the overall lighting system in the building must be designed to respond to such changes on the time scale with which they occur. Trackers can be designed to collect light from a larger solid angle of the sky than the narrow image of the sun's disc. However, the concentration ratio possible with such larger angle trackers is directly limited by the radiance theorem.

Three alternatives to active tracking optical systems have been discussed. The first would use fixed optical elements arrayed so that at various times of the day the sun's image is properly introduced into the optical transmission system. These systems tradeoff the simplicity of no moving parts for poorer optical performance. In general, they would require larger apertures to introduce the same average amounts of light compared to a tracking system. However, for non-critical lighting situations, such as circulation areas or other non-task areas, lack of precise optical control may not be a serious penalty.

The second option is the use of holographic coatings to collect light from different portions of the sky as the sun moves and introduce the light into an interior space. While it can be shown that it is physically impossible for such a system to collect light from anywhere in the sky and introduce it to a single spot with good efficiency, it is possible to exert some angular control for limited wavelengths and redirect the light in ways that may be useful in the building. Several theoretical papers have discussed these possibilities and new experimental work is starting with support from the Department of Energy.

A third option is the use of fluorescent concentrators in which a fluorescent dye absorbs incident light and then readmits light within a narrow set of wavelengths. Much of the emitted light is totally internally reflected light within the fluorescent plate. The light collected over the area of the plate migrates to the edges where it may be introduced into a light guide system. Fluorescent concentrators have been extensively studied as energy concentrators for photovoltaic systems. The possible use of such systems as non-tracking daylight collectors and concentrators in buildings is under investigation at Lawrence Berkeley Laboratory.

While both the holographic films and the fluorescent concentrators both show theoretical promise, neither has been convincingly demonstrated as a near-term practical option for daylight collection and concentration. However, both represent radical departures from the more conventional reflective and refractive optical systems. We suggest, however, that there may still be opportunities for combinations of refractive and reflective systems that can track the sun's image with a minimum of moving parts and effectively introduce the solar beam into a building. This is an area in which good optical engineering as opposed to some fundamentally new optical breakthrough could provide the impetus for a practical and cost-effective system.

6.4.6.3 Transmission Systems

Light guide systems are essential to transmit the light collected by any of the foregoing collection systems to the point of use in the building. As in the previous section, limited theoretical and experimental work has been conducted on a number of these systems but definitive performance results have not yet been generated. We describe four different options here.

Hollow reflective light guides are perhaps the first that would come to mind if one describes conduits to transmit light into a building. These guides which might have circular, rectangular, or square cross section would have a highly reflective coating on the interior surface. In the past, simulation results and measurements have suggested that typical reflective surfaces, with 80 to 90% reflectivity, do not yield very promising results except for beams that are highly collimated. However, new advances in thin film coatings for mirror designs have resulted in surfaces with 95% reflectivity with the possibility that the reflectivity could be enhanced several percent more. At this level, light guides with a length-to-diameter ratio of 50:1 could transmit in excess of 50% of the incident light under many conditions. The actual transmission depends specifically on the degree of collimation of the incident beam or the angle which the collimated beam makes with the axis of the light guide. This is a case where relatively small improvements in surface reflectivity make a relatively large improvement in system performance.

Hollow dielectric light guides have recently been patented by Whitehead in Canada. The guide surface is a prismatic cross section which traps light by total internal reflection and redirects it back down the core of the light guide as long as the incident light remains within a cone of 26 ° half angle. Optical losses are due only to imperfections in the prismatic wall surfaces. In practice, these amount to about 1 percent loss per foot of length for typical materials produced to date. However, when the guide is used as a light distribution conduit, the light lost from the sides may contribute to illumination in the space. This material is available as a commercial item for electric lighting use and a number of experiments are underway to investigate its feasibility with beamed sunlight.

Lens guide systems have been discussed for some time. Lenses and mirrors would be used to transmit and redirect the beam through an optical system. Each lens element introduces a source of optical losses which must be minimized to maintain high system efficiency. For systems with reasonably large guide cross sections, thin plastic fresnel optics would probably be used. Limited demonstrations of such systems have been completed but no practical systems have been fabricated or tested.

Solid light guides can also be used to transmit light. Fiber optic systems have the potential benefit of using flexible cables which can be routed as desired through the interstices of buildings. However, their small cross section requires highly concentrating optical systems to collect an adequate total flux and transmit it to the point of use. Solid guides of very large cross section, either of glass, plastic or even liquid-filled, seem impractical due to the weight and massive amount of material involved. In the fiber optics field, most materials have been optimized for transmission in the near infrared for communication purposes. However, both glass and plastic fibers have good transmission in the visible portion of the spectrum. This could no doubt be enhanced by further optimizing the composition of either the glass or plastic fibers for daylight transmission.

Several general issues recur in examining light guide systems. First there is a relationship between guide selection and collection/concentration optics. For example, small diameter fiber optic systems would require concentrating collectors to introduce adequate amounts of luminous flux to a space through a small cross-sectional area. The intensity of incident sunlight (10,000 footcandles) is 200 times the required illuminance levels in a typical building. Therefore, in principle, a square foot of sunlight can light 200 ft^2 within a building. However, optical system losses will reduce this by a factor of two, and the intensity of beamed sunlight varies considerably depending upon atmospheric path length, local atmospheric conditions, and cloud cover. Thus, on the average much lower ratios between collection and use would be expected. This in turn sets limits on the fraction of floor area that must be devoted to light guide area. In some buildings, the light guide cross section may be introduced at the exterior of a building or in core areas that will not be otherwise used. However, in some cases the guides will usurp valuable rentable, floor space in which case the economic viability may be severely limited. The light guide cross section can always be made smaller at the expense of increasingly sophisticated concentration systems. At the point of collection, conversely, no concentration is needed and sunlight at its original intensity can be introduced if there are no limits on the guide cross sectional area. At the present time, there is enough uncertainty both in the performance and the potential cost of both the concentration collection systems and the guide systems, so that no single option or combination of options is clearly preferable.

6.4.6.4 Conclusions

Research on advanced materials and designs for daylighting deep within buildings is at an early stage. While a number of theoretical studies have been published there is little systematic or extensive investigation of this field. In recent years several studies supported by the Department of Energy have been initiated but have not yet produced definitive results. If successful solutions can be found, these approaches may the impact of daylight utilization in some building types for which daylight utilization would otherwise be impractical. This would be particularly appropriate in densely built up areas in which the vertical surfaces of buildings have limited sky view but there is access from the roof.

6.4.7 *SUMMARY*

Carefully designed integration of electric lighting with daylighting is essential both from the perspective of energy savings and of occupant comfort. An effective lighting control system is a prerequisite for electric lighting energy savings in a daylighted space. An effective solar shading and control system is a prerequisite for successful daylighting in a space and control of solar thermal gains. An appropriate strategy by which electric lighting and daylighting are properly integrated is in turn a prerequisite to the overall success of any system.

In this chapter we have outlined the control options available to effect energy savings with daylighting. Except for manual switching, these control systems incorporate new technologies that are subject to continuing development. At present, hardware is commercially available for both new construction and retrofit. Properly designed, selected, and installed hardware used in conjunction with daylight can provide substantial energy savings now. In our review of basic concepts involved in the use of daylight as a energy saving strategy several issues emerge repeatedly.

- Any design for integrating electric lighting and daylighting must recognize and account for the possibly unique circumstances and user needs associated with that specific design problem. Various integration strategies emphasize one or more aspects of lighting design but usually not all equally. It is important to select the integration strategy that best responds to the specific needs of the building situation being considered.
- An appropriate design strategy requires that user needs be adequately defined. There is not unanimous agreement on all quantitative and qualitative aspects of lighting requirements for a broad range of visual tasks. More work is needed to understand and quantify occupant needs, satisfaction, and preferences in the context of a wide variety of elements and individual environments. These concerns extend to the issues of window size, window location in the wall, and view from window--all of which may have some impact on occupant reaction to a daylighted space. Some of these issues can ultimately be reduced to some simplified quantitative guidelines. Others are more qualitative and subjective in nature and will remain so, although more information on the subject would be desirable and useful to design professionals.
- Once lighting integration strategies that go beyond task footcandles are defined, more sophisticated lighting control systems and sensor systems that respond through appropriate

software and hardware in daylighted rooms may be needed. The technology for such systems is presently available with improvements appearing regularly. We lack a sufficient understanding, however, of the appropriate and desired reactions for the range of lighting conditions that would normally be encountered in a daylighted space. Some related issues in this area are discussed in the section on lighting controls.

- A further dimension to the control problem is integration of electric light and daylight with fenestration controls to modulate solar gain and with other building operating systems such as the HVAC systems and security systems. A variety of systems presently is available and it is fair to assume that increasingly sophisticated automated systems will become available.
- The final decisions regarding lighting integration issues will often be made with cost as the criterion. It is thus important to recognize that design decisions which provide an integrated lighting system must address not only lighting energy and visual performance concerns but a variety of other constraints that may be totally unrelated to lighting issues.

To realize the full energy saving potential of daylighting will require further investigation in control system design and interaction with daylight. Some areas in which further investigation is needed to provide better guidance for California utility planners are discussed below.

Analysis of Control System Performance

Energy savings and load management opportunities are critically dependent on the interaction of control system type with other key variables such as glass area and transmittance and design illuminance level. Simulation results are present in section 6.3 of this report but this is an area that requires additional study. Control logic to optimize total building energy consumption might be quite different from approaches which minimize lighting energy consumption.

Lighting Control Hardware

Analysis of the type recommended in 1) above can reveal useful information about the performance of existing lighting control hardware but can also provide insights into requirements for new control hardware. For example, studies that should lead to better design of the photometric sensor. The need for development of elements in control systems are currently underway at LBL. Other control hardware elements might emerge from analytical studies in 1) or from observations in buildings in 3) below.

Building Monitoring and Demonstration

Data collection in occupied buildings serves several useful purposes. First it can be used to validate or build confidence in predictions from the analytical studies. Second, these studies can identify critical performance issues that affect savings but may not be accounted for in computer simulations (e.g., occupant response issues). Third, successful demonstrations build confidence in the conservation technologies, and help accelerate acceptance and utilization of the approaches.

Handbooks and Design Guides

To have maximum influence, the useful information distilled from technical results in items 1), 2), and 3) above should be assembled into a package that can assist building designers in specifying effective design solutions. These manuals should include not only the technical results but critical design guidance on non-energy aspects of the design of lighting controls.

6.5 BUILDING CASE STUDIES

6.5.1 Introduction

The following case studies provide glimpses of how various window and daylighting technologies are being applied in commercial buildings in the western states (see Table 6-7). Most of the cases presented are office buildings, although the two-story high open-plan processing facilities included are representative of the rapidly growing list of projects which feature rooftop skylights. In each case our reported observations are based primarily on site visits and discussions with the building designers, managers, and occupants. However, at best, this exposure provided a limited view based on projects that are, excepting one, less than three years old.

Table 6-7.
Daylighting Case Studies

Name	Type	Location	New/Retrofit
Chabot Center	Office	Pleasanton, CA	New
U.S. Postal Service General Mail Facility	Mail Processing/ Office	Santa Ana, CA	New
California Hardware	Office	City of Industry, CA	Retrofit
Portland Medical Office Building	Office	Portland, OR	Retrofit
Metro Center Building	Office	Oakland, CA	New
Wells Fargo Office Mortgage Company	Office	Santa Rosa, CA	New
Ventura Coastal Corporation Administration Building	Office	Ventura, CA	New

In the absence of measured operating data for any of these case studies, we can make no definitive statements about their overall energy use or of the specific benefits/costs of the window and daylighting technologies employed.

To help improve the substance of case study documentation, further in-depth information is needed in two related areas. First, submetered electricity end-use data is needed, especially for the trendsetting buildings types discussed here. Secondly, an understanding is needed of how the installed window and daylighting technologies are being managed. This can be accomplished by surveying several buildings of each type. With these related data we could begin to better understand and assess the role of window and daylighting technologies as energy-saving features in commercial buildings--by orientation, building type, and climate.

6.5.2 Chabot Center, Pleasanton, CA

6.5.2.1 Introduction

Chabot Center is a three-story-high, 72,000 ft^2, office building located in the rapidly growing Hacienda Business Park in Pleasanton, CA. The oblong north-south plan is centrally divided by a full-width (14 x 68) east-west entry/circulation atrium covered by a tinted glazed barrel vault (see Figure 6-29). On the southern and western exposures of office areas, partial exterior shading aids sidelighting; eastern and northern exposures have no exterior shading controls. Linear skylights are located above certain third floor core areas. After 14 months of occupancy, building management is unaware of any strong criticism of window and daylighting conditions by the building occupants. Management is now exploring "smart" energy controls, including dimming and on/off electric light switching, for this as well as other office buildings.

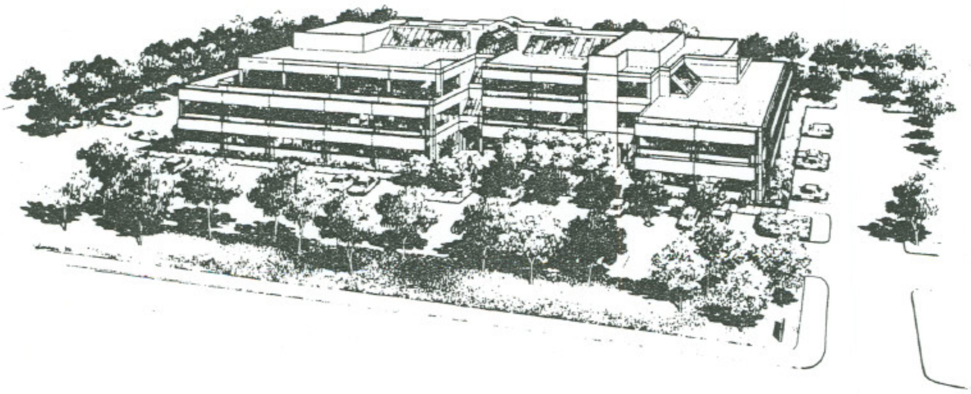


Figure 6-29. View from west.

The semicircular glazed atrium vault provides the intended, distinctive identity, visible from major access roads, and repeats the form of the drive-through arch at the main entry. It also locates building access from parking areas on either side. The tinted glazing allows dramatic daylight penetration into atrium areas as well as into the adjacent stairwell, via a perforated wall, but there are no openings to adjacent offices. The high cooling load penalty for the atrium was understood during design and led to exploration of exterior shading of perimeter glazing in order to compensate and meet Title 24 requirements.

A high percentage of exterior perimeter glazing was desired for marketing the office views to surrounding hills. Architectural studies of exterior shading approaches led to use of translucent glass fiber panels which provide low contrast sidelighting for perimeter offices. The panels are positioned vertically and supported by pipe frameworks which extend the full height of the building and located 4' outside of all southern and western window exposures. Additional shading of high summer sun is provided on the southern exposure by horizontal steel grating sections positioned between the panels and window heads. (See Fig. 6-30) There is no exterior shading on northern exposures nor on eastern exposures where computer analyses indicated net energy benefits for building winter warmup

Toplighting is introduced to top floor core areas by linear north-south skylights glazed with sloping--east and west respectively--glass fiber panels. Varied spaces (separated by full height walls with clear glass panels above ceiling height) are located beneath, including a conference room, now difficult to darken, and video display units, to which polarizing screens have been added to control glare (see Fig. 6-31). Above circulation corridors the skylights provide pleasant "shoji screen" lighting.

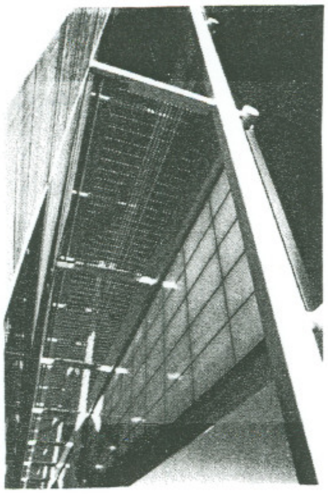


Figure 6-30. Exterior (vertical and horizontal) shading controls in south elevation.

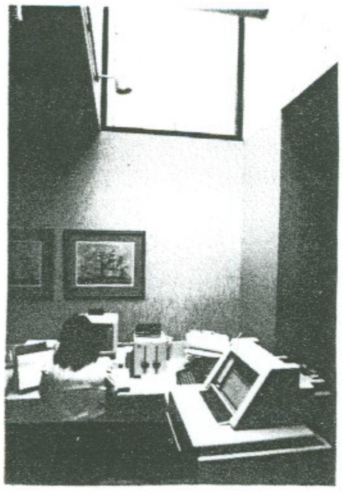


Figure 6-31. Work station located beneath skylight.

Interior shading controls at perimeter windows are limited to 1" wide venetian blind units with dark slats, which exaggerate the lighting contrast. On eastern exposures, these blinds are often closed to shade morning sun, but (in some areas toured) not later reopened.

Ceiling 2 x 4 lay-in fluorescent lighting fixtures are fitted with either parabolic louvers or acrylic lenses. Because the ceiling lighting fixture layout preceded the partition arrangement, several task lights have been added in order to supplement lighting or overcome the shadow effects on certain work surfaces. Also, "smart" energy controls, including dimming and on/off electric light switching, are now being considered by building management for this facility as well as others under their management. These "smart" controls could further exploit the available daylighting potential, particularly in perimeter office areas with exterior shading.

6.5.2.2 Summary

For this office building, the desired aesthetic and memorable image was consciously given precedence over energy saving features. Nevertheless, the exterior shading systems specifically applied for energy conservation harmonize well with the building. They provide substantial shading while which reduces cooling loads and daylighting contrast in perimeter offices. The additional electric lighting controls being considered could result in substantial additional energy savings.

This fixed exterior shading system could also be readily adapted to flush perimeter walls common to many similar existing office buildings. With greater space constraints, comparable solar control could be achieved with the panels located closer to the building or fitted like sloped awnings.

6.5.3 U.S. Postal Service General Mail Facility, Santa Ana, CA.

6.5.3.1 Introduction

This two-story high postal facility includes office spaces and open plan high-bay areas for mail processing. (See Fig. 6-32). This facility replaces a similar, smaller operation in downtown Santa Ana. Rooftop skylights are used most extensively throughout the processing areas and selectively in office and employee areas, as well as above outdoor mailbox and loading deck areas. Electric lighting in high-bay areas consist of high pressure systems fixtures with dimming controls. The energy savings provided by these features were estimated using DOE-2.1B analyses during the design phase of the project, but in order to implement some of the daylighting controls and operating strategies, several variances from standard US Postal Service building standards were required. Following six months of occupancy, worker responses to window and daylighting technologies have been generally positive. Submetering of electric end user is needed to accurately assess the actual benefits/costs of the windows and daylighting technologies for this project.

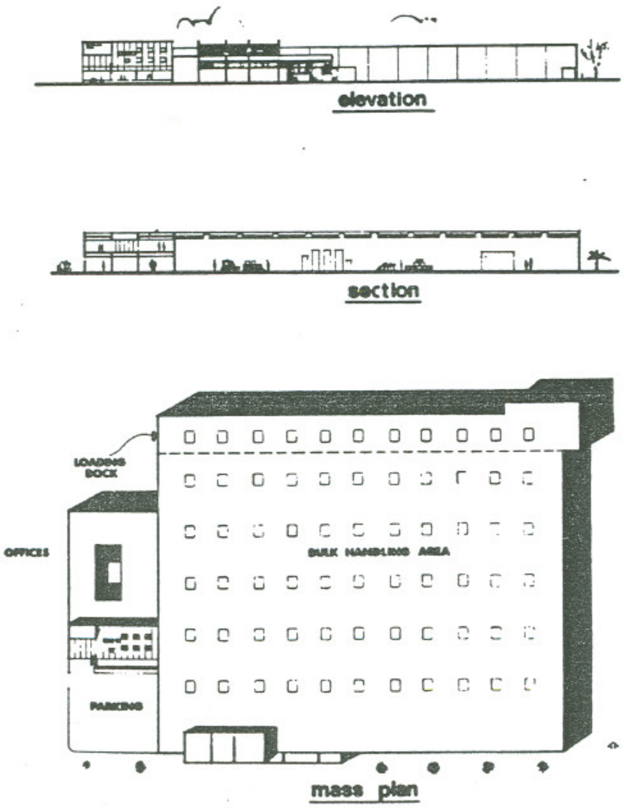


Figure 6-32. Santa Ana General Mail Facility.

Daylighting is provided throughout the high-bay open plan processing areas by uniformly spaced rooftop skylights. This toplighting is supplemented by pendant-hung high pressure sodium lamps with controls to maintain 50 footcandles at floor level. Automatic control is provided by downward facing sensors mounted near the tops of certain structural columns. The light reflective rubberized floor covering material, which enhances diffusion of daylighting in the high-bay areas required a variance from USPS building standards. Now, however, several large sections of this flooring have peeled off due to excess moisture underneath, exposing the darker concrete. Where control system sensors face these dark areas, erroneous readings are made. Also, wheeled carts or other obstructions darker than the flooring are often clustered near columns beneath sensors, triggering the lights "on" for an entire zone. A sample area of rubber flooring (without the raised discs) will soon be tested and assessed before the entire floor covering is replaced.

Similar rooftop skylights are also located above certain second level closed offices, above outdoor mailboxes and loading dock areas, and most dramatically, above splayed frames in the employee cafeteria/lounge ceiling.

The office areas are organized around two interior atria, each covered with sloped glass fiber panels resting on laminated wooden joists. The daylighting distribution in these atria is enhanced by light wall surfaces, nicely rendering interior planting materials and wall murals. Daylight from one of the atria is spilled into an adjacent processing area via clear glazing.

Second level office areas bounding the two atria also benefit from the atria daylight. Ambient electric lighting in these areas is supplied by indirect high-intensity discharge units mounted atop 60" high furniture. Several maladjusted louvers, which directed light to eye level caused visual discomfort and were commented on by several office workers.

6.5.3.2 Summary

This USPS facility employs varied toplighting configurations to provide daylight for a range of interior activities. However, energy savings from the sensor controlled HPS lamps above the extensive high-bay areas now varies (by zone) according to flooring conditions. This suggests that another reference surface for the sensor might help resolve this problem. Also, submetering of electric end use is needed to more accurately assess the daylighting benefits/costs compared with other electric end uses.

6.5.4 California Hardware City of Industry, CA Retrofit

6.5.4.1 Introduction

This tilt-slab high bay office facility is located in the City of Industry, CA. Rooftop skylights are used extensively to provide daylighting for most warehouse areas. Dramatic electric energy savings are expected, according to SCE estimates. Some related concerns by warehouse workers involve overheating and glare, particularly when skies are clear. The office lobby entrance is marked by a full height, south-facing, tinted glass wall with no shading controls.

Glass fiber skylights were added to supplement the existing few skylights and to greatly increase daylighting levels with corresponding energy benefits according to SCE estimates. The daylight level is monitored by sensors located in certain skylight wells. Pendant hung high-pressure sodium lighting fixtures are dimmed according to daylight levels. However, skylight units with glazing of 80% visible transmittance were installed instead of 50% as recommended by SCE. This may contribute to some periodic complaints of overheating and glare by floor workers, particularly on clear sunny days. However, most of these workers are near large overhead doors near the loading dock which are open during warm weather, while tow motor operators are frequently circulating among stacks and reading numbers on overhead rack often shaded by overhanging pallets which exaggerate the contrast of toplighting from above.

Within the high bay areas the returned goods area is served by hung fluorescent tube fixtures. Because the morning shift begins at 0630, the lights are often on all day, as the on/off switch is inconveniently located.

The entry/reception lobby for the offices is located at the southwest corner of this facility. It is marked by a full-height, south-facing, vertical and sloped tinted glass wall. During our visit interior ceiling mounted incandescent spotlights were on, pointing to planting materials already bathed in unshaded daylight during most days.

6.5.4.2 Summary

This facility installed skylights above extensive high-bay areas in response to rebate incentives and technical advise from SCE. The daylighting improves the quantity and distribution of light.

6.5.5 The Portland Medical Office Building Portland, OR Retrofit

6.5.5.1 Introduction

This 13-story squarish-plan medical office building is located in downtown Portland, Oregon, was converted in 1959 from a 9-story department store. (See Fig. 6-33). Horizontal window bands, each of 1-inch-thick insulating glass, were added along with new spandrels, both separated vertically by channel mullions that extend the full height of the building. (See Fig. 6-34).

Along with these architectural envelope design changes, a new HVAC system was installed. However, it was discovered following occupancy that not enough air handling capacity was available to provide adequate cooling on all four sides of the building simultaneously.

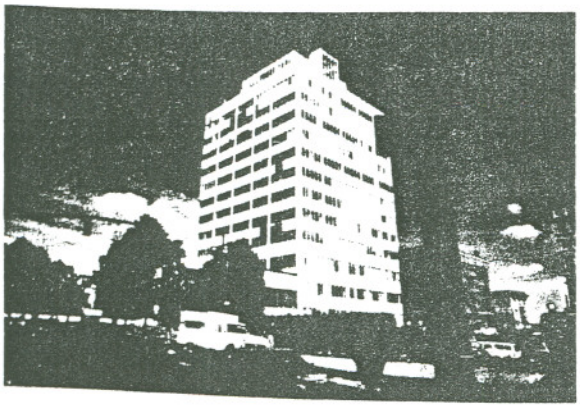


Figure 6-33. Building view from southeast.

Figure 6-34. Detail of south elevation.

To reduce cooling loads, two different approaches were tried. Tinted polyester film was added to the inside surface of the insulated glass windows in one south-facing office. This trial resulted in unsatisfactorily high glass and room air temperatures and the approach was abandoned. Next, green-colored anodized aluminum sunscreens were framed and fitted on tracks between the window mullions on the southern exposure, allowing vertical adjustment of the screen position. The screen could then be seasonally adjusted to either shade or expose the glass. This strategy reduced indoor air temperatures in the adjacent offices by up to 10°F by substantially reducing transmitted sunlight.

Later, additional screens were added on east- and west-facing windows at the request of individual office tenants. Screen adjustment, occurred seasonally along with window washing, included cleaning the mullion tracks and repositioning screens over the windows. However, during recent years, a succession of building operators allowed individual tenant preferences to determine screen locations. Further, screens damaged by window washers or wind were periodically removed but not replaced. The building elevations appeared irregular, with some screens up, some down, and others missing.

To improve the building appearance, current management has recently removed all exterior screens and installed, over a four-month period, interior venetian-type blinds on all four building exposures. Consequently, there have been some complaints concerning overheating although not all tenants appear to be using their blinds to their potential.

6.5.5.2 Summary

This exterior, manually-operable shading system was initially installed to reduce overheating in building perimeter areas recently converted to individual offices. The system succeeded while under the control of building managers cognizant of its functions and aware of its limitations and benefits. However, system weathering along with changes in building management led to the option of system adjustment per individual tenant preferences which resulted in an appearance unacceptable to building management.

6.5.6 Metro Center Building Oakland, CA

6.5.6.1 Introduction

Metro Center, a headquarters office building, is a four-story-high (approximately) rectangular structure situated approximately NW-SE and located adjacent to the Lake Merritt Bart Station in Oakland, CA. (See Fig. 6-35). The steel framework is clad with lightly colored precast concrete panels, including curved sections at the main SE entry. Overall, it projects a streamlined appearance to a neighborhood of "elderly" two and three story high residential and light commercial buildings. Exterior shading controls include automatic operable blinds on the NW and SE "end" exposures and fixed overhangs with integral louvers on the long SW terraced exposures. There is no exterior shading on the NE exposure, based on the assumption that in this climate most summer mornings are foggy. First year problems included HVAC balance and adjustments of the automatic louvers. Building occupant responses to these window and daylighting technologies vary by their location in the building: workers near windows (including partially shaded windows) cited glare and overheating during low sun conditions, but still enjoy the view and light while basement workers, who have only one skylight, cited insufficient connection with the outdoors. Plans (following the initial contract) to add electric light dimming controls were abandoned due to estimates of long payback periods.

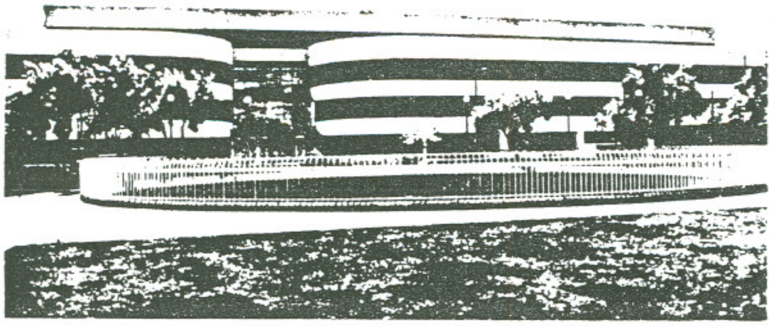


Figure 6-35. View to southeast entry.

Exterior operable blinds are provided on all three orientations of each full height notch, on the NW and SE ends. All blinds on either end are automatically controlled by a single sensor mounted on their respective parapet wall; the lower blades are adjusted to intercept all direct solar radiation. Additionally, there is a single manual override for the blinds on each end of each floor. However, this control arrangement permits unnecessary shading of windows which can only be manually overridden at the expense of exposing the opposed windows to direct sun.

The NE exposure has flush, grey-tinted glass. Interior shading is provided by 1" wide venetian blinds. Exterior shading was not included, based on the assumption that morning fog would prevent significant direct solar gain buildup. However, this relatively "clear" year has caused building occupants to complain of overheating in perimeter areas adjacent to this window wall as well as to the overcooling meant to compensate.

The SW exposure is the most problematic. The long second, third and fourth terraced levels include full height fixed and sliding glass door panels. Each is partially shaded by an overhang with an integral array of fixed vertical louvers at the outside. However, interior venetian blinds are now scheduled to be installed to reduce the impact of low winter sun. The balconies include highly reflective decks, which will be partially shaded by the addition of proposed planting materials. They will also partially shield line of sight to the asphalt parking lot below, which covers the remainder of the block. The balconies are now used by office workers as evidenced by office chairs and a typewriter stand situated outside there during our visit. Also, several of the sliding glass doors were ajar, despite building management's efforts to keep them closed to maintain HVAC system balance.

Indoors, many of the workers located adjacent to window walls cited glare; yet they like the view and light. Their responses contrasted sharply with workers in the basement offices, who feel they enter through a "tunnel" into a "dungeon" and that they had come from "much better office environments." Although their offices are furnished similarly to the upper levels, their only daylight enters through a linear skylight along the NE edge of their open plan area.

A similar skylight is used to provide daylight to the interior computer room located on the fourth floor. Despite its proximity to outside fresh air louvers and fans in the mechanical equipment penthouse, noise transmission into occupied areas is insignificant.

Ceiling electric lighting fixtures are provided throughout the open and closed offices. Dimming was considered as an add-on option for the open-plan areas coupled to the long window walls. However, the addition of intermingled closed offices complicate the switching, and yielded an unacceptably long estimated (30 years) payback period.

6.5.6.2 Summary

This building uses several different window and lighting control features and operating strategies. However, it appears that the exterior shading systems are not matched with exposures to maximize their energy saving capabilities. For example, the operable exterior venetian type blinds now limited to SE and NW exposures would be better suited to the extensive and problematic SW and NE exposures while the fixed horizontal overhang and louvers now on the SW would be more effective on the limited SE. And the limited NW exposure could more easily be left unshaded than the extensive NE. Further, to optimize the benefits of the operable blinds, manual overriders for each exposure may be necessary. With more strategic deployment of the same fenestration and daylighting technologies some improvements in energy performance might well be expected.

6.5.7 Wells Fargo Mortgage Company Santa Rosa, CA

6.5.7.1 Introduction

This three-story-high corporate office headquarters was built to consolidate scattered offices for about 500 employees. The architect was charged to include energy saving features with short payback periods. Phase two, when needed, will be built as a mirror image just to the south, joined at the entry, and will approximately double the capacity. The elongated east-west plan features basic window shading and daylighting controls, including staggered and stepped ends and a central (see Fig. 6-36) atrium. The staggered and stepped design provides self-shading and maximizes perimeter exposures. Shading and glazing vary by orientation. Perimeter electric lights are wired for automatic on/off control, but after 14 months of occupancy, they have yet to be used. HVAC is provided by a system designed to rely heavily for summer cooling on ice storage using off-peak electricity. If HVAC and electric lighting controls can be operated as originally planned, additional energy savings should result.

Figure 6-36. View from southeast.

The building configuration is self-shading on eastern and northern exposures; the western exposure has no windows (see Fig. 6-37). On southern and eastern exposures exterior shading is provided by sloped fabric awnings. Awnings were chosen in preference to overhangs or recessed windows because of cost and appearance. The off-white color chosen mitigates the problem of airborne particulate from nearby highway 101. Maintenance includes monthly washings with water. As part of the landscaping along the southern exposure, raised water ponds reflect high summer sun onto the underside of the sloped awnings. Although aesthetically pleasing when viewed directly from indoors, this fluttering light source could produce annoying glare for VDU operators located near window perimeters. It probably has little energy impact. However, the visual and thermal impacts of awnings were fully appreciated by building occupants when first installed, shortly after building occupancy (during summer months).

Figure 6-37. View from southwest.

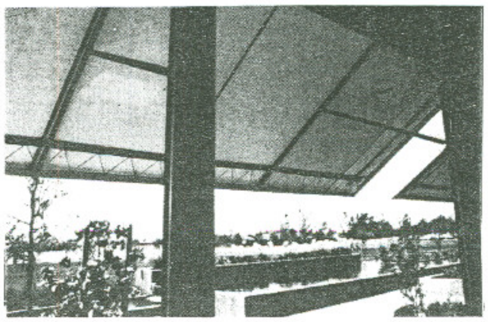


Figure 6-38. View to exterior awnings (southern exposure).

Vertical perimeter glazing varies by orientation: south and east are tinted while north is clear except where combined with sloped glazing above the two-story high cafeteria and a few office areas above is tinted also. Exposure to direct sunlight on these office areas has caused overheating and interior manually operable slat blinds have been installed to help compensate. Still, according to the occupants, the space is perceived as significantly warmer than adjacent zones. No overheating has been reported in the cafeteria. The HVAC system uses four cooling options, including outside air, direct and indirect evaporation cooling, and an icemaker using off-peak electricity.

Tinted pyramidal skylights are used above the atrium. Partial interior shading of direct sun is provided by triangular fabric kites stretched between the nodes of the space frame.

Typical ceiling electric lighting fixtures are 2 x 2 airflow units with 16 cell parabolic louvers which use warm and/or cool white fluorescent u-tubes. Although the perimeter suites are wired for on/off sensing they had not been used by the time of our visit, about 14 months after occupancy. The ceiling lights are designed to provide 80 fc at working surfaces and to exhaust 60% of light generated heat. No task lights were originally planned in connection with the 60" high furniture systems, but some task lights have since been installed.

6.5.7.2 Summary

This office project demonstrates that basic, well-integrated, yet distinctive window and daylighting control technologies can be built within the limits of a modest budget. Here the prominent window management features are visible from the building exterior as well as from certain interior atrium, circulation, and office areas. Yet their contributions to overall energy-savings ultimately depend on how they directly or indirectly affect the responses of the building occupants, especially building managers. This helps to explain why the installed electric lighting and cooling control technologies have not been exploited as planned. To facilitate improved further control over these systems, the newly arrived building engineer has proposed the addition of an energy management system.

6.5.8 Ventura Coastal Corporation Administration Building, Ventura, CA.

6.5.8.1 Introduction

This elegant two-story-high headquarters office building is sited atop an open grassy bluff in Ventura, CA. The boomerang shaped plan (see Fig. 6-39) stretches roughly N-S and is accented at the bend by a glazed entry lobby/lounge atrium. Various window and daylighting technologies have been carefully integrated (see Fig. 6-40) to provide daylighting for most of the occupied office and some ancillary areas.

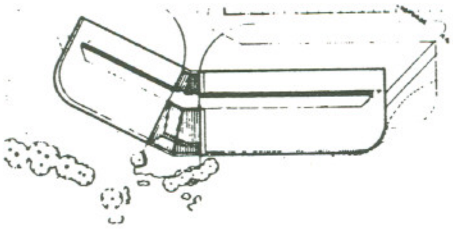


Figure 6-39. Site plan.

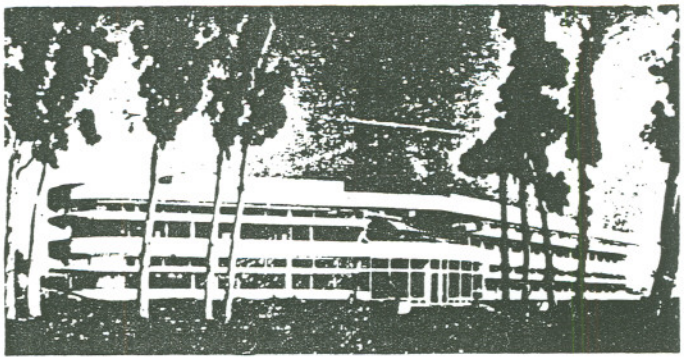


Figure 6-40. View from west-northwest.

Features include exterior overhangs, light shelves, rooftop clerestories (see Fig. 6-41), as well as tinted and clear glazings, interior light colored reflective surfaces, and vertical blinds. Electric ambient lighting has on/off control with photosensors. However, during our visit the system was not being managed as intended. This is probably resulting in increased energy use although actual use figures have not yet been disclosed. This project has received extensive recognition and has been presented an Owens Corning Fiberglas energy award.

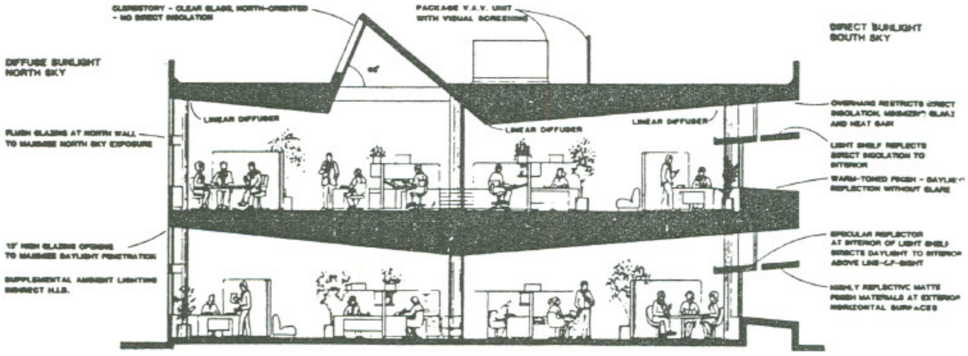


Figure 6-41. Typical cross-section.

The entry lobby/employee lounge atrium is enclosed by vertical and sloped tinted glazing. The interior is highlighted by vigorous planting materials and the second level connecting bridge, which helps shade the reception area while framing exterior views toward the coast. There are limited window connections between the atrium and the adjacent office areas, and this is the only space which relies on natural ventilation.

Exterior shading controls along the ocean exposure wrap around the corners and include a prominent overhang and exterior and interior light shelves beneath. Each restricts direct insolation while reducing heat gain and glare. Additionally the light shelves direct overhead daylight into the core of the building via specular reflecting surfaces and sloped interior ceiling surfaces. The underside of the light shelves has a light colored matte finish while the sill areas beneath have a warm toned finish to reflect daylight without glare. Remote from these ocean exposures are a row of Eucalyptus "blue gum" trees which were selectively pruned to enhance distant views while still providing lacey shading of low winter sun.

Vertical perimeter glazing all-around is 1/4" thick and tinted blue green up to the 7' height of the light shelves and with clear glazing above to the 12' height of the sloped ceiling. Inside are manually operable vertical blinds.

The second level core areas receive additional daylighting via linear overhead clerestories. They feature north facing, sloped--and originally clear, but now frosted--glazing as well as interior sloped reflecting surfaces. Restrooms and kitchen areas beneath also benefit through openings which borrow light from above. Many of the light reflecting ceiling surfaces beneath these clerestories are becoming soiled, especially those enclosing unlined return air plena. The dirt is most noticeable around the edges. HVAC is supplied by gas/electric variable air volume rooftop units with heat reclaim and economizers.

The daylighting features for this project were designed to provide 75% of the ambient light needs (on an annual basis) for the open plan office areas. The concept hinged on light colored 60" high office furniture and open areas for support staff. Supplemental (indirect) ambient lighting was to be provided by furniture-mounted ambient indirect HID and task fluorescent tube fixtures computed at a power density of 1.2 and 0.2 W/ft^2, respectively. Many of the office furniture panels are darker than intended, however, and during our visit the photosensors for the HID units had been altered, leaving these lights on despite available daylight. Also, in one of the first level core areas, adjustable ceiling-mounted track lighting had been installed above certain secretarial work surfaces to provide task lighting.

It is unclear whether these alterations are in response to the need for more light or whether the current building personnel is not familiar with the purpose of the lighting controls. To help clarify any misunderstanding the architect has recently proposed to develop a building operating manual.

6.5.8.2 Summary

This office showcases several well integrated daylighting features. Also, because the project was designed and built within the limits of a standard budget, it should inspire other designers and clients to consider and explore the benefits of daylighting. Further, the management of this organization believes that the building design enhances their ability to attract and keep qualified personnel as well as improved productivity. However, in order to more accurately assess the dollar benefits/costs of the energy-saving technologies, as in the other case studies, submetering is still needed.

6.5.9 Los Angeles Harbor Department Administrative Office Facility San Pedro, Ca.

6.5.9.1 Introduction

This five-story high office headquarters was built to consolidate several offices; it has been occupied since 1981. Its rectangular plan, is framed within full-height exposed core trusses made by ten-steel and sited north-south (see Fig. 6-42). This configuration allows commanding views from the upper floors to the east, south, and west to the nearby harbor facilities. Window and daylighting features include extensive perimeter glazing in conjunction with exterior fixed horizontal shades and automatically operable roller blinds. Additional solar controls, retrofitted inside the the perimeter glazing, included plastic film and vertical blinds. In open plan office areas, portable indirect HID fixtures have been added to supplement similar pendant hung fixtures. And, within the past year, the controls to the "conventional" HVAC systems have been reprogrammed by a newly arrived building engineer, resulting in dramatic energy savings.

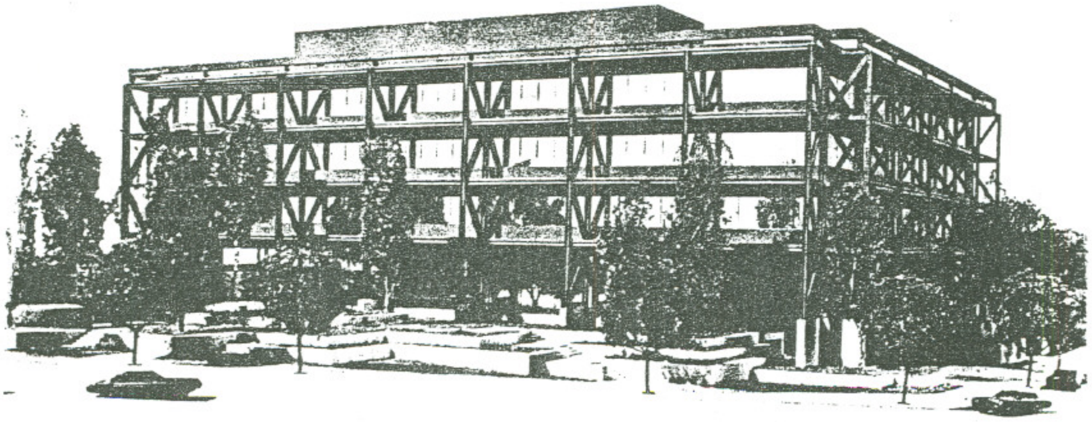
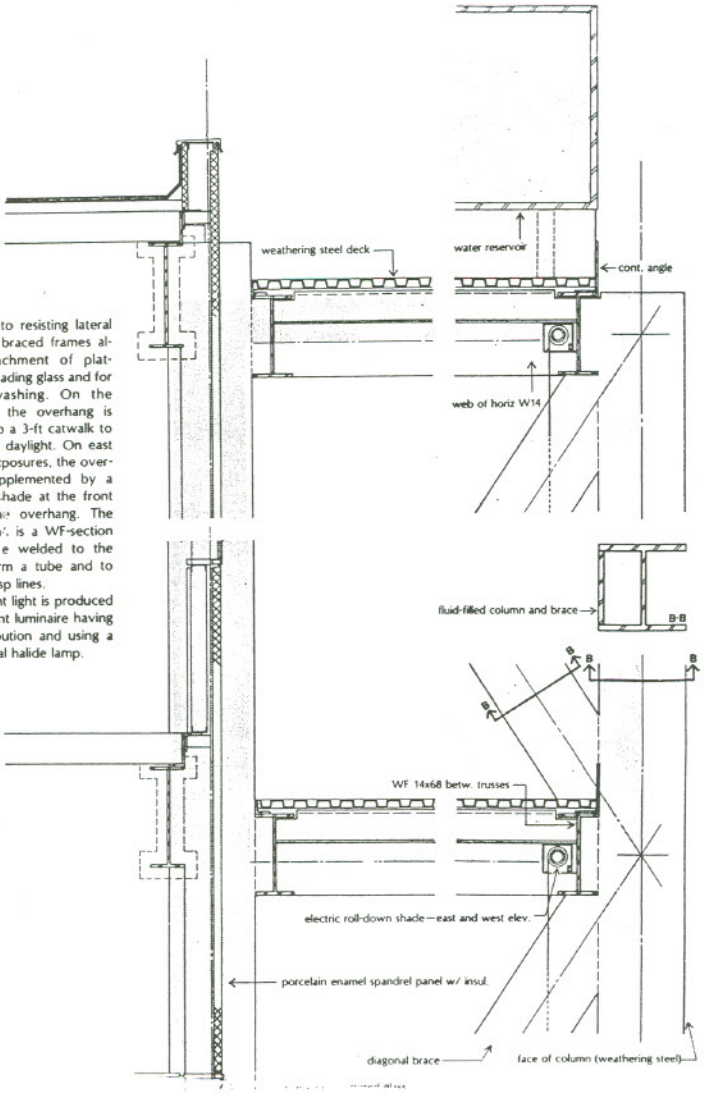


Figure 6-42. View from west-southwest.

Partial exterior shading of perimeter glazing is provided for all exposures for the three floors above ground by fixed horizontal weathering steel (now rusting beyond expectations are to inadequate drainage and high humidity conditions) platforms that extend from the perimeter walls to the outsides of the seismic truss framework. (See Fig. 6-43). This configuration facilitates window washing as well as access to the roller blinds attached to the outside edge of the platforms (on east and west exposures). The blinds, of bright blue fabric, are automatically controlled by a light sensor and/or anemometer. Initially the lighting sensitivity adjustment resulted in frequent blind operation which annoyed many building occupants.



In addition to resisting lateral forces, the braced frames allowed attachment of platforms for shading glass and for window washing. On the north side, the overhang is narrowed to a 3-ft catwalk to admit more daylight. On east and west exposures, the overhang is supplemented by a motorized shade at the front edge of the overhang. The front column is a WF-section with a plate welded to the back to form a tube and to produce crisp lines.

Ambient light is produced by a pendant luminaire having wide distribution and using a 250-W metal halide lamp.

Figure 6-43. Exterior truss, platforms, and roller shades.

Consequently, the blinds along one top (executive) floor exposure have been permanently locked in the open position. Also, gusty winds, common to this area, sometimes tear individual blinds loose from their velcro attachments to the horizontal battens. (see Fig. 6-44). One of these was loose during our site visit in July. Now the blind adjustments include a 3-minute delay for lighting and a 10-minute delay along with a 25 mph threshold for wind.

In interior open and closed plan office areas, ceiling pendant hung indirect HID fixtures, and furniture-mounted fluorescent fixtures were designed to provide ambient lighting for work areas which used system furniture (60-inch high); task lighting is provided by downward-facing fluorescent fixtures. (see Fig. 6-45). However, additional freestanding HID units were soon added to supplement ambient lighting levels and areas of coverage. More recently, two retrofits have been made on the inside of the perimeter glazing, mainly to control glare for the increasing number of video display unit operators. Approximately two years ago, plastic film was affixed to glazing on the north exposure. Six months later, manually adjustable vertical blinds were installed on east, west, and south exposures. Each addition was completed within 1 or 2 working days, minimizing disturbance to the building users.

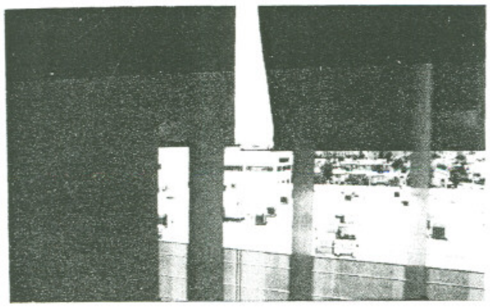


Figure 6-44. View of loose velcro connection.

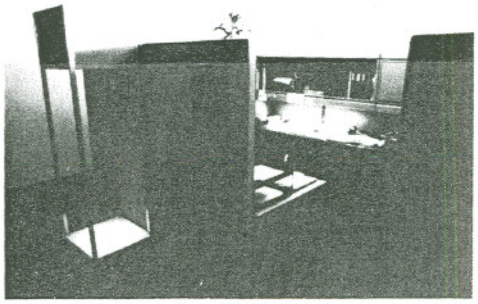


Figure 6-45. Office task and ambient lighting.

6.5.9.2 Summary

This building uses its bold, exposed weathering structural frame to support fixed and operable blind systems to provide shading while maintaining distant views. The operable blind system was initially unfamiliar to the building operators and users, resulting in unsatisfactory startup operation.

These experiences suggest the need to assess the implications of unfamiliar window management technologies during design. It is also a vote for developing building user manuals that explain the building equipment and its use in enough detail so that building operators and occupants understand the behavioral quirks that unfamiliar technologies might exhibit.

6.5.10 Long Beach State Office Building Long Beach, CA

6.5.10 INTRODUCTION

This four-story high, 156,000 square-foot building is located on a rectangular block in downtown Long Beach. Like the seven other energy-efficient state office buildings developed during Governor Brown's administration, this facility was built to consolidate several scattered state agencies while demonstrating energy-efficient technologies appropriate to its respective climate. This building features a saw-toothed perimeter and open air atrium, providing both self-shading and increased exposure to daylight. Each exterior exposure is framed by heavy dark structural members contrasted with an integral light-colored space frame infilled with shading panels. (See

Fig. 6-46). Interior offices feature high ceilings, having exposed wood structural members and flush-mounted metal halide electric lighting fixtures. Energy-efficient control of these units has been complicated by inadequate switching and improper sensor locations. Some switching and lamp changes have already occurred. Further modifications could help exploit the intended energy-saving potential designed into this "demonstration" state office building, the only one located in Southern California.

Each exterior exposure of the saw-toothed plan is rotated at 45° to cardinal orientations and to the rectangular site. This configuration provides self-shading while increasing the daylighting potential for perimeter areas. Each exposure is dominated by darkly-finished laminated wooden structural beams, contrasted with an integral lightweight and light-colored space frame infilled with transite shading panel configurations that differ by exposure. Some horizontal panels are now warped due to rainwater ponding.

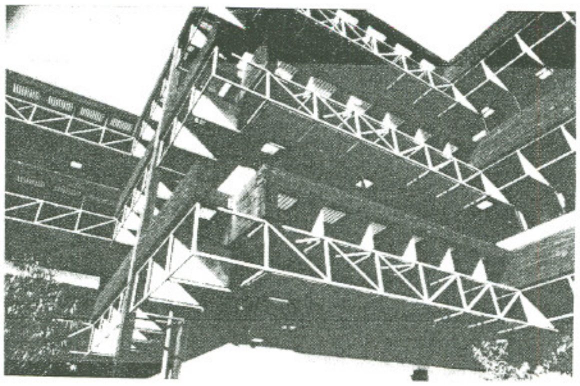


Figure 6-46. View from south.

Inside 14-foot high ceiling bays are bounded by the approximately 3 feet deep dark structural beams. In between exposed cross beams are flush-mounted, 2 x 2 metal halide lighting fixtures, some with 250- and others with 400-watt bulbs. (See Fig. 6-47). However, even with diffusing lenses, these units cause harsh glare against the dark structural members and light-colored ceiling tile infill and a dark tile floor in the cafeteria (see Fig. 6-48). Further, in one area where the ceiling is lower, this same fixture caused complaints of overheating; smaller bulbs were installed to mitigate this condition.

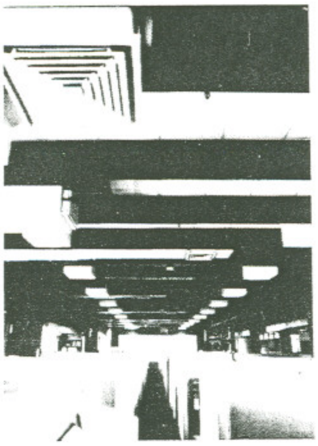


Figure 6-47. Typical office ceiling.

Figure 6-48. Cafeteria lighting.

Perimeter metal halide units are automatically controlled by ceiling-mounted sensors, some improperly located in areas shaded by structural features. Also, many of the dimming units initially overheated due to their installed locations inside unvented ceiling boxes. Consequently, venting of boxes and relamping has occurred to mitigate this problem.

The 777 metal halide units, located throughout the building, can be manually controlled only by the few zone switches on each floor. Several of these switches are inconveniently located--one is closeted within a women's restroom. These switching limitations often result in excessive electric lighting use, especially in zones which include outdoor atrium areas or office areas used during evenings or weekends (when individuals in state enforcement agencies often work). Office workers are now instructed to defer light switching control to the timeclock, which turns off all lights (weekdays) at six p.m., although, most building users depart at 5 p.m. Daytime janitorial services are used.

Lighting control switching for eight conference rooms that originally could not be darkened for visual presentations have been rewired. Several other areas have been identified for separate switching but must await funding to do so.

6.5.10.2 Summary

These lighting experiences suggest the need to consider lighting and controls simultaneously during the design program and development phases. Improved switching zone controls of electric lighting in the facility would help to exploit the intended energy savings from daylighting and electric lighting sources.

Acknowledgement

The content of this chapter extensively benefits from prior research done by the Windows and Daylighting Program at Lawrence Berkeley Laboratory directly or indirectly for the U.S. Department of Energy, New York State ERDA, American Society of Heating Refrigeration and Air-Conditioning Engineers and others. The coverage we are able to present would not have been otherwise possible. Some of the material presented has emanated from this prior work and has appeared in other reports, many of which, are included in the references.

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APPENDIX A

ENERGY MANAGEMENT AND CONTROL SYSTEMS

Appendix A

Preliminary Assessment of Conservation Potential: Energy Management and Control Systems

Overview

Energy management and control systems (EMCS) have *not* been selected as a conservation strategy receiving detailed analysis in the current project principally because EMCS "measures" cannot properly be evaluated simply as an item of hardware, like an efficient fluorescent ballast, without taking into account the specific changes in building operation that they are programmed to accomplish. Data on commercial building operating parameters are largely unavailable at present. In principle, though, they could readily be extracted from the EMCS itself, in most cases, with the addition of straightforward record-keeping and communication procedures as a condition for customers to receive EMCS rebates from the utility.

This appendix provides a preliminary review and assessment of available data, a sample case study, and a summary of the steps needed for a more thorough assessment of EMCS potential.

We briefly outline several characteristics that distinguish EMCS from other commercial conservation hardware and suggest some steps which might help the utility to assess the stockwide potential for EMCS savings. At the same time, improved data on costs and performance would assist individual customers planning to install EMCS systems under the rebate program.

1. EMCS technologies are becoming increasingly prevalent in commercial buildings; a large fraction of customers are installing EMCS either on their own or through utility-sponsored rebate programs. However, reliable data on **actual changes in building management**, resultant energy and peak savings, and hence cost-effectiveness are virtually non-existent.
2. A complete analysis of EMCS conservation potential (on a site-specific or stock-wide basis) is even more demanding than for other conservation technologies, since EMCS performance depends directly on specific changes in building operations. Evaluating EMCS performance requires a thorough understanding of building equipment *and* operation before installation as well as the same level of understanding of equipment and control functions--and the changing role of operating personnel--after the EMCS installation.
3. Such an analysis would draw on information from two sources:
    - o detailed **stock characteristics** (from a modified commercial customer survey)
    - o empirical **case studies**, beginning with selected performance indicators reported by the EMCS systems themselves

Potentially, both of these resources are available within the utility, from commercial survey results and through a requirement for feedback from customers' EMCS installations subsidized by utility rebates.

4. Developing these information resources would serve three main purposes:
    - improve the assessment of stock-wide potential for EMCS
    - ensure cost-effective rebate levels for EMCS installations
    - provide useful information to customers considering future EMCS installations.

In addition, EMCS-derived data could usefully complement the more general data used for load forecasting, obtained from commercial surveys. For example, end-use and load-profile data could be obtained for representative buildings, and in some cases the effects of individual new or retrofit conservation features might be directly monitored by the EMCS already in place.

Steps Towards Assessing EMCS Potential

An in-depth analysis of the conservation potential from EMCS installation would include the following elements:

1. Compile data from manufacturers' specifications for available EMCS products (and anticipated near-term future products), including cost, size ranges, and capabilities (examples are outlined below). Based on a revised commercial survey and program data from utility rebates and commercial audits, estimate the number of EMCS presently installed, by building type, size, and location. Project the potential market for EMCS purchases today and in the future.

2. Develop and field-test standard procedures for EMCS recording and reporting (in machine-machine format or hard-copy) of a common set of performance indicators for specified building types and configurations. (Beyond this core set of data, additional or alternative performance indicators could be reported, where warranted by the characteristics of the building, its usage patterns, or the control system itself.) After an initial field-test, these protocols would be distributed to EMCS vendors as one condition for receiving future utility rebates (probably limited to larger EMCS systems, or to rebates over a certain dollar amount).

   The utility or an outside contractor would compile these data and periodically report summarized results in a form suitable for conservation potential studies, load analysis and forecasting, and planning/management of commercial customer service programs.

3. Gather detailed case-study information on selected customers' EMCS installations, in order to bracket the range of possible savings and to identify possible contributing factors, such as equipment "fine tuning," improved maintenance, load shedding, optimal start/stop, etc. An example case study has been included in this appendix (Attachment A), to illustrate the type of information that can be obtained from empirical analysis.

4. Based on the case studies, identify successes and potential problems with EMCS, and assess the persistence of savings over time. It is likely that any analysis of a sufficient number of case studies will turn up certain trends and similarities among installations. More importantly, tracking installations over a few years can help to characterize the longevity of EMCS equipment and software, and any recurring costs. Do frequent software changes need to be made? Do sensors malfunction or wear out? Can initial operational problems be identified and corrected after an initial "breaking-in" period? Clearly, a time-trend analysis will require several years of post-installation data, and should not be anticipated as a near-term result.

5. Tabulate stock-wide information on existing buildings and new construction, through commercial survey responses, in order to extrapolate case-study results to the larger commercial building stock and use the data as inputs to utility conservation potential models.

   This will require some changes and additions to the survey to reflect the important parameters in determining EMCS potential. Many of these changes will also allow for a better assessment of the potential of other conservation measures, as discussed in the proceeding chapters. An initial list of items needed but not now included in the survey is as follows:

   - overall operating hours for the building; daily/weekly schedules for subsystems and major items of equipment
   - HVAC zoning; number and size of fans, chillers, etc. (potential for central vs. local control, duty cycling, more tightly controlled ventilation, etc.)
   - existing type of lighting and HVAC control (manual, photocell, seven-day timeclock, demand limiter, EMCS, etc.)
   - existing monitoring/data logging systems

The next two sections review briefly some of the readily available information on current EMCS products and indicators of market potential. Both topics should be pursued in greater detail as part of any future EMCS assessment project.

Typical EMCS Costs, Size Ranges, Capabilities

Looking at the large number of EMCS vendors and products on the market today, it becomes clear that there is a wide range of equipment available. Within this range, certain types of EMCS are best suited to specific applications. It is useful to categorize the available products into groups by type of load and general control strategy. A scheme of categorization was developed from a survey of EMCS for the U.S. Navy [1]. There is some overlap between groups, but when choosing an EMCS for a particular building or control situation, the choice usually falls within at most two of the following groups:

- Timeclocks and thermostats with timeclocks
- Demand-limiters and duty-cyclers
- Equipment controllers dedicated to specific equipment (e.g., chiller optimizers or day-lighting controls)
- Programmable controllers for multiple systems in a building
- Full-fledged microcomputer systems

In general, the larger the building, the further down the list the choice of an EMCS will fall. Among these five categories the range of total system cost is from less than $100 (solid-state timeclock) to over $1,000,000 (microcomputer multi-building system). However, cost is largely a function of the number of control points; normalizing cost per point controlled greatly reduces the variance in costs for a given system category.*

Table A-1 illustrates the range of typical values for EMCS hardware costs, *excluding* installation [2]. Normalizing costs per load controlled (for time clocks/duty cyclers) or per input/output point (for larger systems) often does not accurately reflect other differences in system capabilities (peripherals, type of control (analog/digital), number of control variations per load, and the like). Further, labor costs for installation are not included; these can be as much as 50-70% of total installed costs. [2]

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* One exception to this is equipment controllers, where cost per point controlled is not applicable since they generally control only one piece of equipment. These systems are not discussed specifically here since they are mentioned in several of the earlier chapters of the report.

Table A-1

EMCS Types and Cost Ranges (Hardware Only)*

Type	System Cost Range	Cost Range Per Control Point
(1) Timeclocks, Timeclock Thermostats	$100-$2,000	$100-$300
(2) Demand Limiters, Duty Cyclers	$200-$20,000	$300-$600
(3) Equipment Controllers	$200-$20,000	N/A
(4) Programmable Building Controllers	$500-$15,000	$100-$1,500
(5) Microcomputer Systems	$1,000-$1,000,000	$100-$1,200

* Installation costs not included; cost range per control point is per load controlled for categories (1) and (2) and per input/output channel for categories (4) and (5).

Source: Reference [2]

Notes:

(1) Scheduled start/stop. Night setback with thermostats.

(2) Demand control, duty cycling. Most are capable of programmed start/stop.

(3) Optimize startup/operation of specific equipment (usually HVAC). Some include demand-limiting.

(4) Several functions incorporated into single panel. Have start/ stop, demand limiting/duty cycling, at a minimum. Most are now used on process (industrial) equipment.

(5) Same features as (4), with greater programming flexibility, higher-level languages, more peripherals (printers, etc.). Monitoring and data logging features are often available. More operator feedback features. Additional non-energy functions often include fire control, security, and maintenance tracking.

The Market for EMCS

An understanding of existing activity in the EMCS market can help to shed light on possible future activity. Three questions need to be answered more definitively; we offer only preliminary observations here:

1. **Who is now buying EMCS** (by building type and size)?

   According to Southern California Edison's commercial survey tabulations, only 2% of commercial survey customers have installed EMCS as a retrofit measure [3]. In contrast, over 50% of the 100-plus buildings in LBL's BECA-CN data base (energy-efficient new commercial buildings) have EMCS as "original equipment" [4]. We have no information on the number of EMCS installations as a percentage of all new buildings in the PG&E service territory, but from casual observation we would presume that almost all large buildings and many medium-sized ones completed in the past few years include some sort of EMCS. As hardware costs decline, there is also a growing market for small building (under 50,000 square feet) EMCS systems. Lower costs may be increasing the retrofit market, as well, a trend accelerated by utility rebates. In 1983, Pacific Gas and Electric gave out $4.3 million in rebates for EMCS retrofits to 670 of their customers. These represented 25% of all participants in the large-customer rebate program (i.e., those over 100,000 kWh/year).

2. In general, what have been the **positive and negative experiences** with these installations?

   For example, have building managers been satisfied with the systems? Have maintenance costs for the building gone up or down? Have building tenants been content with comfort levels provided by the new system? Has the system operated as promised over an extended period of time (several years)?

A soon-to-be-completed EPRI study, "Evaluation of Commercial Building Energy Management Systems," based on a survey of 200 building owners/managers, attempts to address these first two points [5]. Important preliminary conclusions are:

- 70 percent of large buildings (over 50,000 square feet) now have EMCS. The greatest future potential seems to be in smaller buildings, particularly as demand charges spread to smaller customer classes.
- Customer satisfaction is most closely tied to EMCS maintenance requirements. Generally, installations where vendors provided continuing software support and modification as needed were more satisfactory than "turnkey" installations where the vendor sold and installed the system only. On the other hand, some building managers felt that maintenance contracts were too expensive.
- Of those building operators surveyed who had *not* installed an EMCS (about half of those surveyed), 60 percent had not done so because they felt that their present method of building control was adequate. The remaining 40 percent felt either that EMCS were too expensive or that savings estimates were questionable. (This last point underscores the potential value of measured performance and cost-effectiveness data to accelerate market acceptance.)

3. What is the **future market** likely to be, based on present penetration, vendor emphasis, and trends in EMCS technology development?

   Some recent developments include: decreasing costs for microprocessor hardware and software; development of direct digital control, or DDC (which bypasses the transfer of computer signals via pneumatic control loops and thus allows closer control tolerances); and distributed processing (keeping local controls separate from the central unit to decrease the volume of information transmitted and reduce the dangers of central CPU failure).

Case Study Analysis

In addition to EMCS installation costs, one needs to understand resultant energy and peak savings in order to determine cost-effectiveness. Variations in building operation and EMCS strategy become critical. An underutilized microprocessor energy management system can easily become a glorified (and expensive) timeclock. A few solid-state timeclocks and an attentive building staff can yield substantial savings (at least until the staff gets promoted or retires) [6]. Present experience with EMCS installations indicates four main problem areas:

- specification of control needs
- quality of hardware, accuracy of calibration
- quality of control software and support services
- ability (or willingness) of building personnel to operate the system.

The first step in understanding these problems is to carefully review actual experience with present EMCS installations, both successes and failures. We have suggested the utility's EMCS rebate customers as an excellent source for these case studies.

We outline here the critical elements in evaluating an EMCS installation, along with an example case study (Attachment A) to illustrate what can be learned from empirical analysis. The ultimate goal of the case study analysis would be to more accurately estimate initial and continuing savings by building type and size, EMCS type, and system cost, and to identify the most common pitfalls and the factors associated with successful EMCS installations. When this information is combined with better data on the range of EMCS types, sizes, and capabilities (as above) and with more detailed stock information, a better assessment can be made of the stock-wide conservation potential.

Ideally, the following information should be obtained for each case study:

Conditions Before Installation: Operation and maintenance of building and equipment; energy consumption and peak demand for at least one year; descriptions (and savings estimates) for any other conservation actions taken concurrent with (or within one year prior to) EMCS installation.

Conditions After Installation: Operation and maintenance of building and equipment; energy consumption and demand for at least one year after installation; records of any problems or EMCS down-time; records produced by the EMCS itself (which can also help to verify savings from other actions).

Specific building data needed before, during, and after installation would include:

- HVAC and lighting schedules. Was the EMCS used to turn lights off at night when a simple timeclock would have performed the same function?
- Changes in the scheduled maintenance program. Were major adjustments or repairs made as a result of surveying present building operation to determine proper EMCS functions? (How many fans had missing or torn belts? How many frozen damper controls were repaired?)
- Conservation actions taken as part of the EMCS installation process? Frequently, delamping or economizer installation occur at the time of EMCS installation, but their effects should be separated, insofar as possible, from EMCS savings.
- Equipment sizes (fans downsized?), thermostat settings (set-points changed?), and equipment efficiencies (boiler tuned?).

Costs: EMCS equipment, installation, and continuing support and maintenance costs, along with any changes in in-house labor requirements.

Other: Any other significant changes (weather, occupancy patterns) before and after the installation.

Most of these elements are available from the rebate application itself, the customer's utility billing records, an audit of the facility, or follow-up with building operators. For utility rebate customers, one could first compare pre- and post-installation energy usage and, second, compare actual savings with engineering estimates included with the application. More detailed examination of selected installations would follow from this.

Concluding Remarks

We have outlined some of the information currently available on EMCS installations, along with a proposed approach to a more comprehensive assessment of EMCS conservation potential. A significant portion of the information needed is presently available in utility billing or rebate files. With some additional effort it could be supplemented through direct customer follow-up so that: (a) essential information is gathered for load forecasting and estimating conservation potential, and (b) customers--and more importantly, their engineering consultants-- are encouraged to be accountable for their savings estimates that are the basis for utility rebates.

We suggest the following steps:

1. As a starting-point, compare before-and-after billed energy consumption for customers who have already received rebates to install an EMCS. This will provide a "first cut" at the range of possible savings.
2. Next, for a selected number of installations, use utility auditors to field-verify equipment control strategies and maintenance conditions both before and after EMCS installation. (In cases where the EMCS has already been installed, conversations with building operators and contractors, along with field visits, could serve the same purpose.) While this can be a time-consuming process, it is essential to characterize past savings and thus estimate potential.
3. Related to this, require pre- and post-fielding of all future EMCS installations covered by utility rebates (or, at least those over a specified size). Building and equipment data collected in this way could be combined with commercial survey results and the existing data

base from C/I/A audits. More accurate information on the building stock will make generalizations from all the individual technology assessments, not just those for EMCS, more valid.

4. Perhaps most importantly, develop procedures that take advantage of the ability of the EMCS itself to provide much of the documentation needed to verify energy consumption and savings. Many sophisticated systems routinely provide archival records on equipment operating hours, hourly demand, and energy consumption for the building and identified loads, as well as some operating parameters (such as temperatures and dew-points of outside air and return air, and chilled water temperatures).

Our view is that it would be entirely feasible, for systems above a certain size, for the utility to ask customers to contribute data which for them is essentially free (if the system is properly configured to begin with). This in turn could save future purchasers of EMCS, and the utility's ratepayers, substantial costs associated with data acquisition and sub-optimal decisions about conservation retrofits. Since the utility is investing quite a bit in EMCS rebates (PG&E contributes 30 percent of EMCS cost) it may not be unreasonable to require customers to provide this documentation.

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Attachment A
Sample Case Study - Park Plaza Building, New Jersey

Introduction

The following sample case study, while it is **not** necessarily representative of typical EMCS performance results, illustrates the important elements for an empirical analysis of EMCS potential. In actual practice, not all elements will be available for all case studies examined. Even here, with an intensively monitored demonstration building, some data gaps exist.

As part of a DOE-sponsored project, a large, recently constructed, privately-owned office building was equipped with sensors to measure energy consumption of specific systems over an extended period of time (two years). This case study summarizes the results of the automation analysis part of the project.* The objectives of the automation study were to "evaluate the application of a number of building automation system capabilities.... The study looks at the energy- and cost-effectiveness of some energy management strategies of the building automation system." The system in this particular building had more extensive monitoring capabilities than the typical energy management system, features which allowed building operators to carefully track and optimize system operations. Many control strategies were changed after installation, with resultant improvements in building energy performance.

Building Description

- 26-story glass office tower connected to a second, smaller building
- Gross floor area: 960,000 square feet
- Occupancy: 3,400
- 15% of floor area occupied by computer facilities
- All-electric building
- 1982 usage (fully occupied) - 36.5 million kWh
- HVAC system: two double-bundle chillers for computer cooling and heat reclaim (for perimeter heating and domestic hot water). Two centrifugal chillers for remaining cooling needs.
- Air distribution: interior VAV, perimeter four-pipe fan coil units.
- Special features: outside air economizer cycle, strainer cycle.

Energy Management System Description

The building is equipped with a Johnson Control JC-80/45, providing HVAC control, security, and fire safety. Software components include: enthalpy economizer, optimum start/stop, demand-limiting and duty-cycling. This same energy management system also collected the data on equipment operation and energy consumption. A total of 350 sensors were used to collect data (about double the number that would have been required for control purposes only; it is not clear what additional costs were incurred for these sensors).

Energy performance monitoring sensors included:

- turbine and pressure differential flow meters (water flow)
- air flow monitors to measure air flow in ducts
- air and water temperature sensors

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* See "Building Automation Analysis - Design and Operational Energy Studies in a New High-Rise Office Building," Vol. 4, U.S. DOE, Report # DOE/CS/20271-4, March 1984 .

- dewcells to measure dewpoint temperatures
- watthour meters
- ammeters
- status indicators to give on/off time for electrical equipment, including run-time for building fans, pumps, and chillers.

Results: EMCS Performance

For retrofit case studies, performance would include pre- and post- retrofit consumption. This case study is for a new building. Some attempt was made to estimate energy usage with and without the EMCS, as summarized below.

1. *Energy consumption and system cost summary.* Table A-2 provides a summary of EMCS functions and their incremental costs and estimated contribution to energy savings, as determined by the monitoring project.

Table A-2
Building Automation Energy & Cost Savings

	System Cost ($)	Energy Savings (kWh/yr)	Cost Savings ($/yr)	Simple Payback (Years)
Demand-Limiting*	15,575	80,000 137 kW	18,000	0.9
Duty-Cycling*	9,675	100,000	6,000	1.6
Enthalpy Economizer**	2,700-18,900	2,750-76,000	165-4,600	16.4-4.1
Optimum Start-Time	18,000	0	0	0
Floating Space Temperature	Not enough data to test			
Duty Cycling w/ Floor Damper	No savings; not implemented, no extra cost			
Injection System	155,000	470,000	28,000	5.5
Total***	217,150	728,000	57,000	3.8

* Demand limiting and duty cycling have resulted in both energy and power savings. All demand savings have been included under demand limiting. Costs have been split between the two; the cost for one strategy alone may be different.

** The range of values for Enthalpy Economizer reflects its use in individual fan systems and the entire building.

*** The total value assumes the best-case savings and payback for the Enthalpy Economizer.

2. *Discussion of results: equipment and implementation.* The total cost of the control system includes other features such as fire control and security. The costs and savings tabulated above are incremental, assuming that the basic system is already in place. This suggests that the savings from any of the energy optimization functions would be extremely marginal, if they had to justify the entire system cost. Further, the injection system (strainer cycle) indicated greater energy savings than all the optimization strategies combined, but is not really an automation function since it can be controlled without an energy management system. (The injection system has not been operated in actual practice due to equipment problems.)

As with most EMCS, the Park Plaza system was sold on the basis of optimization software. However, implementation problems have limited the use of such software in this building. As the summary report states:

> "the difficulties of using the [optimum start] program were so overwhelming that the staff will probably never use it again. The adjustment of constants in the software was such that the routine never performed properly and lost all credibility with the operating staff. Moreover, they discovered that they could develop their own morning routine that worked efficiently."

In general, the EMCS has required continuous adjustment and tuning by knowledgeable building personnel. It is not clear from the report whether or not the vendor provided continuing support after installation.

One of the limits on optimization software effectiveness in the Park Plaza building was its "reliance on the use of commercial instrumentation, which is notoriously inaccurate." According to the report summary, more accurate, industrial-type instrumentation can not be cost-justified in commercial buildings, and typical commercial building operating conditions (e.g. dirty condenser water, frequent changes in building needs and operating conditions) tend to strain the limits of proper instrumentation functions.

The most cost-effective controls in the system turned out to be those with the most reliable and accurate inputs - demand-limiting and duty-cycling, which only required inputs from a demand meter and a time clock, plus the ability to switch a single circuit on or off. However, demand limiting and duty cycling generally only save energy or reduce demand if 1) the system is oversized to begin with, or 2) as a result of implementing the strategy space comfort conditions are not met. Down sizing fans will save more energy than cycling, due to fan laws. In this building, duty cycling has been applied to VAV fans, which will actually *increase* their consumption. The report documentation gives no explanation for these problems; caution should be exercised in relying on the reported results.

Further, due to economizer sensor malfunction (dewpoint sensors) the economizer has been operated as a drybulb rather than an enthalpy economizer.

In spite of the problems encountered, the report concludes the following:

- With today's EMCS technology, many control problems could have been avoided at little extra expense;
- Building management feels that avoided O&M costs due to central control have been "significant," and reduced labor needs are estimated to have resulted in savings greater than direct energy savings from all the optimization strategies combined;
- The inclusion of fire safety systems, security systems, and a staff which uses the system as a tool to optimize building operation has justified the cost of the EMCS in this application.

System Information Gathering Abilities

Many EMCS, including this one, have the ability to collect and tabulate data on equipment operation and energy consumption. This has allowed the building operators to determine which control strategies are most cost-effective, and will help to get most of the bugs out of the system over time. While the system is somewhat limited in the type of reports that can be generated, many newer systems have improved monitoring capabilities at little increased expense.

Information Gaps, Data Problems

The following is a list of the major data problems with the Park Plaza building automation study. In general, the data seem to be sufficiently reliable and accurate, and these problems do not affect the major project conclusions.

- some sensors failed;
- monitoring system unable to generate daily load profiles of some equipment (e.g. chillers);
- some temperature and pressure sensors not calibrated, or located improperly;
- initially, at least 50% of the sensors generated erroneous data due to improper installation or improper signal ranging (most sensors have since been repaired);
- data collection start-up difficulties, including a failed CPU, failed remote loop multiplexing, and failure and deviation of sensors.

APPENDIX B

NATURAL GAS COOKING IN THE PG&E SERVICE TERRITORY

Appendix B

Commercial Natural Gas Cooking in the PG&E Service Territory

Introduction

Over the last several years Pacific Gas and Electric (PG&E) has conducted a number of field studies designed to assist customers in saving natural-gas cooking energy and to determine the conservation potential for gas-fired cooking equipment. This appendix briefly summarizes the results of these studies. * In addition, we discuss some of the research and development work on new high-efficiency gas cooking appliances being conducted by the Gas Research Institute. [1]

Natural gas usage for cooking accounts for about one-percent of the natural gas consumed by the PG&E commercial sector. However, its small contribution to total gas use is partially offset by the large contribution to restaurant, grocery, and hotel/motel energy use. Table B-1 summarizes cooking natural-gas use by major building type. [2]

Table B-1
Pacific Gas and Electric
Actual and Projected Natural Gas Usage for Commercial Cooking

Building Type	Usage (10^6 BTU/year) 1982	2000	EUI[a] (10^3 BTU/ft^2) 1982	2000
Restaurant	365136	319674	8.055	6.794
Hotel/Motel	94478	151521	3.288	2.516
Retail	64757	64973	.737	.569
Health	49421	39493	.996	.778
Office	41139	43214	.481	.385
Grocery	40150	42462	5.957	4.698
Miscell.	23076	22462	.280	.208
Elem/Sec Sch.	12967	10770	.150	.125
Col/Trade Sch.	8058	5872	.140	.117
Warehouse	761	834	.075	.077

[a] EUI- Energy Utilization Index

Source: Pacific Gas and Electric Company, "Commercial Sector Model Run" October 5, 1983.

PG&E Demonstration Projects.

The PG&E cooking demonstration/conservation projects during the last four years have covered a wide range of equipment and activities. Equipment studies have included pizza [3] and general purpose ovens. [4] Activities examined included hospital menu planning, [5] restaurant,[6] and fast food restaurant operations. [7] The nature and scope of these demonstration projects make it difficult to develop generalized conservation savings estimates. There are, however, five major areas of savings that can be identified.

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* Because this is only a limited discussion of natural gas cooking technologies we have not provided either summary data tables or summary data sheets.

1) Menu Planning
2) Decrease in equipment standby time
3) Equipment maintenance
4) More effective use of existing equipment
5) Match equipment to the task

Menu planning

Menu planning for energy conservation calls for changes in the types of food prepared rather than alterations in equipment or changes in food preparation techniques. By its nature this approach is best suited to institutional food preparation facilities such as schools and hospitals.

One example of the impact of menu planning on energy use was provided by the Kaiser Hospital program in Walnut Creek. [8] In this instance the hospital program of frozen preplated meals was found to be "very energy efficient at point of service." The report also noted the system eliminated the need for some capital equipment such as hot food tables, plate warmers, etc.

Decrease in equipment standby time

A common recommendation, in nearly all of the cooking demonstration projects, called for the limitation or elimination of equipment preheating and non-productive standby time. Specific recommendations included cold start or reduced warm-up time for equipment, turning off appliances when not in use, and decreased simmering times for food prepared ahead of time.

Equipment maintenance

In other sections of this report we have emphasized the importance of periodic maintenance for maintaining equipment efficiency. This is no less the case for cooking equipment. The American Gas Association has published a brochure, "Maintenance Tips That Will Help Conserve Energy and Improve Your Food Service Operation", that briefly catalogs such procedures. [9] The energy savings resulting from such measures is difficult to quantify and depends on the operating characteristics and original condition of the equipment.

More effective use of existing equipment

The PG&E studies often indicate there are a number of food preparation techniques that can decrease energy use. This is not surprising since cooking procedures have seldom been developed with energy use in mind. Sometimes something as simple as covering pots when they are being heated can save energy and cooking time. The Lyons restaurant study indicated that putting lids on pots can cut both energy and cooking time in half. [10]

Match equipment to the task

An important energy conservation strategy matches cooking equipment to the task for which it is specifically designed. This matching was well illustrated by tests conducted by Southern California Gas Company in which five different sets of appliances were compared. [11] Open burners were compared to hot top ranges, convection ovens to range ovens, pressure fryers to standard fryers, and grooved griddles to broilers. Water was boiled using five different appliances. Energy savings from these side-by-side experiments clearly demonstrated significant energy savings ranging from 20% less energy for pressure fryer cooking of french fries to 59% less energy for boiling water on an open burner range.

New high efficiency cooking equipment

The PG&E field studies did not examine the potential for improved cooking efficiencies through replacement of equipment. Nonetheless, a very large conservation potential exists for such an approach. According to research conducted by the American Gas Association, nearly two-thirds (64.6%) of annual, national, commercial-cooking appliance sales are for the replacement of equipment. Furthermore, the AGA contends that the operating or cooking efficiency of many old appliances is "well below 40 percent". Table B-2 contains general estimates of the operating efficiency and purchase price of some typical appliances. [12]

Table B-2
Conventional Efficiency and Cost of Various Commercial Appliances

Appliance	Dealer Net Cost ($)	Thermal Efficiency (%)
Griddle	1000	45 to 50
Fryer	900 to 1000	45 to 50
Oven	1300	58
Range	1200 to 1400	45

Source: James R. Hurley, and Robert A. Panora, "Opportunities for New and Existing Technologies in Commercial Cooking Equipment", presented at *11th Energy Technology Conference*, March 19-21, Washington, D.C.

In response to these factors the AGA has developed (and tested), and manufacturers are now marketing high-efficiency, free-standing, direct-fired, forced-convection ovens, infrared-fired deep fat fryers, and direct-fired, range convection ovens. Development is also underway of power burners for open top ranges and pulse combustion burners for top fryers or closed top ranges.

Table B-3 summarizes energy savings and the additional cost premium for various generic improvements in cooking appliance efficiency.

Table B-3

Cooking Appliance Technology Improvements

Estimated Additional Selling Cost

Technology	Percent Improvement Range			
	0-10	10-25	25-50	50+
Conventional Technologies				
-Reduction in Excess Air	$50			
-Improved Insulation	$75			
-Simple Extended Surface		$120		
Advanced Technologies				
-Pulse Combustion				$500
-Heat Pipe/ Power Combustion				$600
-Jet Impingement Power Combustion			$300	$500
-Infrared Burners/ Power Combustion			$500	
-Catalytic Burners			$400	

Source: James R. Hurley, and Robert A. Panora, "Opportunities for New and Existing Technologies in Commercial Cooking Equipment", presented at *11th Energy Technology Conference,* March 19-21, Washington, D.C.

Tables B-2 and B-3 show that equipment improvements can represent up to a 60% cost addition above the conventional unit. Hurley [13] notes that "[i]t is generally accepted in commercial cooking that a payback period of 3 years is considered the maximum." How close these design improvements will be to the 3 year threshold will depend on the amount of use the equipment receives annually and the efficiency of the original equipment. For example adding a catalytic burner to a typical griddle will improve the thermal efficiency of a unit about 35%. If the griddle cooks an average of 300 pounds of food per day, annual fuel cost savings (at $0.55/therm) will be $214 for a 1.9 year payback. If the griddle only handles 100 lbs/day the savings drop to $115 or a 3.5 year payback. [14]

Simple payback will not be the only factor influencing a decision to by new high-efficiency equipment. Other non-economic factors including equipment reliability, ease of operation, ease of maintenance, operating features, and equipment lifetime may be even more important.

Conclusions

The material presented above is very limited in its coverage of natural gas cooking conservation, nevertheless, there are several significant conclusions;

- Although natural gas use for commercial cookings represents only a small fraction of total sector gas consumption, usage in individual establishments (especially restaurants) can be high.

- The conservation potential for both improved utilization of the cooking equipment (e.g. menu planning) and high efficiency replacements for existing equipment is high.
- High-efficiency equipment can result in energy savings of up to 40 to 65 percent.
- In many instances, operating changes offer large energy savings, but may be difficult to implement. Care must be taken to avoid problems such as increased cooking time, reductions in food quality, or other changes that influence food preparation and quality. PG&E should continue to offer energy conservation outreach programs to help minimize these problems.
- Menu planning for energy conservation should concentrate on institutional, rather than retail cooking establishments.
- There is substantial variation in food preparation techniques and menus for restaurants. These differences make it difficult to generalize conservation program approachs and customized assistance programs will continue to be needed.
- It is estimated that two-thirds of annual cooking appliance sales are for the replacement market. New equipment offers very large increases in efficiency at relatively modest incremental cost increases. Consequently PG&E should consider targeting information and incentive programs to encourage replacement purchases of the new high-efficiency models in place of lower-efficiency units. [15]

Notes and References

1. This material is based on Hurley, James R., and Robert A. Panora, "Opportunities for New and Existing Technologies in Commercial Cooking Equipment", and Himmel, Robert L., "Advanced Commercial Cooking Equipment", both presented at the *11th Energy Technology Conference,* March 19-21, 1984, Washington D.C.
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5. "Preplated Hot Food Meal Service in Health Care: An Evaluation of Microwave Oven Energy Use, Kaiser Hospital--Walnut Creek, CA, August 1982; Cushman, Suzanne, and Bettie C. Ferlin, "An Energy Evaluation of Menu Preparation Within a Health Care Facility from a Study at Intercommunity Hospital, Fairfield, CA., *PG&E Demonstration Project No.* 06D-82-01.
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8. Kaiser Hospital, Walnut Creek, op. cit., p 8.
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11. Results of these test are reported in the PG&E *Technical Services Bulletin,* 1981-18, February 12, 1981.
12. Robert L. Himmel, "Advanced Commercial Cooking Equipment", presented at, *11th Energy Technology Conference,* March 19-21, 1984, Washington D.C.

13. Hurley, op. cit., p 5.
14. Hurley, op. cit., p 8.
15. Himmel, op. cit., p 1.

APPENDIX C

GAS SPACE HEATING EQUIPMENT

Appendix C

Gas Space Heating Equipment

Introduction

This section reviews some of the latest developments in gas space heating equipment, specifically, condensing heating equipment (furnaces, water boilers, and add-on heat exchangers), pulse combustion burners and direct-fired space heaters for improving boiler and furnace efficiency. This portion of the report is limited in scope; we identify available products and their performance, and cite costs where possible. We have not examined any shell improvements or systems modifications for reducing space heating consumption. In commercial buildings, a large portion of heating energy can be used for both morning warmup and reheating of cooled air, depending on the HVAC system type (see Section 2.4, HVAC Systems). Shell improvements have little impact on reducing heating consumption for these purposes. In many instances, elimination of simultaneous heating and cooling will have the biggest impact on overall heating consumption. Here, however, we only discuss options for improving heating equipment efficiency.

TECHNOLOGY DESCRIPTIONS

1. Condensing Equipment

Improvements in conventional heating equipment efficiencies are constrained by the fact that the heat in hot combustion gases are wasted out the stack (or flue). *Condensing equipment* recovers the latent heat of vaporization of water by lowering the temperature of the combustion products until the water vapor condenses out. This heat can be 1) transferred to the supply air stream, 2) used to preheat combustion air or boiler feed water, or 3) used for some other building heating requirement, such as domestic hot water. Manufacturers claim steady state efficiencies of 90-95%, compared to 60-85% for conventional equipment. (Efficiencies are based on Btus of heat delivered vs. Btus of fuel input, and do not include consumption of any auxiliary equipment, such as fans.) [1] In conventional systems, the high temperature of the combustion products helps to carry the products up the flue (stack effect). Lowering the temperature of the combustion products to the condensing point results in a loss of stack effect. Although condensing equipment does not require a flue, the uncondensed gases must be blown out mechanically, and the condensed water drained or pumped out of the system. Since the condensed water is slightly acidic, the condensing heat exchanger must be protected from corrosion; however, conventional drains are adequate to dispose of the water.

Available Products. Condensing equipment has been developed (and is being aggressively marketed) for residential systems (less than 100,000 Btu/hr output). Systems of this size are suitable for some small commercial applications. Further, some units are modular and several can be used together to meet the needs of larger buildings. Condensing equipment is available for new construction or retrofit applications. Elimination of the flue offsets increased costs, and increases retrofit flexibility. Either new furnaces or boilers can be installed, or condensing heat exchangers can be installed in the exhaust stack. Some of the condensing equipment currently available includes:

- Heat Extractor, Inc. (Massachusetts), manufactures a direct water contact secondary heat exchanger that can be retrofitted on oil or gas hot-air furnaces. The manufacturer claims a steady-state furnace efficiency of 95%. One independent test of the unit showed a 15% efficiency improvement (from 77% to 92%); another showed an efficiency drop of 0-5%. (There was no explanation available for these discrepancies.) These are residential sized units. [2]
- The Condensing Heat Exchanger Corp. (New York) manufactures a condensing heat exchanger coated with corrosion-resistant Teflon. The manufacturer estimates fuel savings

of up to 15%. Intended for the commercial and industrial heat reclaim market, this unit is available in a wide range of sizes. [3]

- Arkla and Lennox also manufacturer condensing furnaces (residential scale, less than 100,000 Btuh).

2. Pulse Combustion Burners

Pulse-combustion burners ignite the fuel-air mixture within a combustion chamber, creating a pressure pulse that closes the inlet valves and ejects the combustion products. The subsequent pressure drop draws in more air and fuel, which is ignited by heat and flames left from the previous cycle. The positive pressure forces the combustion products out of the device; neither a mechanical blower nor a flue is required. The combustion products can be passed through a heat exchanger (condensing or non-condensing) to recover waste heat. The high turbulence of the combustion products improves heat transfer and improves efficiency. Manufacturers claim steady state efficiencies of 90-95%.

Potential problems with pulse combustion burners include high noise levels, and difficulties in scaling successful designs up or down to other sizes (meaning that successful residential designs may not be easily transferred to larger commercial systems).

Pulse combustion technology is also being considered for non-space heating equipment. Present research efforts aimed at commercial applications include development of pulse-combustion cooking appliances (deep-fat fryer and griddle), water heaters, and steam boilers.

Table C-1

Commercial Pulse Combustion Equipment Under Development

Appliance	Commercialization Target Date	Efficiency	Comments
Deep Fat Fryer	April 1985	80%	40-50% more efficient than conventional. 15-20% more efficient than infrared.
Griddle	December 1985	N/A	Prototype (12"x24") has 20,000 Btu/hr input.
Water Heater	April 1986	90%	Likely input capacities of 500,000; 750,000; 1,000,000 Btu/hr.
Steam Boiler	October 1987	86%	Two sizes being developed: 500,000 and 2,000,000 Btu/hr.

Source: "Pulse combustion - A Versatile Technology for High Efficiency Appliances," Gas Research Institute Digest (GRID), Volume 7, Number 3, May/June 1984.

Available Products. Pulse combustion burners, like condensing equipment, have been developed primarily for residential scale systems. Some small commercial buildings may be able to use this equipment.

- HydroTherm, Inc. (New Jersey), manufacturers a pulse combustion boiler called the Hydro-Pulse. Several units can be combined for larger systems (Multi-Pulse). One unit has a rated input of 100,000 Btu/hr. The manufacturer claims efficiencies of over 90%. One college (New York) installed 3 units, at a cost of $10,000, and has steady state efficiencies of 91-94%. This system had a payback of 8 months. A girls' day school (Connecticut) installed 28 units at a cost of $215,000, with annual savings of $22,800. [4]

o Lennox manufactures a pulse combustion furnace (residential) with a steady state efficiency of 91-96%. [5]

3. Direct-Fired Space Heaters

Direct-fired space heaters without heat exchangers are now available for some commercial applications. These heaters send combustion gases directly into the space to be heated, and rely on enough outside air to dilute combustion products to safe levels. These heaters are primarily used to heat make-up air where there are high air change ratios. In theory, these heaters can be 100% efficient. [6]

CONCLUSIONS AND DATA GAPS

There is little *commercial sector* experience with these types of gas space heating equipment. Manufacturer's claims and laboratory tests need to be verified through sub-metered case studies, and reliability and maintenance questions need to be answered. It does seem that efficiencies in the 90-95% range are possible. With condensing equipment, increased equipment costs may be partially offset by elimination of flue costs.

We identified the following data gaps:

o Characteristics of gas-heated building stock suitable for small-scale equipment: loads, operating schedules, equipment characteristics, physical constraints (from surveys, site visits).

o Long-term performance and reliability of systems under non-residential conditions.

o More extensive comparison of performance and cost-effectiveness of condensing gas heating equipment vs. gas heat-pumps (absorption cycle and gas-engine), including combined heating/cooling performance and economics, electrical peak demand avoidance, and various system scales.

Notes and References

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ABBREVIATIONS

A_e	Effective Aperture
AC	Alternating Current
ACEEE	American Council for An Energy-Efficient Economy
ADL	Arthur D. Little
AEE	Association of Energy Engineers
AGA	American Gas Association
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
BECA	Buildings Energy Use Compilation and Analysis
BTU(H)	British Thermal Units (per Hour); also Btu(h)
CA	California
CEC	California Energy Commission
cfm	Cubic feet per minute
C/I/A	Commercial-Industrial-Agricultural
COP	Coefficient of Performance
CPU	Central Processing Unit
CRI	Color Rendering Index
CV	Constant Volume
DB	Dry Bulb
DC	Direct Current
DDC	Direct Digital Control
DX	Direct Expansion
EER	Energy-Efficiency Ratio (equal to COP x 3.412)
EMCS	Energy Management and Control System
EMI	Electro-Magnetic Interference
EPRI	Electric Power Research Institute
EUI	Energy Utilization Index
EVSD	Electronic Variable Speed Drive
FC	Footcandle
ft^2	Square foot (also sf)
FY	Fiscal Year
GJ	Gigajoules (10^9 joules)
HID	High-Intensity Discharge
HP	Horsepower
HPS	High-Pressure Sodium
HVAC	Heating, Ventilating, and Air Conditioning
kHz	(kilo)Hertz
IEEE	Institute of Electrical and Electronics Engineers
IES	Illuminating Engineering Society
kW	Kilowatt
kWh	Kilowatt-hour
LBL	Lawrence Berkeley Laboratory
LLF	Light Loss Factor
LPS	Low-Pressure Sodium
MBTU	Million British Thermal Units
mph	Miles per Hour
MVSD	Mechanical Variable Speed Drive
NEMA	National Electrical Manufacturers Association
O&M	Operation and Maintenance
ORNL	Oak Ridge National Laboratory
OSA	Outside Air
PG&E	Pacific Gas and Electric
RFI	Radio Frequency Interference

SC	Shading Coefficient
SCM	Shading Coefficient Multiplier
SCE	Southern California Edison
SEER	Seasonal Energy-Efficiency Ratio
SHC	Simultaneous Heating and Cooling
TEFC	Totally-Enclosed Fan-Cooled (motor)
TES	Thermal Energy Storage
TMY	Typical Meteorological Year
Tv	Visible Transmittance (also VT)
VAV	Variable Air Volume
VSD	Variable Speed Drive
VT	Visible Transmittance (also Tv)
VT	Variable Temperature (cooling)
VTM	Visible Transmittance Multiplier
W	Watts
WB	Wet Bulb
WF	Well Factor
Wh	Watt hour
WYEC	Weather Year for Energy Calculation
WWR	Window-to-Wall Ratio

GLOSSARY

This glossary contains terms that are widely used throughout this report. Material for this glossary was taken from the following sources:

1) California Energy Commission, "Energy Savings Potential in California's Existing Office and Retail Buildings," Staff Report, June 1984.
2) Federal Energy Administration, "Guidelines for Saving Energy in Existing Buildings: Building Owners and Operators Manual, ECM 1," June 16, 1975.
3) American Society of Heating, Refrigerating and Air-Conditioning Engineers, *Cooling and Heating Load Calculation Manual,* 1979.
4) California Energy Commission, "Guide to HVAC Equipment," September, 1980.
5) Illuminating Engineering Society, *Lighting Handbook: Reference Volume,* 1981
6) American Society of Heating, Refrigerating, and Air-Conditioning Engineers, *1981 Fundamentals,* 1981.

Absorption Chiller: A water chiller which produces chilled water directly from the application of heat energy. An absorbing material absorbs refrigerant when cold and rejects refrigerant when hot.

Absorptivity: The physical characteristic of a substance describing its ability to absorb radiation.

Ambient: Surrounding (i.e. ambient temperature is the temperature in the surrounding space).

Ambient Lighting: Lighting throughout an area that produces general illumination.

Apparent Efficiency (motor): This is the product of a motor's efficiency and its power factor.

ASHRAE 90: Voluntary new-building standards developed by ASHRAE. These standards include minimum equipment efficiencies, building envelope characteristics, and required control strategies for non-residential buildings.

Average Efficiency (motor): See nominal efficiency.

Building Envelope: All external surfaces which are subject to climatic impact; for example, walls, windows, roof, floor, etc.

Cavity Ratio: A number indicating cavity proportions calculated from length, height, and width. The Title 24 Building Standards (Nov 29, 1983) define Room Cavity Ratio as

$$RCR = \frac{5H(L + W)}{LW}$$

where:

RCR = Room Cavity Ratio
L = Length of the room
W = Width of the room
H = vertical distance from the work plane to the lighting fixture
(Equation 2-53P)

Centrifugal Chiller: A refrigeration machine which uses centrifugal action to raise the pressure level of the refrigerant gas. Chiller unloading is generally regulated by varying the flow of refrigerant gas with variable inlet vanes on the input side of the chiller.

Centrifugal Fan: Device for propelling air by centrifugal action. Forward curved fans have blades which are sloped forward relative to direction of rotation. Backward curved fans have blades which are sloped backward relative to direction of rotation. Backward curved fans are generally more efficient at high pressures than forward curved fans.

Chiller: A refrigeration machine that produces cooled water, generally at a temperature of 40-55°F. Types include reciprocating, screw, centrifugal, and absorption.

Coefficient of Performance (COP): A measure of cooling or refrigeration equipment efficiency, defined as cooling output/energy input, with both quantities in the same units (e.g. kW or Btuh). Electric cooling equipment has COPs ranging between 2 and 6. See also EER.

Compressor: A mechanical device which increases the pressure, and thereby temperature, of a refrigerant gas.

Condenser: In refrigeration cycles, the component which rejects heat; a heat exchanger which removes latent heat from a vapor by changing it to its liquid state. Condensers can be either air cooled, water cooled, or evaporatively cooled (heat rejected by evaporating water into air).

Conductance, Thermal: A measure of how easily heat flows through a substance.

Constant Volume System: An air transport system which has a *fixed* air flow rate.

Coefficient of Utilization (CU): The ratio of lumens (luminous flux) from a luminaire received on the work plane to the lumens produced by the luminaire's lamps alone.

Color Rendering: A general expression for the effect of a light source on the color appearance on objects in comparison with their color appearance under a reference light source.

Color Rendering Index (CRI): A measure of the degree of color shift objects undergo when illuminated by the light source as compared with the color of these same objects when illuminated by a reference source of comparable color temperature.

Cooling Load: The heat and moisture additions to a building that must be removed in order to maintain comfortable temperature and humidity conditions.

Cooling Tower: Device that cools water directly by evaporation. Used to reject heat from one or more condensers.

Damper: A device used to vary the volume of air passing through an air outlet, inlet, or duct.

Desiccant: A substance possessing the ability to absorb moisture. Air passed through a desiccant loses moisture (latent heat) as it gains sensible heat (dry bulb temperature increases).

Diffuser: A device to redirect and scatter the light from a source.

Direct Evaporative Cooler: An evaporative cooler which cools an air stream by passing it over a wetted media. By evaporating water into the air stream, the sensible heat is lowered while the latent heat increases.

Direct Expansion (DX): Generic term used to describe refrigeration systems where the cooling effect is obtained directly from the refrigerant. The refrigerant is evaporated directly in a cooling coil in the air stream, as opposed to using cold refrigerant to chill water, which is then sent to the cooling coils.

Discharge: The outlet (high pressure) side of a refrigeration compressor.

Discharge Dampers: Dampers which regulate the flow of air on the outlet side of a fan on variable air volume system. This is the least efficient method of regulating air flow.

DOE-2: A computer program that simulates the energy consumption of a building. Developed at Department of Energy research labs.

Double Bundle Condenser: Condenser (usually in refrigeration machine) that contains two separate heat exchangers for rejecting heat, allowing for the option of either rejecting heat to the cooling tower or to another building system requiring heat input, such as hot water for space heating or domestic hot water needs.

Dry Bulb Temperature: The measure of the sensible temperature of air.

Dual Duct System: An air transport system in which there are two air ducts, one of which is heated and the other cooled. Air of the correct temperature for a particular zone is obtained by mixing varying amounts of each stream.

Economizer Cycle: A control system which brings in outside air to cool zones when outside air conditions are favorable. A dry-bulb economizer is controlled by dry bulb temperature only (sensible heat content). An enthalpy economizer compares total heat content (latent and sensible) of outside air and return air.

Effective aperture (A_e): A measure of the daylight admitting capability of a glazed opening obtained by multiplying the window-to-wall ratio times the visible transmittance. For skylights the value is further multiplied by the light *well factor*.

Efficiency (motor): In general, this is the ratio of the mechanical power output to the electrical power input. See other efficiencies: Apparent, Minimum, and Nominal.

Efficacy: (More precisely, "luminous efficacy of a source of light") The quotient of the total luminous flux emitted by the total lamp power input. It is expressed in lumens per watt.

Electric lighting power density: The total installed lighting power, including ballast and lamp power, per square foot of lighted space.

Energy Efficiency Ratio (EER): A measure of cooling equipment efficiency, defined as (cooling output in Btuh)/(electric input in Watts). EER = COP x 3.413. SEER is seasonal energy efficiency ratio, averaged over the different part load ratios of equipment throughout the cooling season.

Enthalpy: For the purpose of air conditioning, enthalpy is the total heat content of air, usually in units of Btu/lb. It is the sum of sensible and latent heat content.

Evaporative Cooling: The adiabatic exchange of heat between air and a water spray or wetted surface. The water assumes the wet-bulb temperature of the air, which remains constant during its traverse of the exchanger.

Evaporator: In a refrigeration system, the component which absorbs heat; a heat exchanger which adds latent heat to a liquid changing it to a gaseous state. In a direct expansion system, the evaporator is the cooling coil. In a chilled water system, the evaporator exchanges heat with water, which is then circulated to the cooling coils.

Expansion Valve: A valve located between the condenser and the evaporator used to provide a pressure drop which allows the refrigerant to vaporize at a low temperature in the evaporator.

Exterior Zones: See "Perimeter Zones."

External Load: Any load due to sources external to the space, such as conduction through walls or solar radiation through glass.

Ground-Source-Heat Pump: A heat pump which uses the ground as a heat source or heat sink.

Ground Water Source Heat Pump: A heat pump which uses the ground water (or aquifer) as a heat source or heat sink.

Heat Gain: Heat addition (either sensible or latent) to the building interior.

Heat Loss: Heat transferred from the building interior to the outdoors. Conduction through building elements and infiltration are two heat loss sources.

Heat Pump: An air conditioner which is capable of heating by refrigeration, and which may or may not include a capability for cooling.

Heat, Latent: Heat required to effect a change in state. With regards to HVAC, refers to the energy associated with water in the vapor state. Energy is required to condense the water in order to remove it from the building.

Heat, Sensible: Heat that causes a temperature increase. (To be contrasted with latent heat, which does not change temperature but adds water vapor.)

Hermetic Compressor: Also known as Welded-shell Hermetic Compressor. A type of refrigeration compressor in which the electric motor is welded inside the compressor housing. The motor heat is removed by the refrigerant. The unit is generally not serviceable.

High-Intensity Discharge Lamp (HID): An electric discharge lamp in which the light producing arc is stabilized by wall temperature, and the arc tube has a bulb wall loading in excess of three watts per square centimeter. HID lamps include mercury vapor, metal halide, and high-pressure sodium.

High-Pressure Sodium Lamp: An HID lamp whose output is mainly dependent upon sodium vapor at a pressure of about 10^4 Pascals.

Horsepower: A unit of power equal to 746 watts. In compressor sizing, it is the full-load (output) rating of the electric motor driving the compressor.

Humidity, Relative: A measurement indicating moisture content of air, expressed as a percentage of the saturation moisture content at the same dry bulb temperature.

HVAC System: A system that provides either collectively or individually the processes of comfort heating, ventilation and/or cooling within or associated with a building.

Hydronic Heat Pump: A system of multiple heat pumps (each serving one zone) which reject or gain heat from a common circulating water loop.

Indirect Evaporative Cooler: An evaporative cooler which cools an air stream by exchanging heat with another air stream which has been cooled by a direct evaporative process. The sensible heat (dry bulb temperature) of the air-stream decreases, while the moisture content remains constant.

Infiltration: The uncontrolled inward air leakage through cracks in the building envelope, and especially around windows and doors.

Inlet Vanes: In a variable air volume system, variable vanes on the inlet side of a fan which regulate fan flow.

Interior Zones: The areas of the building which do not have significant amounts of exterior surfaces. Such zones have heating or cooling needs (usually cooling only) largely dependent upon internal loads such as lights.

Internal Load: Any load due to sources contained in the space such as machinery waste heat, lighting, or people.

Lamp Lumen Depreciation Factor (LLD): The multiplier expressing the decrease in the light output of a lamp over its lifetime. Lumen depreciation is due to blackening, phosphor deterioration, and other factors.

Latent Load: The energy required to remove moisture from the room air in order to maintain comfortable humidity conditions. See "Heat, Latent."

Light Loss Factor (LLF): A factor used in calculating illuminance mainly taking into account the light losses because of dirt accumulation on the luminaires (LDD) and wall surfaces, lamp depreciation (LLD), maintenance intervals, temperature, and voltage. This term formerly was known as 'maintenance factor'.

Load Leveling: Deferment of certain loads to limit electrical power demand to a predetermined level.

Load Profile: Time distribution of building heating, cooling, and electrical loads, usually on an hourly basis over a day.

Low-Pressure Sodium: A discharge lamp in which light is produced by radiation from sodium vapor operating at a low pressure (1 Pascal or less).

Lumen: SI unit of luminous flux.

Luminaire: A complete lighting unit consisting of lamp(s), ballast(s), reflector(s), and the housing.

Luminaire Dirt Depreciation (LDD): The decline in the the light output of a luminaire due to the accumulation of dirt on luminaire.

Maintenance Factor (MF): A term formerly used for Light Loss Factor.

Mechanical Cooling: Cooling that is done by energy-using cooling equipment such as chillers and air conditioners. Cooling accomplished through use of outside air or by evaporative collers is *not* considered mechanical cooling.

Mercury Vapor Lamp: An HID lamp, whose light is mainly produced by radiation from mercury vapor.

Metal Halide Lamp: An HID lamp, whose light is mainly produced by radiation from metal halides.

Minimum efficiency (motor): The efficiency below which none of a group of motors of the same specification will fall. Sometimes guaranteed by the motor manufacturer. *not* mechanical cooling.

Mixing Box: A device used in a dual duct system to receive hot and cold air and to discharge air of a desired temperature. An internal, movable vane adjusts the mixture under the control of the room thermostat.

Multi-zone System: An air conditioning system which functions like a dual duct system, but the mixing takes place at the air handler. A separate duct, carrying air at the correct temperature, goes to each zone.

NEMA: National Electrical Manufacturers Association

Nominal efficiency (motor): The average expected efficiency for a group of motors of the same specification. Half of the motors are expected to fall below the nominal value, half above.

Open-Drive Compressor: A type of compressor where the motor and compressor are in separate housings, coupled by a shaft or belt drive.

Part Load Ratio: The ratio of output from a piece of equipment at a given time to the equipment's rated output. For example, if a piece of cooling equipment is putting out 60% of its full cooling capacity, the part load ratio is 0.6.

Pascal: SI unit of pressure equal to one Newton of force per square meter of area. One atmosphere is about 10^5 Pascals.

Peak Cooling Load: The maximum rate of cooling occurring during the year in a building.

Perimeter Zones: The areas of a building with significant amounts of exterior wall, windows, roofs, or exposed floors. Such zones have heating or cooling needs largely dependent upon climate conditions.

Phase Change Material: For use in cold storage systems, a material which changes phase (liquid/solid) at a temperature which is close to typical air conditioning operating temperatures (40-55°F).

Power factor: The ratio between the real power (measured in kilowatts) and apparent power (measured in kilovolt-amperes). It is equal to the cosine of the phase angle between the voltage and current waves.

Pressure Drop: Pressure loss in fluid or air transport system due to friction. An example is the pressure loss from one end of a duct to the other.

R-Value: The resistance to heat flow expressed in units of ft^2-hr $^{\circ}$F/Btu.

Reciprocating Compressor: A refrigeration machine which uses positive displacement pistons for compression.

Refrigerant: The working fluid of the refrigeration system. Common refrigerants include R-12, R-22, and R-502 (called halocarbons because they are halogenated hydrocarbons) and R-717 (ammonia).

Reheat System: An air conditioning system that first overcools the air, then heats it to the desired temperature. Usually there is a single cooling coil, and many heating coils. Each heating coil is controlled by a room thermostat.

Reset Control: A control strategy where the set point temperature of a heating or cooling device can be changed. For example, as cooling demand diminishes, the temperature of air leaving the cooling coils can be raised.

Roof Spray Cooling: A system that reduces heat gain through a roof by cooling the outside surface with a water spray.

Rotor: The part of the motor which rotates.

Screw Compressor: A machine which compresses refrigerant by trapping a volume of it between a stationary wall and two mating, helical rotors.

Seasonal Efficiency: Ratio of useful output to energy input for a piece of equipment over an entire heating and cooling season. It can be derived by integrating part load efficiencies over time.

Semi-hermetic compressor: A type of refrigeration compressor where the motor is in the same pressure vessel as the compressor, but the two are bolted together and are thus field-repairable.

Sensible Cooling Load: Sensible heat gains that need to be removed to maintain comfortable space temperatures. (See "Heat, Sensible").

Shading coefficient (SC): The fraction of solar thermal gain through a glazing material or system compared to a reference glazing material. The reference glazing material is typically 1/8" thick clear glass.

Shading coefficient multiplier (SCM): The multiplicative effect of a secondary fenestration component on the primary component. In this report it is the multiplier used for a shading device (blind or drape) with glazing.

Slip: The difference in operating speed from the synchronous motor speed. For example, an 1800 rpm motor operating at a full load speed of 1725 rpm is running at a slip of 4.2%.

Space Conditioning Loads: The heat gains and losses in the building that need to be counteracted by heating and cooling in order to maintain comfortable temperature and humidity conditions.

Stator: The non-rotating magnetic section of a motor. In the induction motor, the stator contains the windings.

Suction: The inlet (low pressure) side of a refrigeration compressor.

Synchronous speed: The speed at which the motor's magnetic field rotates, and the approximate speed of no-load operation. A four-pole motor running on 60 cycle per second power will have a synchronous speed of 1800 rpm; a two-pole motor at the same frequency, 3600 rpm. See also "slip".

Task Lighting: Lighting directed to a specific surface or areas that provides illumination for visual tasks.

Task-ambient Lighting: A combination of task lighting and ambient lighting within an areas such that the general level of ambient lighting is lower than complementary to the task lighting.

Title 24: Building standards in California for new buildings. Every new building design must comply with these standards, either by meeting a set of prescriptive standards or by showing, through computer simulation, the building design performs below a set energy budget.

Ton-hour of Refrigeration: A measure of cooling storage; 1 ton-hour = 12,000 Btu.

Ton of Refrigeration: A measure of cooling capacity, 1 ton = 12,000 Btu/hour of cooling.

Torque: The twisting force exerted by the motor shaft on the load. Torque is measured in units of length times force, e.g. foot-pounds or inch-pounds.

Troffer: A recessed luminaire with the opening flush with the ceiling.

Variable Air Volume (VAV): An HVAC system where the amount of cooling is controlled by changing the air flow rate.

Variable Speed Drives: Motor drives which change motor speed to regulate fan air flow in a variable air volume system.

Ventilation: The fresh air introduced specifically for the purpose of maintaining good air quality (i.e. free from impurities) in the building. Usually is taken from outdoors, but can be *purified*, recirculated air.

Visible transmittance (Tv or VT): The fraction of visible light transmitted by a glazing material or system.

Visible transmittance multiplier (VTM): The fraction by which the visible transmittance of a primary glazing system must be multiplied to obtain the visible transmittance when the primary system is combined with a secondary system.

Well factor (WF): The fraction of admitted visible light transmitted through a skylight well to the interior space.

Wet Bulb Temperature: The lowest temperature attainable by evaporating water in the air without the addition or subtraction of energy. The wet bulb temperature is a good measure of the enthalpy (sensible plus latent heat content) of air. The wet bulb temperature is less than the dry bulb temperature; as the humidity of air rises, the wet bulb approaches the dry bulb, equaling it under saturation conditions.

Window-to-wall ratio (WWR): The ratio of glazed aperture area to total area of the building envelope plane. For walls the total area is measured from floor to ceiling. For roofs the total area is measured wall to wall.

Zone: A space or group of spaces (a room, portion of a room or group of rooms) which has similar heating and cooling needs and can therefore be controlled by a single thermostat.