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Buildings Sector Demand-Side Efficiency Technology Summaries

J.G. Koomey, F.X. Johnson, J. Schuman, E. Franconi, S. Greenberg, J.D. Lutz, B.T. Griffith, D. Arasteh, C. Atkinson, K. Heinemeier, Y.J. Huang, L. Price, G. Rosenquist, F.M. Rubinstein, S. Selkowitz, H. Taha, and I. Turiel

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BUILDINGS SECTOR
DEMAND-SIDE EFFICIENCY TECHNOLOGY SUMMARIES

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Table of Contents

Abstract

This report provides descriptions of the following energy efficiency technologies: energy management systems; electronic fluorescent ballasts; compact fluorescent lamps; lighting controls; room air conditioners; high albedo materials, coatings and paints; solar domestic water heaters; heat pump water heaters; energy-efficient motors; adjustable-speed drives; energy-efficient refrigerators; daylight control glazing; insulating glazing; solar control glazing; switchable glazing; tree planting; and advanced insulation. For each technology, the report provides a description of performance characteristics, consumer utility, development status, technology standards, equipment cost, installation, maintenance, conservation programs, and environmental impacts.

Introduction

The buildings sector technology summaries in this report were developed at Lawrence Berkeley Laboratory (LBL) for use in a database of supply-side and demand-side technologies developed by Pacific Northwest Laboratories under contract to the U.S. Department of Energy (DOE).[1] DOE funded the creation of this database so that the Intergovernmental Panel on Climate Change (IPCC) could disseminate the latest information on carbon-reducing technologies in electronic form to individuals and institutions around the world. This report was initially prepared as the basis for the building technologies section of the database. We have updated the original summaries and added a short discussion (with references) of complex integration issues not explicitly treated in this report.

The energy-efficiency technologies described in this report were chosen by DOE from a list of possible options submitted by LBL. While this compilation is by no means comprehensive, we feel that the short synopses on important efficiency technologies contained in this report will be helpful to policy makers and analysts.

LBL has unique expertise on energy demand and conservation potential in buildings. Researchers in LBL's Energy Analysis Program have substantial experience in assessing national energy forecasts and policies affecting energy use, in the development and application of techniques for forecasting energy demand, and in building an extensive and documented energy conservation supply curve for the residential sector. LBL collaborated in the development of many of the technologies described in this report, including electronic fluorescent ballasts, compact fluorescent lamps, daylight control glazing, insulating glazing, solar control glazing, switchable glazing, and advanced insulation. Room air conditioners, heat pump water heaters, and energy-efficient refrigerators have been extensively analyzed by LBL researchers in conjunction with the analysis of the U.S. appliance efficiency standards. LBL has also pioneered research on tree planting and high albedo materials, coatings, and paints through its Urban Heat Island studies.

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1. This report was created under the supervision of Jonathan Koomey, with substantive contributions and editorial assistance from Francis X. Johnson, Jennifer Schuman, Ellen Franconi, Steve Greenberg, Jim D. Lutz, Brent T. Griffith, Dariush Arasteh, Celina Atkinson, Kristin Heinemeier, Y. Joe Huang, Lynn Price, Greg Rosenquist, Francis M. Rubinstein, Steve Selkowitz, Haider Taha, and Isaac Turiel. We would like to thank the following reviewers for their valuable comments: Michael Shepard and staff (E-Source), Evan Mills (Center for Building Science. LBL), Rich Brown (Energy Analysis Program, LBL), and Nathan Martin (Energy Analysis Program, LBL). This work was funded by the Office of Policy, Planning, and Analysis of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Systems Integration Issues

This report treats individual technologies in isolation and does not discuss benefits that occur from interactions when individual components are combined either at the equipment level or through smart building design. Benefits from such systems integration generally include capital cost and energy savings. They sometimes also include the added side benefits of improved indoor environment, reduced noise, enhanced labor productivity, and increased amenity. This section provides a brief list of references on this topic for readers interested in exploring them further.

Capital cost savings from integrated designs

Reducing heat losses and gains from the building shell can allow the designer to reduce the size of the furnace or cooling equipment, or eliminate it entirely. In some cases, such redesign saves capital costs, but successful application of this technique requires a whole-system approach to design. The following references explore these issues.

- Capital cost credits for displaced heating systems

Gregerson, J., Stickney, B.L., Houghton, D., Newcomb, J., George, K., Shepard, M, and Wilson, A., 1993. *Space Heating Technology Atlas*, Boulder, CO: E-Source.

Hodges, Laurent, 1985. "The Effects of Internal Gains on Residential Space-Heating Analyses," *Energy* 10(12):1273-1276, December.

Kweller, E.R., 1992. "Derivation of the Combined Annual Efficiency of Space/Water Heaters in ASHRAE STANDARD 124-1991," ASHRAE Transactions: Symposia.

Pacific Gas and Electric Company, 1993. "Stanford Ranch Residential Demonstration," ACT2 for Maximum Energy Efficiency Fact Sheet, December.

- Capital cost credits for displaced cooling systems

Houghton, D.J., Bishop, R.C., Lovins, A.B., Stickney, B.L., Newcomb, J.J., Shepard, M., and Davids, B.J., 1992. *State of the Art: Space Cooling and Air Handling*, Boulder, CO: E-Source, TA-SC 92, August.

E-Source, 1993. "Hot-Climate House Predicted to Need No Air Conditioner, Cost Less to Build," Tech Memo TM-93-5, November.

Pacific Gas and Electric Company, 1993. "Davis Residential Demonstration," ACT2 for Maximum Energy Efficiency Fact Sheet, September.

Pacific Gas and Electric Company, 1993. "New Cooling System at Pilot Demonstration," ACT2 for Maximum Energy Efficiency Fact Sheet, September.

- Integrated appliances

EPRI, 1993. "High-Efficiency Powermiser Introduced," *End Use News*, Summer.

Sims, C., 1989. "New Heat Pump Cuts Power Cost," *New York Times*, February 8.

Associated energy savings for HVAC systems

Reducing lighting loads by using more efficient equipment or by using daylighting has implications for HVAC energy use. The following references explore these issues.

- Interactions between lighting and HVAC energy use

Atkinson, B., McMahon, J.E., Mills, E., Chan, P., Chan, T.W., Eto, J.H., Jennings, J.D., Koomey, J.G., Lo, K.W., Lecar, M., Price, L., Rubinstein, F., Sezgen, O., and Wenzel, T., 1992. "Lighting Interactions with Heating, Ventilation, and Air-Conditioning Energy Use," Appendix H in: *Analysis of Federal Policy Options for Improving U.S. Lighting Energy Efficiency: Commercial and Residential Buildings*, LBL-31469.

Busch, J.F. , du Pont, P. and Chirarattananon, S., 1993. "Energy-Efficient Lighting in Thai Commercial Buildings," *Energy - The International Journal*, 18(2): 197-210.

Dunbar, M., 1991. "Engineers Debate First-Cost Lighting, HVAC Link," *Energy User News*, 16(3):30-31, March.

Rundquist, R.A., Johnson, K.F., and Aumann, D.J., 1993. "Calculating Lighting and HVAC Interactions," *ASHRAE Journal*, November.

Selkowitz, S. and Schuman, J., 1992. *Integrated Envelope and Lighting Technologies for Commercial Buildings*, LBL-32736, July.

Sezgen, A.O., and Huang, Y.J., 1994. "Lighting/HVAC Interactions and Their Effects on Energy Consumption and Peak HVAC Requirements in Commercial Buildings," to be presented at the American Council for an Energy-Efficient Economy 1994 Summer Study on Energy Efficiency in Buildings, Asilomar, CA, August-September.

- Interactions between lighting, glazing, and HVAC energy use

Selkowitz, S.E., Lee, E.S., Rubinstein, F., Klems, J.H., Papamichael, K., Beltran, L.O., DiBartolomeo, D., and Sullivan, R., 1993. *Realizing the DSM Potential of Integrated Envelope and Lighting Systems*, Presented at the Second National New Construction Programs for Demand-Side Management Conference, San Diego, CA, LBL-34731.

Selkowitz, S. and Schuman, J., 1992. *Integrated Envelope and Lighting Technologies for Commercial Buildings*, LBL-32736, July.

Non-energy benefits

In addition to capital cost and energy savings, certain integrated systems have non-energy benefits, such as: improved indoor environment, comfort, health and safety; reduced noise; enhanced labor productivity, and increased amenity/convenience.

Mills, E. and A. Rosenfeld, 1994. "Non-Energy Benefits as a Motivation for Making Energy-Efficiency Improvements," to be presented at the American Council for an Energy-Efficient Economy 1994 Summer Study on Energy Efficiency in Buildings, Asilomar, CA, August-September.

Vine, E. and J. Harris, 1990. "Evaluating Energy and Non-Energy Impacts of Energy Conservation Programs: A Supply Curve Framework of Analysis," *Energy: The International Journal* 15(1):11-21.

Design of lighting systems

Comprehensive design of lighting systems that integrate task ambient lighting, energy efficient lighting technologies, and lighting controls can result in improved lighting quality as well as increased energy savings.

Atkinson, B., J.E. McMahon, E. Mills, P. Chan, T.W. Chan, J.H. Eto, J.D. Jennings, J.G. Koomey, K.W. Lo, M. Lecar, L. Price, F. Rubinstein, O. Sezgen, and T. Wenzel, 1992. *Analysis of Federal Policy Options for Improving U.S. Lighting Energy Efficiency: Commercial and Residential Buildings*, LBL-31469.

Mills, E. and Piette, M.A., 1993. "Advanced Energy-Efficient Lighting Systems: Progress and Potential," *Energy: The International Journal* 18(2), pp. 75-97.

Piette, M.A., Krause, F., and Verderber, R., 1988. *Technology Assessment: Energy-Efficient Commercial Lighting*, Berkeley, CA: Lawrence Berkeley Laboratory (LBL-27032).

I. ENERGY MANAGEMENT SYSTEMS

END-USE: Lighting, HVAC

SECTORS: Commercial, Industrial, Residential

DESCRIPTION

Performance: Energy Management Systems (EMSs) are special-purpose computerized control systems which can be programmed to operate building lighting and HVAC equipment such as chillers, fans, boilers, pumps, dampers, valves and motors. They vary in complexity from a single function controller that performs simple control of one piece of equipment to a system with a distributed architecture, in which controllers throughout the building operate local control loops, supervised by a central, or "host" computer. Energy conservation potential is related to the functions the EMS performs, such as programmed start and stop, optimal start and stop, duty cycling, economizer control, HVAC optimization, and demand limiting.

Consumer Utility: Most EMS functions will not affect consumer utility. Duty cycling, optimum start and demand limiting may in some cases cause occupant discomfort. The EMS has a beneficial effect of reducing building operation personnel requirements and providing fire protection and security functions. However, operation personnel may require additional training to use the EMS properly.

Development Status: The technology has been developing quite rapidly. EMSs for commercial buildings are readily available, with many manufacturers, vendors, and contractors in the market.

COSTS

There is a wide range in EMS savings potential because there are so many different energy management functions and the base case control strategies vary so widely. There is also a wide range in system cost, due to the range in complexity of the systems. Often, a simple and inexpensive controller can be much more effective than a complex system that has not been implemented correctly, or is not operating correctly. In an EMS survey, system costs varied from $300 to $18,000, depending on the type of system; and the average energy cost savings was about 15%.

IMPLEMENTATION

Installation: Installation costs are highly dependent on the degree of complexity of the system, and the number of input and output points. System commissioning and operator training are essential.

Maintenance: The EMS itself should require little maintenance, although sensors and actuators may require periodic attention, and some energy management functions may cause additional wear on equipment. An EMS can be an aide in performing other building maintenance. Operations and maintenance personnel must be trained to use the EMS properly.

Conservation Programs: Several utilities offer incentives for installation of an EMS.

ENVIRONMENTAL ISSUES

Use of EMSs results in improved energy efficiency and reduced energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants. Further, by monitoring stack gases, EMSs can help to reduce emissions from building boilers. By allowing for 100% outside air during mild temperatures, EMSs can increase indoor air quality.

I. ENERGY MANAGEMENT SYSTEMS

1. Description

1.1 Performance Characteristics

Energy Management Systems (EMSs) are special-purpose computerized control systems that can be programmed to operate building lighting and HVAC equipment such as chillers, fans, boilers, pumps, dampers, valves and motors. When properly installed and operated, EMSs can control buildings more efficiently and effectively than human operators, and are useful tools in troubleshooting and maintaining buildings as well as in managing energy consumption.

Because of improvements in information and communications technologies, computerized EMSs are a growing technology in all building sectors. Industrial buildings use EMSs to control building services, while the energy used by industrial processes is usually controlled by very specialized and process-specific control systems. In residential buildings, the technology for controlling building systems is typically referred to as home automation, and is a newly emerging and promising technology. However, by far the most common application of EMSs is in commercial buildings, and they are the main focus of this review. Note that EMSs are sometimes referred to as "Energy Management Control Systems," or EMCSs.

The term Energy Management System can refer to a wide range of technologies for controlling building systems, and varying in complexity. The simplest EMS might consist of a single function controller, used to perform one task, controlling one or more building systems. A more complex EMS utilizes a centralized computer to control systems throughout the building, implementing several different functions. The most commonly installed EMSs today utilize a distributed architecture, in which controllers throughout the building operate local control loops (for example, controlling a Variable Air Volume [VAV] box in a zone, based on input from the local thermostat). The local controllers communicate with one another over a local area network. These controllers can then be supervised by a central, or "host", computer (for example, the central computer would send a temperature setpoint to the local loop controller, which would implement control). The host computer can be used for many other tasks, such as graphic communication with the operators, data collection and analysis, and providing a more convenient environment for programming the local controllers.

While the foregoing discussion covers the architecture of an EMS, its energy conservation potential is related to the functions it can perform or how it controls the equipment. Listed below are several of the most common energy-management functions typically implemented in an EMS:

Programmed Start and Stop: An on/off schedule is defined for the operation of each end use, and implemented by the EMS. The schedule can vary by day of week and can include contingencies, i.e., different ways to respond depending on conditions in the building, such as operation of other end uses or past operation of this end use. Occupant and operator override, invoked from central or remote locations (by telephone or a timer device, for example), are helpful in maintaining flexibility.

It is useful to compare this function to that of a simple time clock, which is often considered as an alternative to a full EMS. With most time clocks, it is possible to turn equipment on and off several times a day, and to have a separate schedule for each day of the week. However, an EMS can automatically adjust for daylight-savings time and reduce operation during holiday periods. Time clocks are notorious for becoming out of synchronization with real time, often with disastrous results. One final advantage to an EMS is that each end use can be controlled individually and their start times can be staggered. With a time clock, entire systems may begin operation at the same time, often creating a power spike.

Programmed start and stop is often responsible for most of the energy savings from an EMS. To evaluate the savings, it must be compared with the alternative method of turning equipment on and off. For example, if a building has a dedicated operations staff who turn equipment on and off at the correct times, there will be no energy savings from this technique. One study estimated that the HVAC savings over and above those made possible by a 7-day time clock are on the order of 5% to 20% (Guntermann, 1982).

Optimal Start and Stop: With this function, historical performance and outdoor temperature are used to determine the latest possible time to begin conditioning each day, and the earliest time to stop conditioning so that the building will always be comfortable while occupied. Historical performance determines the response time of the building which is used with indoor and outdoor temperatures to calculate the optimum times.

Optimal start and stop times may result in large savings, depending on the alternative means of control. Often, in buildings without an EMS, occupants or building managers guess on an appropriate time to begin conditioning. If occupants complain that the building is uncomfortable prior to the set start time, then the time is moved earlier and earlier, until complaints stop. That setting will then be used throughout the season, resulting in inefficient, "worst-case," scheduling.

Duty Cycling: With this function, equipment is periodically switched on and off in order to reduce its average output. The fraction of time that it is switched on is referred to as its "duty cycle." This is usually used for single speed equipment that has been oversized or sized for worst-case conditions. The duty cycle can be a fixed value, or proportional to zone temperature. To prevent equipment from turning on and off too rapidly, minimum on and off times are usually specified. For a single piece of equipment, this technique does not reduce building peak demand. However, when coordinated with several pieces of equipment, it can be set so that there is always at least one piece of equipment off at any time, and demand can be reduced. This illustrates an advantage of integrated building operation, made possible only by a whole-building EMS.

One should note that such systems are usually only specified as a retrofit, since there are preferable ways to reduce equipment output in new buildings or when installing new equipment. More appropriate sizing or staging of the equipment would take advantage of higher efficiencies found when operating a piece of equipment closer to its full load. Also, adjustable speed equipment has a reduction in demand that is nominally proportional to the cube of the reduction in output. In fact, adjustable speed drives can be installed as a retrofit and work very well in conjunction with EMS control.

Economizer Control: Cooling energy can be minimized by monitoring the temperature (and possibly humidity) of return and outdoor air, and selecting a supply airstream with minimum temperature. This will vary anywhere from 100% outdoor air on mild days to a specified minimum amount of fresh outside air on hotter days. Although this technique is common even in buildings without EMSs, the EMS can more closely control the system to optimize its performance. For example, while a standard economizer controller will typically be set to change over from outdoor air to mechanical cooling at a certain temperature, an EMS that is controlling multiple zones with different conditioning requirements can more effectively modulate the amount of outdoor air to provide the optimum supply air temperature.

Another advantage of using an EMS to implement economizer operation is that the EMS can monitor the performance of the economizer, and can alert the operations personnel when it is failing to perform. Since economizers are prone to problems throughout their life cycle, this is an important benefit.

HVAC Optimization: The operation of the fans, chillers, and boilers can be optimized in several ways. A few examples are resetting supply air and heating and cooling coil temperatures, efficiently combining several small chillers, adjusting the rate at which setpoints are approached, and monitoring stack gases to increase fuel-burning efficiency.

Demand Limiting: For buildings that are charged for peak demand as well as energy consumption, limiting building demand is an important means of controlling costs. An EMS can limit demand by cutting back use of non-critical equipment when the building demand approaches a preset target. Equipment is turned off or reduced sequentially, according to a prioritized list. When demand is reduced to a sufficiently low level, end uses are restored, either in the same order they were shed (rotating load shed) or in the inverse order (priority load shed). An algorithm that predicts upcoming demand (by extrapolating past trends) will allow the EMS to prevent, rather than respond to, demand excesses. Demand limiting may or may not reduce energy consumption since it is primarily a load management strategy.

Monitoring: Most EMSs are capable of monitoring electricity consumption and reporting it at different time intervals. This information is used in energy management efforts such as energy accounting (tracking the performance of the building) and in detection of equipment malfunctions or inefficient operation. EMSs are also capable of monitoring many different building operation variables, such as zone temperatures and central equipment thermal parameters. This capability is useful in detecting or diagnosing operational problems, and in responding to occupant thermal comfort complaints. EMS-based monitoring can also be used to assist utilities and ESCO's in efforts such as load research, DSM evaluation, and savings calculation for shared savings contracts.

1.2 Consumer Utility

Most EMS functions will not affect consumer utility. For example, economizer operation or plant optimization will provide the same energy services with increased efficiency. Some EMS functions, if not properly implemented, could have negative impacts on occupant comfort. For example, if optimum start times or duty cycles are incorrectly calculated, the building may become uncomfortable. Demand limiting, in particular, has the potential for negative impacts. Although the algorithms for starting and stopping end uses and assigning priority and rotation schedules are well thought out and implemented, care must be taken in selecting loads to be shed. There will be an effect on comfort if shed loads include HVAC, and shedding process and other miscellaneous loads will often affect productivity.

As a tool for building operation, the EMS allows the building to be operated from a central location and sensors throughout the building can detect fluctuations in operation and conditions. The EMS can monitor trends in building or system performance and can also be useful in keeping track of equipment runtime and maintenance schedules. These abilities can allow for a reduction in building operations staff. EMSs also often serve fire protection and security functions, in addition to energy management.

1.3 Development Status

As with most micro-electronics, EMS technology has been developing quite rapidly. EMSs for commercial buildings are readily available. There are over 150 EMS manufacturers (EPRI, 1986), and many manufacturer's representatives, vendors, and contractors in the market. According to one survey, 69% of all commercial buildings over 50,000 square feet had an EMS, 32% of all commercial buildings between 10,000 and 50,000 square feet, and 15% of all commercial buildings less than 10,000 square feet (EPRI, 1986). Although technological improvements come quickly, most systems can be upgraded with new software or computer hardware while still making use of much of the existing hardware.

1.4 Technology Standards

Few standards exist for EMS technology. With over 150 EMS manufacturers and a trend towards distributed architecture, there is a growing appreciation for the need to standardize. The American Society for Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) has provided guidelines for specifying measurement requirements and recommended methods of verifying accuracy of EMS instrumentation (ASHRAE, 1986). ASHRAE is now in the process of creating a standard for communications, BACnet, which will allow equipment from different manufacturers to communicate (ASHRAE, 1990). Standardization is also under way in residential automation systems, based on two different technologies; they are commonly referred to as the Smart House Limited Partnership and the CEBus standard. These standards should help to transform home automation into a more viable energy management strategy.

Some building energy standards also refer to EMSs. For example, ASHRAE/IES Standard 90.1-1989 suggests that all new buildings with a floor area of over 40,000 square feet should consider installing an EMS (ASHRAE, 1989). Standard 90.1 recommends that the EMS should at least have the following capabilities: monitoring of energy consumption on a daily basis with weekly summaries; programmed stop and start on HVAC, service water heating, and lighting; reset control on HVAC equipment; monitoring operation on HVAC systems; override capability on lighting and HVAC; and optimum start and stop for HVAC.

2. Cost

2.1 Equipment Cost

It is difficult to assess EMS cost effectiveness in a generic way. There is a wide range in EMS savings potential, because there are so many different energy management functions, and the basecase control strategies vary so widely. There is also a wide range in system cost, due to the range in complexity of the systems. For example, often a simple and inexpensive controller can be much more effective than a complex system that has not been implemented correctly, or is not operating correctly. According to a survey of EMSs carried out for the Electric Power Research Institute (EPRI), the cost for single function controllers was from $300 to $8,000, depending on the complexity and number of controlled devices (EPRI, 1986). The minimum cost for centralized systems was $10,000, and the minimum for distributed architecture systems was $18,000. In their survey, the average energy cost savings was about 15%. One should also remember that EMSs, when used by properly trained operations personnel, may reduce building operation and maintenance costs as well as provide fire and security functions.

3. Implementation

3.1 Installation

Installation costs are highly dependent on the degree of complexity of the system and the number of input and output points. Installation of communications paths throughout the building is often a large part of the cost. Systems are typically configured, installed, and commissioned by the vendor or a manufacturer's representative. Two essential and often overlooked steps in EMS installation are making sure the system is doing what it was designed to do (commissioning) and making sure the operators understand and trust the system (training). A survey of EMS users found that one EMS in five had been disconnected by building personnel (Schwed, 1988). With appropriate attention to commissioning and training, such problems can be avoided.

3.2 Maintenance

The EMS itself should require little maintenance, as it consists primarily of solid-state electronics. Sensors and actuators may require periodic attention. Some energy management functions, such as duty cycling of motor-driven devices, may cause additional wear on belts, motors, and electric starters, requiring much more frequent maintenance. EMSs can be an aide in performing other building maintenance and operations.

It should be emphasized that EMS operators may require training to use the system properly. The added complexity of the EMS increases the potential for problems, especially in the face of changing building needs. Without such training, an EMS may be underutilized, overridden, or disconnected.

3.3 Conservation Programs

Several utilities offer incentives for installation of an EMS. In these programs, certain EMS functions must be implemented or an EMS contractor must calculate estimated savings. Many of these programs are oriented more towards load management rather than efficiency.

4. Environmental Issues

Use of EMSs results in improved energy efficiency and reduced energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants. Further, by monitoring stack gases, EMSs can help to reduce emissions from building boilers. By allowing for 100% outside air during mild temperatures, EMSs can increase indoor air quality.

5. References

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ASHRAE, 1990. "BACnet--A Data Communication Protocol for Building Automation and Control Networks," Working Draft 4. SPC-135P-015.

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The North Carolina Alternative Energy Corporation, 1987. *Assessment of Commercial Load Management Opportunities Using Energy Management Systems*, May. Research Triangle Park, NC.

Schwed, Robert L., 1988. "Service, Training, and Programming Plague Energy Management System Owners," *Engineered Systems Magazine*, p. 52-56. October.

6. Contacts

ASHRAE Journal
ASHRAE Technical Committee 1.4, Control Applications and Theory
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II. ELECTRONIC FLUORESCENT BALLASTS

END-USE: Interior lighting

SECTORS: Commercial, Industrial

DESCRIPTION

Performance: Controls voltage and current supplied to linear or compact fluorescent lamps. Uses integrated circuits instead of a core and coil mechanism. High quality ballasts with high power factors and low harmonic distortion do not significantly affect power quality. Savings are achieved from improved lamp performance and lower ballast losses. Electronic ballast/lamp systems have improved efficacies of 20-25% over standard magnetic ballast/lamp systems (that no longer meet U.S. Federal standards) and about 15% over energy-efficient magnetic ballast/lamp systems. Electronic ballast lamp control may be on/off, step dimming, or full range dimming.

Consumer Utility: Operating at higher frequencies, electronic ballasts eliminate lamp flicker and ballast hum.

Development Status: Available from major ballast manufacturers and some specialty companies. Compatible with T12, T10, or T8 fluorescent lamps and compact fluorescent lamps.

COSTS

Electronic ballasts range in price from $20 to $80, the high-end models can be continuously dimmed and adjusted automatically with photosensor controls. Prices are dependent on the quantity ordered. Paybacks for electronic ballasts typically range from six months to two years depending on operating hours and electricity prices.

IMPLEMENTATION

Installation: Local codes may require a licensed electrician to install the ballasts. Replacing a ballast may take 10 to 40 minutes depending on accessibility.

Maintenance: Typical rated life is between 20 and 25 years, but the actual average lifetime is 12 years due to building remodeling and renovation projects. Burnouts will occur at a rate of a few percent a year, with the rate increasing with ballast age.

Conservation Programs: Some utilities offer rebates for replacing standard core and coil ballasts with electronic ballasts, although the new ballasts may need to meet specified performance requirements. In the U.S., these rebates range from $5 to $30 per ballast.

ENVIRONMENTAL ISSUES

Use of electronic fluorescent ballasts results in improved energy efficiency and reduced energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuel used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

There are solid waste issues associated with the replacement of fluorescent ballasts. When replacing older core and coil ballasts with electronic fluorescent ballasts, care must be taken with ballasts manufactured prior to 1978 because they may contain polychlorinated biphenyls (PCBs). These ballasts must be disposed of as a hazardous waste. Disposal costs for PCB ballasts are estimated at $4 per ballast. When retrofitting lighting systems (with both electronic fluorescent ballasts and energy-efficient fluorescent lamps), disposal of the old lamps must also be addressed because of the mercury contained in each lamp. Mercury, which is a toxic heavy metal, is used to excite the phosphors in the lamp and is gradually deposited onto the glass, filaments, and phosphors. Mercury releases can occur during the manufacturing process, when a lamp breaks, or at the time of lamp disposal, even if the lamp has completed its useful life.

II. ELECTRONIC FLUORESCENT BALLASTS

1. Description

1.1 Performance Characteristics

Discharge lamps require a ballast to provide a sufficiently high voltage to initiate the lamp arc and to regulate current flow in the lamp. Electronic ballasts control the voltage and current supplied to the lamp using integrated circuits, an improvement over standard magnetic ballasts and energy-efficient magnetic ballasts with a core and coil mechanism.

Electronic ballasts are more efficient than magnetic ballasts for two reasons. First, electronic ballasts drive the lamps at high frequencies (typically 20 to 60 KHz) which results in more efficient lamp operation because of reduced losses at the lamp's electrodes. For a four-foot lamp system, this results in about a 10% improvement in efficacy. The efficacy improvement is more significant for shorter lamps. The second reason for improved performance is that electronic ballasts operate at lower temperatures. Since reduced light output has been associated with overheating (from improper lamp and fixture geometry, wattage, ballasts, ambient temperature, lamp orientation, and air circulation), the cooler operation contributes to improved lamp performance (Mills, 1993). These two factors result in about a 20% to 25% improvement in system efficacy over a standard ballast/lamp combination (that no longer meet U.S. Federal standards) and an improvement of about 15% over energy-efficient magnetic ballast/lamp systems (Nadel, et al., 1993).

In selecting a ballast, one must consider the effect the ballast will have on the line power quality. Power quality can be affected by the ballast's power factor, harmonic distortion, and crest factor. The power factor is the ratio of real to apparent power. Some utilities penalize customers who have low power factors. Generally, ballasts with power factors greater than 0.90 are considered high-power-factored ballasts and are acceptable. Harmonic distortion from the ballast must be minimized to insure there is limited current flow in the neutral wire. Harmonic distortion can destroy electronic data, cause short circuits, and decrease energy efficiency. Low harmonic distortion levels are defined as less than 10%. Lamp current crest factor refers to the shape of the voltage wave form supplied to the lamp. A pure sine wave is desired which has a crest factor of 1.41. Electronic ballasts are available with crest factors of 1.5 which is nearly identical to the sine wave.

Although virtually all magnetic ballasts run lamps in series, electronic ballasts are usually designed to operate lamps in parallel. There is some advantage to parallel operation since the other lamps will still operate even if one or more of the lamps powered by the ballast should fail.

Instant Start Ballasts: With an instant-start ballast system, the ballast must provide a sufficiently high starting voltage to start the lamp, since the lamp's electrodes are not heated. Instant start lamps have single pin ends. Instant-start lamps can only be started with ballasts that have an instant-start circuit. Since they are started with a higher voltage, over the long term it is believed that these lamps fail earlier, although recent tests are challenging this belief. Rapid-start lamps can be started with instant-start ballasts but doing so greatly reduces the lamp life.

Rapid-Start Ballasts: With rapid-start ballast systems, the lamp's electrodes are heated just before the arc is initiated, which permits a lower starting voltage. Rapid-start lamps have medium bi-pin (double pin) ends. Rapid-start lamps dominate the market. Another distinction between ballast types are those which operate T12/T10 rapid-start lamps and those operating T8 rapid-start lamps. T12/T10 lamps are best operated by their ballast at

430 milliamps (ma). T8 lamps are designed to be driven at 265 ma. Ballasts supplying 430 ma will drive the T8 lamps, but they will not do so as efficiently as the lower amp ballasts.

Light Output: When comparing ballast performance, it is important to examine the light output as well as the input power. Two important parameters of ballast performance are the ballast factor and the ballast efficiency factor. The ballast factor (BF) is the ratio of lumen output of the lamps operated by the ballast to the rated lumen output of the lamps. Thus, the BF is a relative measure of how much light is produced using a specific ballast. Since rated lamp output varies depending on the lamp type, meaningful comparisons of BF can only be made between ballasts operating the same type of lamps. Most BFs are less than 1, but some new electronic ballasts have BFs greater than 1. This results in lamps having higher than rated lumen output.

The ballast efficiency factor (BEF, sometimes called ballast efficacy factor) is the ballast factor times 100 divided by the lamp/ballast input power. Thus, like BF, BEF only provides a meaningful comparison of different ballasts operating the same type and number of lamps. An energy-efficient core and coil ballast will operate two 40 watt lamps (rated output of 3150 lumens each) with a BF = 0.94 using 86 watts resulting in a BEF = 1.09. A typical electronic ballast using the same lamps has a BF = 0.88 at 71 watts, giving a BEF = 1.24. Generally, an electronic ballast having a higher BF will produce light more efficiently yet consume more energy than one with a lower power factor. But if the higher BF ballast produces more light than needed in the space, the lower BF ballast will probably be more cost effective since it uses less power in producing less light. The performance of different rapid-start lamp/high power factor ballast systems are listed in Table II-1 (EPRI, 1993).

Table II-1
Performance Comparison of High Power Factor Ballasts and Rapid-Start Lamp Systems (Two-Lamp Systems)

Rapid-Start Lamps	High Power Factor Ballast	Input Watts	Ballast Factor	Ballast Efficiency Factor	System Efficacy (lumens/watt)
F40WT12	Standard Magnetic	96	0.94	1.00	62
	Energy Efficient 1	88	0.94	1.07	68
	Electronic 1	72	0.88	1.22	78
F34WT12	Energy Efficient 1	72	0.87	1.21	68
	Electronic 1	60	0.85	1.42	79
F32WT8	Energy Efficient 2*	70	0.94	1.34	78
	Electronic 2*	62	0.88	1.42	82
	Electronic 3*	51	0.71	1.39	81

* These ballasts operate at 265 milliamps.

Electronic ballasts are available to control one to four lamps. Ballasts with controls other than just on/off switching are available. The control options include step dimming or full-range dimming with automatic adjustment from a photosensor. Dimming capabilities allow the system to compensate for lumen depreciation over time and to incorporate the use of daylighting in the illumination system. Ballasts that have full range dimming capabilities are limited in availability. One hundred percent dimming ballasts are available for three or four lamp T8 systems. Also, few electronic dimming ballasts offer individual ballast control. Table II-2 lists a number of electronic ballast manufacturers and describes their products and features (Energy User News, 1992).

Table II-2
Electronic Ballasts

COMPANY	MODEL & TYPE	PRICE & PAYBACK	RATED LIFE & FEATURES	WARRANTY & SERVICE
Advance Transformer Co. Rosemont, IL (708) 390-5000	Advance Discrete Electronic, Advance Reduced Harmonic Discrete Electronic, Advance Mark V Integrated Circuit, Advance Mark VII Controllable Integrated Circuit electronic ballasts.	Prices range from $25-$80, depending on model. Energy savings up to 43% over standard system; up to 75% with the controllable Mark VII. Payback can be from 6 months to 3 years.	Average rated design life of 20-25 years. Light output of all models meets proposed ANSI standards. All ballasts are high power factor (greater than 0.9), most greater than 0.95. All models 75% quieter than A rated Magnetic ballasts.	Three-year replacement warranty. Service through Advance and Advance Authorized Stocking Distributors
DuraLux Industries Austin, TX (512) 443-3292	EconaLux electronic ballast. 120V and 277V two-lamp rapid-start model for T-12 lamps. Instant-start and multi-lamp ballast introduced in near future.	Typical price is $20 to $30, depending on volume. Paybacks will usually range from six months to two years.	Average rated life 25 years. T-12 and T-8 models operate in true rapid-start mode. T-8 unit is full light ballast. Harmonics less than 13%, reduced flicker.	Three-year warranty. Full replacement service by distributors.
Elba USA City of Industry, CA (800) 626-3522	Elba electronic ballasts, main models: dedicated T-8, dedicated T-10, T-12, eight-foot slimline. Each is two-lamp ballast.	Prices start around $30 (to end user). Paybacks less than two years.	Rated life 25 years. All ballasts are parallel circuit. Most have low harmonic distortion (low-THD), below 10%. Low EMI.	Warranty three years and labor allowance. Service by contractor.

Table II-2
Electronic Ballasts (cont.)

COMPANY	MODEL & TYPE	PRICE & PAYBACK	RATED LIFE & FEATURES	WARRANTY & SERVICE
Electronic Ballast Technology, Inc. Torrance, CA (310) 784-2000	One-, two-, three- and four-lamp ballasts for F40, T-12 and T-8 lamps in both 120 and 277V. Also Slimline and high-output ballasts. Ballast for 39, 40, and 50 watt Biax. High power factor ballast for Quad 4-13, 18, and 26 watt compact fluorescent lamp. Dimming ballast and dimming control system for 2 lamp 32W and 40W applications.	Contact company for price information. Paybacks range from six months to two years, depending on hours of operation and electricity costs.	All EBT ballasts feature a minimum of less than 20% Total Harmonic Distortion (THD). 100,000 hours rated life. No flicker, very low audible noise, meets FCC requirements for electromagnetic interference and radio frequency interference. One-, two- and three-lamp ballasts are for both rapid-start (pre-heated) and instant-start operation. Quad ballasts feature THD 20% and 98% power factor. Dimming ballast control features no additional wiring requirement. The unit wires directly into existing wall switch junction box.	Three years, full replacement, service factory-directed through distributor.
Etta Industries, Inc. Boulder, CO (303) 444-2244	Sinusoidal Electronic Dimming Ballasts. Models include two-lamp, 120 and 277V ballasts for 32 W, 34W, 36W, 39W, and 40W T-12 lamps four-foot, T-10 and T-8 lamps (3 lamp to be available). Also available for 40W Biax (dimming & non-dimming), 26W Quad PL (dimming), 50- and 100W HPS. Continuous dimming.	Typical price for ballasts: Non-dimming $25-$40, dimming $40-$75/ballast, dimming controls and photocells available through Etta or approved control manufacturers. Quantity discounts available. Paybacks one to two years, saves 25%-85% over standard core and coil.	Average rated life more than 20 years. 1.41 crest factor, flicker-free operation. Sinusoidal lamp drive voltage, soft-starting, soft heating of filaments. True rapid-start -- protects lamp life. Meets FCC guidelines on EMI, surge-protected in accordance with IEE Standard 587. Powerline harmonics under 5%, voltage regulation and brownout protection. Continuous dimming capabilities from 100 to 5% of full light output. Power factor 0.99. Digital dimming control system.	Three-year labor allowance $10. Nation-wide service through distributors and technical sales representatives.
King Technology, Inc. Carlstadt, NJ (210) 935-8711	F-40 T-12 2-lamp ballast, 120V and 27V versions. 3-lamp, 4-lamp, F96 Integrated Circuit Ballast with 3-5% THD to be introduced.	Prices range from $17-25 for 2-lamp, 4-ft. rapid start ballast. Quantity discount and contractor's financing available.	Rated life 25 years. THD 3-12%. BEF 1.52 Crest factor 1.5.	Three year warranty and labor allowances.

Table II-2
Electronic Ballasts (cont.)

COMPANY	MODEL & TYPE	PRICE & PAYBACK	RATED LIFE & FEATURES	WARRANTY & SERVICE
MagneTek Huntington, IN (219) 356-7100	Triad electronic. One to four lamps T-12, one to three lamp T-10, one to four lamp T-8, also one to three lamp compact, two-lamp slimline, two-lamp high-output, one to three lamp light-level switching. Reduced Harmonics "RH" full light output (20% THD), High Performance "HP" full light output (10% THD) and Low Wattage "L" reduced light output (20% THD).	Prices from $22 to $50. Energy savings potential up to 60%. Premium payback over magnetic typically less than two years.	Rated life 25 years. Meets FCC guidelines for RFI and EMI, meets IEEE Standard 587 (for single protection). Depending on type of lamp used, ballast-lamp combination has a lumen-to-watt ration between 75 and 105. Light level switching systems available. Most models parallel lamp-configured allowing companion lamps for remaining full lit when one or more lamps fail.	Exclusive 5 year replacement warranty Nation-wide service, call 1-800-BALLAST.
Motorola Lighting, Inc. Buffalo Grove, IL (800) MLI-0089	High performance electronic ballasts. Rapid Start 1,2,3 and 4 lamp for T8 and T12 lamps. Instant Start 1 and 2 lamp T12. All models available in 120 or 277 voltages.	Simple payback can be less than one year depending on burning hours, kWh rate and rebate programs. Two year range is typical. Contact a Motorola Lighting Inc. Authorized Distributor for pricing information.	Power factor greater than 0.99; total harmonic distortion less than 10%; crest factor less than 1.5; no visible flicker; no audible noise; meets all applicable regulatory requirements including UL and FCC. Rated life 20 years plus; features poke-in connector for simplified installation.	Three year warranty includes on-site service through our national Authorized Service Companies.
Royce Electronic Products Inc. Ontario, CA (714) 467-1400	Royce ballasts, 2-, 3 or 4-lamp ballasts, each in 120 and 277V.	$22-$35. Payback less than two years.	Meets FCC noise, EMI, RFI requirements. Comes in variety of output (low-medium and high) for each lamp.	Service by contractor. Three-year warranty.

Table II-2
Electronic Ballasts (cont.)

COMPANY	MODEL & TYPE	PRICE & PAYBACK	RATED LIFE & FEATURES	WARRANTY & SERVICE
Smallwood Technologies Littleton, CO 80123 (303) 973-7401 (800) 458-1635	Saver Plus, sinusoidal electronic ballast. Models include SEB24120, SEB24277 (recommended for T-10, T-12) SEBT8120 (for T-8s), SEB-18127.	Saver Plus in low $20s. Payback within one year. Savings up to 40%. SEB models $15.	Rated life 20 years. Flicker-free, weighs approx. one pound, sound rated A, high power factor. No EMI-RFI interference. Saver Plus has less than 20% harmonic distortion. SEB models: 98% power factor, harmonic distortion under 10%.	Three-year warranty. Service by contractor. $10 labor replacement - each ballast.
Tektron Enterprises, Inc. Santa Ana, CA (714) 641-1988	Solid state full range dimmable ballast model 23A0000. Two lamp ballast for T8, T10 and T12 4ft. lamps.	Price $40-$70/ballast depending on options and quantities. Payback 1-2 years. Saves 25-85% of energy over standard core coil.	Average rated life 25 years. Patented design, custom IC. Dimmable 0-100% (with very low flicker) by a standard incandescent dimmer. One dimmer can control up to 600 ballasts (1200 lamps). Manual, automatic, remote, or multi-function control. Typical power factor 97%. 3rd harmonic distortion less than 5%. Less than 18% THD. Can interface with occupancy sensors, daylighting, etc. Quiet operation class A sound rated.	Three year replacement warranty. Service by contractor.
Terralux, Inc. Oshkosh, WI (800)637-6909	Terralux Electronic Ballasts, Rapid start for 1 or 2 T012 or T-10 lamps. Instant start for 1 or 2 T-8 lamps. All models available in 120 and 277 volts.	Contact company for price information. Payback will range from 6 months to 2 years depending upon application and hours of operation.	Average life rated 20 years. THD less than 10%. Crest Factor 1.5. Meets all FCC requirements for EMI and RFI. High light output available for T-8 lamps.	Three year replacement warranty. $10 labor allowance. Service by contractor.

Table II-2
Electronic Ballasts (cont.)

COMPANY	MODEL & TYPE	PRICE & PAYBACK	RATED LIFE & FEATURES	WARRANTY & SERVICE
Thomas Industries Tupelo, MS (601) 842-7212	REB microchip electronic ballast. One-, two- and three-lamp, four-inch rapid-start, T-12 and T-8, standard and dimming 120 or 277V.	Approx. $30 each, payback approx. one year compared to standard magnetic ballast. Dimming adder approx. $30 each.	Rated life 60,000 hours. Adjusts input voltage to allow constant wattage and light levels to lamps. Compensates for power fluctuation of plus or minus 10% of normal input voltage. Constant light output over life of lamp, weighs only 1 1/4 ounces. Dimming accessories available, can be dimmed to 25%. Meets IEE criteria for RFI and EMI. THD less than 10%.	Three-year warranty, service by Thomas.
Toshiba America Consumer Product, Inc. Buffalo Grove, IL (800)453-4242	Toshiba Electronic Ballasts, 1,2,3, lamp F40, R12 in both 120 and 277 V. Also, Electronic F96, T12 Slimline and high output in 120 and 277V.	Contact company for price information. Typical payback is 6 months to 2 years. Energy savings 20-40% over standard.	Average rated life over 20 years. Flicker free operation. Meets FCC standards for RFI and EMI. Power factor 98%. Meets federal ballast efficiency factor. Operates both rapid start and instant start F40 lamps. Operates 30° cooler which can lower air conditioning costs.	Warranty 3 years and $10 labor allowance.
Valmont Electric Co. Danville, IL (217) 446-4600 (800) 533-7290 (800) 628-6340	Ultra-Miser line of one-, two-, three- and four-lamp ballasts for F40T12 and T-8 lamps. One- and two-lamp slimline and one-lamp high-output ballasts available for 60 to 96 inch lamps. All models available in 120V and 277V ratings.	Typical value prices for F40 models range from mid-$20s to mid-$30s. Input watts for three-lamp F40T12 watt rapid-start is 90 saving 58 watts compared to standard lamps and ballasts. Input watts for four-lamps F32T8 model are 104. Paybacks generally less than two years.	Twenty-five years average life expectancy. Meets FCC requirements for EMI and RFI. All ratings provide full light output. Lamp Current Crest factors range from 1.5 to 1.7. Ratings with total harmonic distortion of less than 20% available in all models.	Wrap-around warranty service program. Three-year replacement warranty. Up to $10 labor allowance.

1.2 Consumer Utility

Core and coil ballasts operate lamps at a frequency of 60 Hz. This causes the output of the fluorescent light to oscillate 120 times per second. This may result in a noticeable flicker which has been associated with headaches. Flicker is eliminated with electronic ballasts because of their high operating frequency.

Electromagnetic core and coil ballasts by nature can produce an audible hum. Although "A" rated (highest sound quality) ballasts are mostly used, even these can produce an audible sound in a quiet space. The hum worsens if the ballast is exposed to high temperatures or is amplified by metal fixtures. Electronic ballasts operate more quietly than even the most quiet magnetic ballast, essentially eliminating ballast hum.

1.3 Development Status

Electronic ballasts are available from most major ballast manufacturers as well as from some smaller specialty manufacturers. Shortages were experienced during 1993 and some orders took six months to one year to fill (Bryant, 1993). Manufacturers increased production during the year and the shortages have been alleviated, although one manufacturer expects smaller shortages will occur during 1994 (Hawk, 1994).

1.4 Technology Standards

An amendment to the U.S. National Appliance Energy Conservation Act (NAECA) went into effect in April 1991 prohibiting the use of standard core-coil ballasts (CEC, 1990). National standards for electronic ballasts do not exist presently in the U.S. but are being considered for adoption. If they are established, they will take effect in 1996, along with the other newly established national standards for lighting (Nadel et al., 1993). The American National Standards Institute (ANSI) standard for electronic ballasts is currently being defined.

2. Cost

2.1 Equipment Cost

Non-dimming electronic ballasts typically cost between $20 and $40. Dimming, electronic ballasts typically cost between $30 and $80. Table II-2 gives prices for the ballasts listed. Ballast cost is best described by a range of prices because actual cost is highly dependent on the number of ballasts purchased.

Table II-3 gives simple payback times based on the energy saved by an energy efficient or non-dimming electronic ballast compared to a standard core and coil ballast, two F40WT12 lamps system. The price of the standard system is assumed to be $10 for the ballast and $2 for each lamp. Table II-4 gives simple payback times based on the energy saved by a non-dimming electronic ballast compared to an energy-efficient ballast, two F40WT12 lamp system. The price of the energy efficient system is assumed to be $15 for the ballast and $2 for each lamp. For each table, F34W lamps and F32W lamps are estimated at $4.50 and $4 each, respectively. The price for electricity is assumed to be $0.08/kWh. It should be noted that electronic ballasts are a relatively new technology and prices lower than those used in this table are to be expected in the near future. Also, many utilities have rebates on electronic ballasts, which further lower the cost and make the payback times shorter. To calculate expected payback for a retrofit system, labor costs and possible lamp and ballast disposal costs must also be considered.

Table II-3
Simple Payback of Ballasts
Basecase: Standard Magnetic Ballast (96W), T12 Lamp System
($10 ballast, $2 each lamp)

Lamp	Ballast	Input Watts	Ballast Cost	Simple Payback (yrs) 2000 hrs/yr	Simple Payback (yrs) 4000 hrs/yr	Simple Payback (yrs) 6000 hrs/yr
F40WT12	Energy Efficient 1	88	$10-$15	0.0-3.9	0.0-2.0	0.0-1.3
	Non-dimming Electronic 1	72	$20-$40	2.6-7.8	1.3-3.9	0.9-2.6
F34WT12	Energy Efficient 1	72	$10-$15	0.0-1.3	0.0-0.7	0.0-0.4
	Non-dimming Electronic 1	60	$20-$40	1.7-5.2	0.9-2.6	0.6-1.7
F32WT8	Energy Efficient 2 *	70	$15-$20	1.2-2.4	0.6-1.2	0.4-0.8
	Non-dimming Electronic 2 *	62	$20-$40	1.8-5.5	0.9-2.8	0.6-1.8
	Non-dimming Electronic 3 *	51	$20-$40	1.4-4.2	0.7-2.1	0.5-1.4

* These ballasts operate at 265 milliamps.

Table II-4
Simple Payback of Ballasts
Basecase: Energy Efficient Ballast (88W), T12 Lamp System
($15 ballast, $2 each lamp)

Lamp	Ballast	Input Watts	Ballast Cost	Simple Payback (yrs) 2000 hrs/yr	Simple Payback (yrs) 4000 hrs/yr	Simple Payback (yrs) 6000 hrs/yr
F40WT12	Non-dimming Electronic 1	72	$20-$40	2.0-9.8	1.0-4.9	0.7-3.3
F34WT12	Non-dimming Electronic 1	60	$20-$40	1.1-5.6	0.6-2.8	0.4-1.9
F32WT8	Non-dimming Electronic 2*	62	$20-$40	1.2-6.0	0.6-3.0	0.4-2.0
	Non-dimming Electronic 3 *	51	$20-$40	0.8-4.2	0.4-2.1	0.3-1.4

* These ballasts operate at 265 milliamps.

3. Implementation

3.1 Installation

Local codes may require that the installation of all ballasts be performed by a licensed electrician. In some cases trade technicians are allowed to perform the job although having an experienced electrician on site is recommended. The time required to replace a ballast can range from 10 to 40 minutes depending the accessibility of the existing ballast and its wiring. In retrofit situations, the lamp sockets may also need to be replaced if instant-start lamps are switched to rapid-start lamps or vice-versa. For new installations, it is helpful to order the ballasts with the lamp sockets already attached to the ballast wires.

3.2 Maintenance

When the electronic ballast market was new, some ballasts suffered from early failure. More recent generations of ballasts have overcome these problems. A three year study conducted at the University of California tested 32,000 ballasts by three different manufactures. Two product lines were found to have between 1% to 3% failure rates. The third was found to be greater than 6%. This last product line has since been discontinued, redesigned, and reintroduced.

Ballasts have lifetime ratings of more than 50,000 hours. For a typical office with lights operating 3,000 hours per year, this represents 20 years. However, actual average lifetime is 12 years due to building remodeling and renovation projects. Burnouts will occur at a few percent a year, with the rate of burnout increasing with ballast age.

3.3 Conservation Programs

Some utilities offer rebates for switching standard core and coil ballasts to electronic ballasts. Because of the effect ballasts have on power quality, electronic ballasts often must meet a minimum harmonic distortion requirement (around 10%) and have a power factor above 0.90 for the utility to give the rebate. In the U.S., rebates range from $5 to $30 per ballast. Shared financing plans are also available from some utilities.

4. Environmental Issues

Use of electronic fluorescent ballasts results in improved energy efficiency and reduced energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuel used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

There are solid waste issues associated with the replacement of fluorescent ballasts. When replacing older core and coil ballasts with electronic fluorescent ballasts, care must be taken with ballasts manufactured prior to 1978 because they may contain polychlorinated biphenyls (PCBs). These ballasts must be disposed of as a hazardous waste. Disposal costs for PCB ballasts are estimated at $4 per ballast.

When retrofitting lighting systems (with both electronic fluorescent ballasts and energy-efficient fluorescent lamps), disposal of the old lamps must also be addressed because of the mercury contained in each lamp. Mercury, which is a toxic heavy metal, is used to excite the phosphors in the lamp and is gradually deposited onto the glass, filaments, and phosphors. Mercury releases can occur during the manufacturing process, when a lamp breaks, or at the time of lamp disposal, even if the lamp has completed its useful life.

Mercury released to the atmosphere as a result of lamp breakage will vaporize and is extremely hazardous in enclosed areas. Burying the lamps in a landfill reduces vaporization, but increases the chance for mercury leaching into the soil and nearby aquifers. In an aquatic environment, mercury moves to a menthylated state and is hazardous to biological organisms (Clear, 1994). This issue is further complicated by considering the mercury released to the atmosphere by a coal-fired power plant producing electricity to operate mercury-free incandescent lamps. Analysts have calculated that the mercury content of the coal is three times greater than the small amount of mercury in the compact fluorescent lamp (Mills and Piette, 1993).

5. References

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6. Contacts

Table II-2 lists U.S. electronic ballast manufacturers. Some other international ballasts manufacturers are:

Osram	Philips Lighting B.V.	Thunderbolt Electronics Co.
Hellabrunner Str. 1	P.O. Box 80020-5600 JM	#105A 358 58th Avenue S.W.
P.O. Box 900620	Eindhoven, The	Calgary, Alberta
D-8000 Munchen 90, BRD	Netherlands	T2H 2M5 Canada
Tel: 49 89 62 13 1	Tel: 31 40 79 11 11	Tel: (403) 259-2124

The Building Technologies Program at Lawrence Berkeley Laboratory (1 Cyclotron Rd., Berkeley, CA 94720, 510/486-6845) can provide technical information on electronic ballasts and their performance. The U.S. Environmental Protection Agency's Green Lights Program is a voluntary, non-regulatory program developed to encourage organizations to upgrade to more efficient lighting to reduce costs and unnecessary pollution. The Green Lights Hotline is (202) 775-6650. Some other sources of technical information are:

E-Source, Inc.	Illuminating Engineering	Energy User News
1033 Walnut Street	Society of North America	Chilton Company
Boulder, CO 80302-5114	345 East 47th Street	1 Chilton Way
(303) 440-8500	NY, NY 10017	Radnor, PA 19089

III. COMPACT FLUORESCENT LAMPS

END-USE: Interior lighting

SECTORS: Commercial, Residential

DESCRIPTION

Performance: Compact fluorescent lamps are three to four times more energy efficient than incandescents and last 10 times as long. They are available with screw-in adaptors for use in incandescent fixtures or in dedicated fixtures equipped with ballasts. Lamp types are usually preheat or instant-start. A few rapid-start systems have been developed. Preheat lamps have a one to two second delay before lighting. Lamp efficiency is related to temperature and orientation. Ballasts can be either magnetic or electronic. Magnetic ballasts may hum and cause lamps to flicker. Ballasts can adversely affect power quality. (See Section II)

Consumer Utility: The lamp walls are coated with rare earth tri-phosphors. This results in compact fluorescent lamps having a high color rendering index (values are in the 80s). Color temperatures are close to those of incandescents.

Development Status: Compact fluorescents are available as integrated lamp/ballast/adapter systems or as non-integrated units. Only the compact systems with rapid-start circuitry have dimming capabilities. Currently, the dimmable systems are only available as modular units.

COSTS

The lower wattage twin tubes cost about $5 per lamp. The more luminous quad tubes cost about $9 per lamp. Integrated units cost $15 to $20. Integrated systems with core and coil ballasts and better than usual power quality characteristics cost about $5 more. Integrated systems with electronic ballasts cost about $25. Modular units cost about $20 to $25 for the ballast/adaptor and lamp.

IMPLEMENTATION

Installation: Compact fluorescents are slightly bigger and heavier than incandescent lamps and may not be a suitable incandescent replacement in every application. Fluorescent lamp performance suffers when operated in a hot environment. This may result in under-lit spaces if the thermal effect is not considered in system evaluation.

Maintenance: Lamp life is about 10,000 hours with ballast life being about three to four times as long. Since lamp life is 10 times that of incandescents, they require less frequent replacement.

Conservation Programs: Utility rebates from $5 to $15 per lamp are usually available to all user sectors.

ENVIRONMENTAL ISSUES

Use of compact fluorescent lamps results in improved energy efficiency and reduced energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

There are solid waste issues associated with the use of compact fluorescent lamps. Integrated lamp/ballast compact fluorescents will result in more solid waste being produced that the non-integrated systems because compact fluorescent lamp life is much shorter than ballast life, forcing the ballast to be discarded before the end of its useful life. On the other hand, since one compact fluorescent lamp is equivalent to ten incandescent lamps, use of compact fluorescents will result in disposal of fewer incandescent lamps. Disposal of compact fluorescent lamps is also an environmental issue because of the mercury contained in each lamp. Mercury, which is a toxic heavy metal, is used to excite the phosphors in the lamp and is gradually deposited onto the glass, filaments, and phosphors. Mercury releases can occur during the manufacturing process, when a lamp breaks, or at the time of lamp disposal, even if the lamp has completed its useful life.

III. COMPACT FLUORESCENT LAMPS

1. Description

1.1 Performance Characteristics

Compact fluorescent lamps are miniaturized fluorescent lamps. They are roughly the same size as incandescent lamps but are three to four times more energy-efficient and last 10 times as long. Typically, a 13 watt compact fluorescent lamp equipped with a 2 watt ballast is suitable to replace a 60 watt incandescent lamp.

Some compact fluorescent systems include an edison base or screw base adaptor enabling the use of the lamp in a standard incandescent socket. Other systems are "hard wired" specifically for compact fluorescents. In the dedicated systems, the single-ended compact fluorescent lamp is installed directly in the fixture.

Compact fluorescents equipped with screw base adaptors are available as integral units or as modular components. The integral units contain the lamp, ballast, and adapter. In the modular units, the ballast/adapter is separate from the lamp.

Integral or modular compact fluorescents can have either a standard magnetic ballast or an electronic ballast. The ballast can consume between one to three watts in addition to the rated wattage of the lamp and this needs to be accounted for in determining system efficacy. Power quality can be characterized by the ballast's power factor, harmonic distortion, and crest factor. The power factor is the ratio of real to apparent power. Harmonic distortion from the ballast must be minimized to insure there is limited current flow in the neutral wire. Lamp current crest factor refers to the shape of the voltage wave form supplied to the lamp. A pure sine wave is desired which has a crest factor of 1.41. Existing magnetic ballasts for compact fluorescents have power factors between 0.85 and 0.90. Their total harmonic distortion ranges between 20% to 50%. For electronic ballasts power factor is above 0.90 but harmonic distortion can be 75% to 160%. Industry standards may help reduce these harmonic distortion levels to 20% to 30%.

The fluorescent lamp circuit type of most compact fluorescents is either preheat or instant-start. The preheat lamps will take one to two seconds to light when switched on. The instant-start lamps turn on almost immediately but have a shorter life. These lamp types cannot be dimmed without lamp life seriously being affected. A few rapid-start compact fluorescent lamps are available. These types of lamps are capable of being dimmed when used with the appropriate ballast. Each lamp type (preheat, instant-start or rapid-start) has its own operating requirements and requires a ballast with matching circuitry. Selecting the right ballast for the lamp is not a concern when using integrated units. For modular units, the lamp's socket will only be compatible with ballasts having the appropriate circuitry.

1.2 Consumer Utility

All compact fluorescent lamps sold in the U.S. use rare earth tri-phosphors as the inside lamp wall coating. These phosphors are the reason for the lamps' higher color rendering index which is in the low 80s for almost all lamps (colors are accurately reproduced if the color rendering value is 100). Color temperatures of compact fluorescents range from 2700 K to 5000 K. When used as replacements for incandescents, concerns about acoustic noise and potential flickering from magnetic ballasts should be addressed. Compact fluorescents have had a low acceptance rate in the U.S. for a number of reasons including the issue of their shape and size compared to incandescents, temperature range of operation, and dimmability.

1.3 Development Status

Manufacturers have been producing compact fluorescent lamps for over 10 years. Currently about 50 companies manufacture the lamps, including General Electric, Philips, Panasonic, and Osram.

Compact lamps come in T4 and T5 diameters (4/12 inch and 5/12 inch diameters). The T4 lamps are available as twin tube or as quad tube. Quad tube lamps provide more lumens per length than the twin tube lamps. T5 lamps are used in the longer compact fluorescents. Twin tube lamps are available in wattages ranging from 5 to 13. They produce lumens equivalent to 25 watt to 60 watt incandescent bulbs. The quad tube lamps are available in wattages ranging from 10 to 27. They are suitable replacements for incandescent bulbs ranging in power from 50 to 100 watts.

Long compact fluorescent lamps are also available. Depending upon the application, they may be too large to be suitable replacements for incandescents, but provide interesting design possibilities. They are available in 1, 1.5, and 2 foot lengths. They put out an equivalent amount of lumens in comparison with regular fluorescent lamps twice their length.

Only the rapid-start lamp/ballast systems are capable of being dimmed. Currently, these systems are only available as modular units.

New compact fluorescent lamp designs have recently been introduced. One is a square-shaped double-D lamp in three sizes and five wattages. Another is a small T-2 diameter lamp available in many lengths and wattages. A third is a compact fluorescent lamp made of three bent tubes (EPRI, 1993).

2. Cost of Equipment

The lower wattage twin tubes cost about $5 per lamp, without the ballast. The more luminous quad tubes cost about $9 per lamp, without the ballast. Integrated units cost $15 to $20. Integrated systems with core and coil ballasts and better than usual power quality characteristics cost about $5 more. Integrated systems with electronic ballasts cost about $25. Modular units cost about $20 to $25 for the ballast/adaptor and lamp.

Table III-1 (attached) lists cost data for compact fluorescent lamps. Calculations for simple payback are included. The payback calculations are based on 3,000 hours of operation a year and electricity cost of $0.08 per kWh and include the avoided cost of the incandescent bulbs.

3. Implementation

3.1 Installation

Incandescent fixtures may not be appropriate for compact fluorescent lamp substitutions because of physical size limitations. Compact fluorescents are bulkier and heavier than incandescent bulbs, but smaller lamps are rapidly being introduced.

Unlike incandescents, compact fluorescent performance is dependent on ambient temperature around the lamp. If the compact fluorescents are installed in tight fixtures or those within a static plenum, the lamps may not achieve their rated output due to high operating temperatures. Also, compact fluorescents that are installed in a base-down position have been found to produce 15 to 12% less light than those installed base-up (Mills, 1993). Such installations may result in under-lit spaces if this thermal effect was not considered in the system evaluation.

Fixtures hard wired for compact fluorescent lamps should be considered if switching back to incandescent use is a possibility.

3.2 Maintenance

Due to the extended life of the compact fluorescent system, compact fluorescent lamps require less maintenance than incandescents. Although some burnouts can be expected, many manufacturers offer extended warranties. Lamp replacements, with corresponding reductions in associated labor and capital costs, are thus minimal compared to incandescent systems.

3.3 Conservation Programs

Some utilities in the U.S. are offering rebates ranging from $5 to $15 per compact fluorescent lamp. These credits are available to residential, commercial and industrial users.

4. Environmental Issues

Use of compact fluorescent lamps results in improved energy efficiency and reduced energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

There are solid waste issues associated with the use of compact fluorescent lamps. Integrated lamp/ballast compact fluorescents will result in more solid waste being produced than the non-integrated systems because compact fluorescent lamp life is much shorter than ballast life, forcing the ballast to be discarded before the end of its useful life. On the other hand, since one compact fluorescent lamp is equivalent to ten incandescent lamps, use of compact fluorescents will result in disposal of fewer incandescent lamps. Compact fluorescent lamps can be recycled for between $0.75 (modular) and $1.50 (integral) (Mills, 1994).

Disposal of compact fluorescent lamps is also an environmental issue because of the mercury contained in each lamp. Mercury, which is a toxic heavy metal, is used to excite the phosphors in the lamp and is gradually deposited onto the glass, filaments, and phosphors. Mercury releases can occur during the manufacturing process, when a lamp breaks, or at the time of lamp disposal, even if the lamp has completed its useful life. Mercury released to the atmosphere as a result of lamp breakage will vaporize and is extremely hazardous in enclosed areas. Burying the lamps in a landfill reduces vaporization, but increases the chance for mercury leaching into the soil and nearby aquifers. In an aquatic environment, mercury moves to a menthylated state and is hazardous to biological organisms (Clear, 1994). This issue is further complicated by considering the mercury released to the atmosphere by a coal-fired power plant producing electricity to operate mercury-free incandescent lamps. Analysts have calculated that the mercury content of the coal is three times greater than the small amount of mercury in the compact fluorescent lamp (Mills and Piette, 1993).

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Table III-1
Compact (Low-Watt) Fluorescents: Product Guide

Style	Lamp Wattage	Mean Lumens (a)	Lumens per Watt (b)	Approximate Incandescent Equivalent (Watts)	Color Rendering Index (c)	Color Temperature (d) (K)	Rated Life (Hrs)	Electric Cost Savings per year (e)	Total Cost Savings per year (f)	Fluorescent Lamp Cost	Payback (g) (years)
Capsule	15	720	48	60	84	2,800	9,000	$10.80	$15.80	$14	0.9
Capsule	18	1,100	61	75	84	2,800	9,000	$13.68	$18.68	$20	1.1
Globe	15	720	48	60	84	2,800	9,000	$10.80	$15.80	$14	0.9
Twin Tube	7	360	57	40	82	2,700	10,000	$7.92	$12.92	$24	1.9
Twin Tube	11	520	55	40+	82	2,700	10,000	$6.96	$11.96	$24	2.0
Twin Tube	15	775	60	60	82	2,700	10,000	$10.80	$15.80	$24	1.5
Twin Tube	20	1,032	60	75	82	2,700	10,000	$13.20	$18.20	$24	1.3
Quad Tube	20	1,100	55	75+	84	2,800	9,000	$13.20	$18.20	$20	1.1
Quad Tube	27	1,550	57	100	84	2,800	9,000	$17.52	$22.52	$22	1.0

Source: Energy User News, No. 10, Oct 1990, p. 32, Chilton Company.

(a) "Mean lumens" lists the mean (maintained) lumens emitted by the lamp at 40% of its rated life.

(b) Lumens per watt represents mean lumens per rated lamp watts, not taking ballast wattage into account.

(c) The closer to 100 the Color Rendering Index is, the closer it is to reproducing colors accurately.

(d) Color temperature (Kelvins) should match other lamps in the room; incandescent lamps are about 2,900 K; natural sunlight is about 5,500 - 6,500 K.

(e) The electric cost savings per year includes the ballast wattage associated with the fluorescent lamp, and is calculated based on 3,000 hours of lamp operation per year and an electricity rate of $0.08 per kWh.

(f) The total cost savings per year assumes that displaced incandescents last 750 hours and cost $1.00 each. Labor to change incandescent bulbs is assumed to be 1.5 minutes per bulb @ $10/hour. These assumptions imply a total annual bulb and labor cost of $5.00/year. This annual savings is added to the energy savings and used to calculate payback. In a residential application with no labor costs for changing bulbs, the annual savings will be less.

(g) Prices are to the end user. Paybacks are based on 3,000 hours of lamp operation per year and based on the cost premium of the energy-efficient fluorescent over the standard incandescent lamp.

IV. LIGHTING CONTROLS

END USE: Interior and exterior lighting

SECTORS: Commercial, Industrial

DESCRIPTION

Performance: Lighting controls are a method to manage lighting energy use more efficiently in commercial an industrial buildings. Controls are used to: 1) reduce lighting during unoccupied periods, 2) switch off or dim lights in daylit areas, 3) efficiently compensate for lumen depreciation, 4) adjust light levels according to local tasks, and 5) shed loads to moderate peak demand. The energy savings resulting from the application of these strategies is highly dependent on hours of operation and occupancy patterns. Systems that use a combination of these strategies, however, have been demonstrated to reduce lighting energy use by over 50%.

Consumer Utility: Lighting controls allow the end-user greater control over the lighting system. An appropriately tuned lighting system may improve worker productivity by reducing glare.

Development Status: Most lighting control components are based on mature technologies. However, there are relatively few manufacturers of complete turnkey systems. Also, there are relatively few dimming ballasts available for the more recent efficient lamp types (the T-8 lamps and the long twin tube lamps).

COSTS

Occupant sensors can be installed at a cost of $0.40 - $1.00/sf depending on mounting-configuration. Programmable timers cost $0.20 - $0.30/sf depending on the control point density. A complete lighting control system for new construction with dimmable ballasts, controllers and an energy management system generally has an incremental cost of $1.00 - $2.00/sf.

IMPLEMENTATION

Effective implementation of lighting controls is constrained by the in-place wiring in existing buildings. In retrofit applications, controls are typically installed in the electric room or existing switches are replaced with occupant detectors. In new construction, more advanced, custom-designed controls can be installed by appropriate wiring of the lighting system.

Utility rebates are available for a wide variety of lighting controls in the U.S. For example, rebates of $15 to $120 per sensor are offered for occupancy controls, of $20 to $100 per timer are offered for timer controls, and of $6 to $18 are offered for dimmable ballasts.

ENVIRONMENTAL ISSUES

Use of lighting controls results in improved energy efficiency and reduced energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

When doing extensive lighting retrofits that involve lamps and ballasts, there may be concerns about mercury in the used lamps and PCBs in the old ballasts (see Section II. Electronic Fluorescent Ballasts).

IV. LIGHTING CONTROLS

1. Description

Lighting controls are used to more effectively manage the way energy is used for lighting. The lighting controls strategies for reducing energy are listed below with estimated energy savings for each strategy. The energy savings are highly sensitive to baseline assumptions, especially hours of use and occupancy patterns.

Strategy	Description	Estimated Energy Savings
Scheduling	Eliminating or reducing lighting during unoccupied periods	10-30% with programmable timers, 30-60% with occupancy sensors
Daylighting	Switching off or dimming lights in daylit portions of a building	10%-15% (switching) 15%-35% (dimming)
Lumen maintenance	Efficiently compensating for lumen depreciation	10%-15%
Tuning	Adjusting light levels to suit local task requirements	10%-20%
Load shedding	Momentarily reducing light levels to reduce peak demand	N/A
Adaptation compensation	Adjusting light levels to suit visual adaptation condition	N/A

1.1. Performance Characteristics

These strategies are implemented using a combination of the following control hardware:

Programmable timers are used to implement time-based control of electric lights. The usual method of implementation is a system of low-voltage controlled relays that are controlled by a programmable time clock. These systems are primarily used to efficiently schedule lighting system operation in areas where the occupant schedule is relatively predictable. To accommodate off-hours lighting needs, these systems usually have overrides so that lighting can be obtained by building occupants either by means of low-voltage switches or telephone override systems.

Occupant sensors are switches that are activated by detecting the presence or absence of people in the sensor's field of view. There are two basic types of occupant sensor: passive infrared sensing and ultrasonic (some sensors combine these two methods). These sensors are most effective in locations where occupancy cannot be well-predicted, such as conference rooms, storerooms, etc.

Photo-switches are photo-electrically controlled switches that can be used to switch off lights in building zones receiving daylight from adjacent windows. These devices are usually installed 1) on each fixture, 2) on groups of fixtures using intermediate relays, or 3) as inputs to low-voltage programmable relay systems.

Dynamic controls are devices that allow standard lighting equipment (including both fluorescent and HID sources) to be continuously dimmed to an intermediate level. These systems can control a single lamp or entire branch circuits. Although these controls can typically provide any light level within the control range, they rarely permit dimming below 40% of maximum. They generally accept an input from a photocell and/or an input from an EMS system.

Static controls are devices that allow the light output of standard lighting equipment to be reduced to one intermediate level. These systems can control a single lamp or entire branch circuits. The larger systems generally accept an input from an EMS system for scheduling control. The smaller systems generally control only a single lamp or ballast - their sole function is to reduce input power (and light output). The primary application of these systems is in areas that are overlit.

Dimmable ballasts represent the state-of-the-art in controllable lighting. Dimmable ballasts allow fluorescent lamps to be dimmed over a very wide range. This technology is available both in magnetic ballasts and as dimmable electronic ballasts. The electronic ballasts are generally controllable through a low-voltage wiring network allowing them to respond to inputs from a photocell, occupant sensor and input from an EMS.

1.2 Customer Utility

Lighting controls permit the occupant to exercise a greater degree of control over the lighting system. Using dimmers and improved switches, the user can change light levels to suit a particular task (such as showing slides or using a graphics terminal). Remote control devices, which let the occupant control lights from a more distant location, are available but not in widespread use. Some lighting management systems also provide an audit function, allowing the facilities manager to track how lighting is used throughout the facility. Lighting loads can also be reduced for short periods of time with appropriate control gear which, in buildings where lighting is a significant fraction of the electric load, may allow avoidance of a peak demand ratchet charge.

It should be noted that controls have a high opportunity for failure due to override. However, simple features such as on/off switches for individual banks of light (vs. the entire floor) help mitigate this problem.

1.3 Development Status

There is hardware currently available to implement any of the above strategies successfully. However, dimming electronic ballasts, which afford the greatest degree of control and permit the best integration of the above strategies are significantly more costly than non-dimming ballasts. Also, dimming ballasts for the more efficient T-8 lamp have recently been developed. Occupant sensors, photo-switches and programmable timers are relatively mature technologies.

2. Cost of Equipment

Programmable timers are usually priced on a per control point basis. Installed costs of $125-$150/point are typical in commercial buildings. Installed cost for branch-circuit based dimmers is generally between $300 (for static control) and $1000 (for dynamic control) per circuit. The cost of occupant sensors depends on the particular technology (infrared detection is cheaper than ultrasonic control) as well as the mounting configuration. The incremental cost of a wall-mounted personnel sensor may be only $30. But, if ceiling-mounted to control a larger area, an occupant sensor may cost $150 installed.

Dimmable ballasts generally cost between $30-$80 each.

3. Implementation

3.1 Installation

The electrical wiring configuration is the major constraint in installing controls in buildings. In existing buildings, it is usually not cost-effective to substantially re-wire the ceiling electric lighting system with the purpose of installing a lighting control. Thus, lighting control retrofits are usually restricted to installing relays in the electric room and implementing control on each branch circuit. In buildings where local manual switching is in place, it is often possible to reduce hours of use simply by replacing the existing wall switch with an occupant detector. To control larger spaces, ceiling-mounted sensors are preferable. Ceiling-mounted sensors typically activate a low-voltage relay that is in series with the lighting load that is controlled.

Dimming packs that dim all lights on a branch circuit can also be installed in the electric room. The relay panels (and/or dimming units) must then be wired to a lighting management system or building EMS (which may control more than just the lighting circuits.) Dimmers are often used in conjunction with relay-based switches because dimmers generally do not allow light levels to be lowered to zero without significant parasitic losses.

In new construction, the lighting wiring can be chosen to complement the control function desired. Thus, lights in the perimeter of the building, for example, should be wired together allowing their operation to be easily controlled with a simple photo-relay. To implement daylight-linked dimming in new construction, photocells are installed at appropriate locations (typically in the ceiling).

Integrating all lighting control strategies requires installing dimmable electronic ballasts along with requisite sensors, controllers and low-voltage control wiring. Fixtures that are to be controlled together are wired together with low-voltage wiring. This allows control zones to be implemented at any reasonable scale -- zones can subdivide branch circuits or even operate across circuits to accommodate daylight conditions or occupancy needs.

3.2 Maintenance

Photocells and occupant sensors require calibration during the commissioning process. Occupant sensors can usually be adjusted to alter their sensitivity to movement and to control the time period between when the sensor last detects motion and the time the lights are switched off. Additionally, occupant sensors that incorporate a daylight switch generally must be calibrated to set the light level above which the sensor will not turn on lights even after detecting movement.

Photocells for daylight-linked control must also be calibrated. Depending on the specifics of the control hardware, the system may be calibrated at night time (i.e., without daylight) and/or during the daytime. Calibration, if properly performed, need only be repeated when there is a significant change in furniture or partition arrangement.

Lumen maintenance is the practice of reducing lighting power at the beginning of the maintenance cycle (about 2 years) when lamps are new and then increasing power at the end of the maintenance cycle to provide consistent illuminance (EPRI, 1993). Lumen maintenance can only be effectively used in a site where group re-lamping is practiced. The system must also be properly calibrated on commissioning to assure energy savings.

Programmable timers do not generally require maintenance. However, upon installation, it is necessary to program the timer according to the local building schedule. This requires that the occupancy patterns be roughly established so that the lighting relays can be appropriately programmed.

3.3 Conservation Programs

Utility rebates are available for a wide variety of lighting controls in the U.S. For example, rebates of $15 to $120 per sensor are offered for occupancy controls, of $20 to $100 per timer are offered for timer controls, and of $6 to $18 are offered for dimmable ballasts.

4. Environmental Issues

Use of lighting controls results in improved energy efficiency and reduced energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

When doing extensive lighting retrofits that involve lamps and ballasts, there may be concerns about mercury in the used lamps and PCBs in the old ballasts (see Section II. Electronic Fluorescent Ballasts).

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V. ROOM AIR CONDITIONERS

END-USE: Air Conditioning

SECTOR: Residential

DESCRIPTION

Performance: High efficiency room air conditioners (window-type units) provide the same cooling performance as lower efficiency models. (Japanese manufacturers refer to their ductless split system units as room air conditioners. These should not be confused with the "window-type" room units being discussed here.) Since the amount of cycling is believed to be low in room air conditioners, a steady-state efficiency rating (EER), rather than a seasonal rating (SEER), is used to evaluate them.

Consumer Utility: High efficiency room air conditioners provide the same utility as less efficient models. Sometimes a high EER is achieved with less dehumidification. Unit size might increase slightly.

Development Status: Room air units with EERs of 8.5 or over have increased from 11.4% of total shipments in the U.S. in 1980 to 60.2% in 1989. The highest rated equipment typically has an EER of 10.0, though units are available with EERs exceeding 12.0. Further increases in efficiency are expected as the current rate of rotary compressor development will produce a 12.0 EER compressor by the year 1995.

COSTS

The incremental cost of improving the EER of the most typical room air conditioner sold (10,000 to 12,000 Btu/h) from 9.0 to 10.0 EER is $31. The 1991 retail list price of a 12,000 Btu/h, 9.0 EER unit is approximately $500.

IMPLEMENTATION

Installation: Room air conditioners are typically installed in windows. Installation of the unit can be performed by the home owner. The chassis size of typical high efficiency room units (10.0 EER) is no larger than lower efficiency models. The most efficient models (exceeding 10.0 EER) are generally wider than their lower efficiency counterparts.

Maintenance: The increased fin density (fins/inch) and enhanced fin surfaces found in high efficiency room units may hasten the build up of dirt particles on the coils. This could lead to coil degradation and shorten the life of the unit. Typical room air conditioner life is 11 years.

Conservation Programs: The National Appliance Energy Conservation Act (NAECA) specified minimum efficiency standards in 1992 for room air conditioners sold in the U.S. (8.0 to 9.0 EER depending on unit capacity). Electric utilities have sponsored rebate programs to increase saturation of these air conditioners.

ENVIRONMENTAL ISSUES

Use of high efficiency room air conditioners results in improved energy efficiency and reduced energy demand which has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

The refrigerant used by all room air conditioners is R-22. R-22 is a hydrochloroflurocarbon (HCFC) and demonstrates both ozone depletion potential (ODP) and global warming potential (GWP) (Fairchild and Fischer, 1991). These are significant environmental concerns and a great deal of work is being done to develop a suitable replacement refrigerant. In addition to ODP and GWP, replacement refrigerants must contend with an array of criteria including nontoxicity, nonflammability and chemical stability, and inertness.

V. ROOM AIR CONDITIONERS

1. Description

1.1. Performance Characteristics

A room air conditioner is an encased assembly designed as a unit to be mounted in a window or through a wall. It is designed primarily to provide cool air to an enclosed space, room, or zone. Heat is sometimes provided by heat pump operation, electric resistance elements or by a combination of both.

A room air conditioner consists of refrigerant-side and air-side components all contained within one cabinet. The refrigerant-side components are the evaporator (indoor conditioning coil), the compressor, the condenser (outdoor coil), and the capillary tube. These components are all connected via refrigerant tubing. The air-side components consist of the fan motor and the evaporator and condenser fans. One fan motor is used to drive both fans. The cabinet that contains these components is split into an indoor and outdoor side. The two sides are separated by a divider wall which is usually insulated to reduce heat transfer between the two sides. The indoor components are the evaporator and evaporator fan. The outdoor components are the compressor, condenser, capillary tube, fan motor and condenser fan.

The present procedure for rating room air conditioners is a steady-state test which establishes an energy efficiency ratio (EER) for the unit being tested (ANSI, 1982). The EER is obtained by dividing the measured cooling capacity of the unit (Btu/hour) by its total electrical input (Watts). A seasonal rating procedure has not been adopted for room air conditioners because cycling effects (where the unit turns off and on to meet temperature setpoint) are believed to be small. When room units are turned on, the room temperature is likely to be high, thus reducing the amount of cycling as compared to central air conditioning systems.

Due to economic and installation considerations, the efficiency of room air conditioners becomes a function of capacity. Manufacturers state that every room air conditioner unit could be designed to optimize performance and efficiency as long as a specific cabinet could be built to best suit the unit's particular capacity and efficiency. A room unit's most typical installation is in a double-hung window. Manufacturers cannot afford the luxury of optimizing every model they produce, so they limit their production of cabinets to three or four sizes, taking into account the size of the most typical double-hung windows. Each cabinet is designed to accommodate models of the same relative capacity size. Having the same cabinet, these models will tend to have the same design constraints. Since these constraints have a direct impact on efficiency, models of the same relative cooling capacity will also tend to have the same efficiency.

The minimum efficiency standards established by the United States through the National Appliance Energy Conservation Act (NAECA), demonstrate how efficiency is a function of capacity (Code of Federal Regulations, 1990). NAECA establishes 12 product classes, five of which depend on capacity, each having its own minimum EER. Table V-1 provides a list of the minimum EERs for the five primary product classes. The five product classes listed in Table V-1 constitute over 95% of total United States' sales of room air conditioners in 1989. NAECA standards for room air conditioners took effect January 1, 1990.

Table V-1
NAECA Minimum Efficiency Standards
as of 1 Jan 1990

Product Class (without reverse cycle and with loitered sides)	**Energy Efficiency Ratio**	**1990 Shipments (%)**
Less than 6,000 Btu/h	8.0	27%
6,000 to 7,999 Btu/h	8.5	19%
8,000 to 13,999 Btu/h	9.0	32%
14,000 to 19,999 Btu/h	8.8	14%
Greater than 20,000 Btu/h	8.2	8%
Weighted Average	8.5	

The energy consumption of the compressor ranges from 82% to 88% of the total room air conditioner electrical energy consumption. This indicates that the greatest energy conservation opportunity lies with reductions in compressor energy use. This can be accomplished by using more efficient compressors or improving the heat transfer performance of the evaporator and condenser coils. Of course, since fan motor energy use accounts for at least 12% of the total energy consumption, opportunities for conserving energy are also available by improving the efficiency of the air delivery system.

Most U.S. room air conditioner manufacturers produce their heat exchangers "in-house." The research and development of new heat exchanger improvements are usually conducted "in-house" as well. Methods for improving the performance of the heat exchanger coils include the following: increasing the frontal coil area, increasing the depth of the coil (adding tube rows), increasing the fin density, adding a subcooler (for the condenser coil only), improving the fin design, and improving the tube design. All U.S. manufactured room air conditioners collect the condensate dripping off the evaporator coil and spray it onto the condenser coil. The spray improves the air-side heat transfer coefficient of the condenser (Tree, et al., 1978).

Heat exchanger coils in U.S. room air conditioners are made of aluminum fins and copper refrigerant tubing. Most, if not all, high efficiency room air conditioner models (EERs of at least 10.0) use "enhanced" fin surfaces and "grooved" tubing. The "enhanced" fin surface usually consists of small strips raised from the base plate fin surface. These surfaces increase the air turbulence over the coil and, thus, increase the air-side heat transfer coefficient. "Enhanced" fins yield better results than wavy or corrugated fin designs (Nakayama and Xu, 1983; Webb, 1990; Beecher and Fagan, 1987). Each room air conditioner manufacturer has developed a unique fin design to achieve the desired heat transfer improvement. "Grooved" refrigerant tubing (also referred to as rifled tubing) has its interior surface augmented with spiral grooves. The added surface area created by the grooves improves the refrigerant-side heat transfer coefficient (Schlager et al., 1990).

Increasing the total coil surface area by adding tube rows or increasing the face area is limited by the chassis in which the room air unit is constructed. A larger chassis is typically required to accommodate more rows or a larger face area as the coils usually have been maximized for the greatest face area and depth. Units with the highest efficiency (12.0 EER) have relatively large coils for their capacity size. All 12.0 EER units have relatively low cooling capacities (8,800 to 10,500 Btu/h). Since manufacturers produce three to four standard chassis sizes, the 12.0 EER units are usually the smallest capacity model to be installed in a particular chassis size. Thus, their high efficiency is due in large part to the higher "coil size-to-capacity" ratio.

Increasing the fin density is another option for increasing the total surface area. But most coil designs already have the maximum fins per inch allowable. Any further increases might lead to premature coil degradation as dirt particles could more easily lodge between the tightly packed fins.

Few room air conditioners incorporate subcoolers. Most manufacturers attempt to get the amount of subcooling desired through redesign of the condenser before trying to incorporate one. Typical subcoolers are added between the condenser outlet and the capillary tube inlet and are submerged near the condenser in the condensate produced by the evaporator. The effect of adding a subcooler is to further cool the refrigerant coming out of the condenser. This is accomplished by essentially increasing the size of the condenser coil.

All U.S. room air conditioner manufacturers purchase their compressors from compressor manufacturers. Most room units (probably over 90% of U.S. models made) use rotary compressors. All rotary compressors are manufactured and sold by Japanese companies (e.g., Matsushita, Sanyo, and Toshiba). These rotary compressors range in efficiency from 10.0 to 11.0 EER. At the current rate of rotary compressor development, 12.0 EER compressors should be available by the year 1995. Some room air conditioner manufacturers use reciprocating rather than rotary compressors. These are bought from U.S. compressor manufacturers (e.g., Tecumseh and Bristol). Some reciprocating models have EERs as high as 11.0. Bristol has developed a higher efficiency reciprocating compressor (the "inertia" compressor) with EERs exceeding 11.0 (Air Conditioning, Heating & Refrigeration News, 1991). Copeland has developed a scroll compressor, with EERs also exceeding 11.0. Both the Bristol "inertia" and the Copeland scroll are available in sizes that can only be used by the largest (over 18,000 Btu/h) room air conditioner capacity units.

Most efficiency improvement measures to the air delivery system are aimed at increasing the fan motor efficiency. Most U.S. room air conditioner manufacturers use permanent split capacitor (PSC) fan motors. PSC motors range in efficiency from 55% to 70%. Only a few room air models still use the low efficiency shaded pole motor (30% to 40% efficiency). The permanent magnet brushless dc motor (efficiency exceeding 70%) is presently much too expensive to be used in room air conditioners. Most fan motors are purchased from U.S. motor manufacturers.

Since cycling effects are small, designs which improve efficiency on a seasonal basis are possibly not effective for room air conditioners. Variable speed systems (using both variable speed compressors and fan motors), thermostatic and electronic expansion valves, and thermostatic controls are all designs that improve the part-load efficiency of central air conditioning systems. Variable speed systems reduce the energy consumption of central systems by as much as 40% (depending on climate location) (Henderson, 1990; Bahel and Zubair, 1989; Hori et al., 1985).

Most high efficiency room air conditioners (10.0 EER) incorporate the following: high efficiency rotary compressors (rating of approx. 11.0 EER), "enhanced" fins and "grooved" refrigerant tubing in the heat exchanger coils, larger evaporator and condenser coils than comparable lower efficiency models (relatively large "coil size-to-capacity" ratio), permanent split capacitor (PSC) fan motors (motor efficiency of 55% to 70%), and the spraying of condensate onto the condenser coil. "Super" high efficiency units (10.5 to 12.6 EER) have even higher "coil size-to-capacity" ratios.

1.2. Consumer Utility

Energy-efficient room air conditioners provide the same consumer utility as their less efficient counterparts. The more efficient compressors and enhanced heat exchanger surfaces that these units incorporate do not shorten the life or reduce the cooling performance of the unit. If not designed correctly, enlarging the evaporative coil could lead to less dehumidification.

1.3. Development Status

Over the past ten years, the efficiency of the average room air conditioner has increased significantly. Table V-2 presents the percent of U.S. room air conditioner shipments in the decade of the 1980s with EERs 8.5 and higher (statistics compiled by the Association of Home Appliance Manufacturers [AHAM]).

Table V-2
Percent of U.S. Room Air Conditioner Shipments with EERs of 8.5 and Higher

Year	Percent
1980	11.4
1981	16.4
1982	18.6
1983	22.4
1984	27.7
1985	39.2
1986	40.9
1987	48.3
1988	47.1
1989	60.2

The AHAM 1991 directory of room air conditioners indicates that high efficiency models (10.0 EER) are available in most cooling capacity sizes (5,600 to 20,000 Btu/h). The most efficient models (EERs over 11.0) have capacities ranging from 7,200 to 10,500 Btu/h (AHAM, 1991).

Further efficiency increases in room air conditioners will most likely come from more efficient compressors and the use of larger heat exchanger coils. The current rate of rotary compressor development will result in 12.0 EER compressors being available by the year 1995. Heat exchanger improvements seem to be restricted to the use of larger coils as there are no foreseeable developments in fin or tube designs beyond the current "enhanced" fins and "grooved" tubing.

Variable speed compressors and fan motors could reduce the energy consumption of room air conditioners. Since room units are believed to cycle infrequently, the effect on efficiency of using variable speed systems is probably small. No U.S. manufacturer has yet attempted to produce a variable speed room air conditioner.

2. Cost of Equipment

In a report titled "Costing Analysis of Design Options for Residential Appliances and Space Conditioning Equipment" written by ADM Associates, Inc. for Lawrence Berkeley Laboratory, the cost of design options for room air conditioners was estimated (ADM Associates, 1987). In the report, cost-efficiency tables for the 12 NAECA product classes are presented. The tables detail the incremental manufacturing costs for incorporating various energy efficiency design options into U.S. room air conditioners. From the tables, manufacturing cost vs. EER equations can be constructed. The report was completed in December 1987, so the assumptions regarding baseline efficiencies and design options are outdated. But the cost vs. EER equations can still be used to estimate the cost to incorporate more energy-efficient design options into room air conditioners. Table V-3 provides a formula to calculate the incremental manufacturing cost vs. EER equations for the five primary NAECA product classes. (The equations are straight line approximations. Data point correlation values are provided.)

Table V-3
Incremental Manufacturing Cost vs. EER Equations

Product Class	Equations	Base EER	Base Cost (1987$)	R^2
Less than 6,000 Btu/h	delta Cost = 12.0 * EER - 88.5	7.5	$115	0.95
6,000 to 7,999 Btu/h	delta Cost = 8.1 * EER - 80.1	7.5	$145	0.96
8,000 to 13,999 Btu/h	delta Cost = 15.5 * EER - 107.1	7.3	$195	0.89
14,000 to 19,999 Btu/h	delta Cost = 20.2 * EER - 156.9	7.8	$220	0.94
Greater than 20,000 Btu/h	delta Cost = 20.4 * EER - 148.2	7.5	$280	0.89

Using the curves in Table V-3 and the NAECA minimum EERs as baseline efficiencies (Table V-1), rough estimates of the increased manufacturing cost due to improving the efficiency of a room air conditioner can be calculated. It is important to note that the costs provided in Table V-3 are manufacturing costs, not retail costs. Typical manufacturing-to-retail cost mark-ups range from 1.7 to 2.0. Table V-4 provides retail prices for several room air conditioner types.

Table V-4
Retail Costs for Room Air Conditioners

Brand	Model	Capacity (Btu/h)	EER	Retail Cost (1991$)
Kenmore	79063	5950	8.0	$297.19
Kenmore	77088	8000	9.7	$413.93
Kenmore	78109	10,000	9.0	$440.89
Kenmore	79129	12,000	9.0	$510.44
Kenmore	76149	14,000	10.2	$624.82
Kenmore	79185	18,000	9.0	$591.32
Kenmore	75219	21,000	8.2	$797.61

3. Implementation Issues

3.1. Installation

Room air conditioners are installed either in windows or through walls. Installation of the unit can be performed by the home owner. Window units have side louvers stamped on the outdoor side of the chassis which enhance the movement of air over the outdoor coil. Units that are intended for installation though a wall require a non-louvered sleeve or a smooth-sided cabinet. Without the side louvers, the air flow past the outdoor coil is not as great as in window units. Through-the-wall units have lower EERs than comparable window-type models.

Window units are typically meant to be installed in double-hung windows. Most room air conditioner models come equipped with expandable side curtains. These curtains are used in those instances where the width of the window is wider than the width of the room air unit. The curtains are expanded out to "close off" the space not occupied by the room air conditioner. Some room air conditioner models are specifically designed to fit in slider/casement or casement only windows.

The chassis size of typical high efficiency room units (10.0 EER) is no larger than lower efficiency models. Because of its larger chassis size, the minimum window width for the highest efficiency room units (exceeding 10.0 EER) is typically greater than comparable low efficiency models.

3.2. Maintenance

The increased fin density (fins/inch) and enhanced fin surfaces found in high efficiency room units might hasten the build up of dirt particles on the coils leading to coil degradation and shortening the life of the unit, though evidence of this problem has not yet been presented. Other than this potential problem, high efficiency room air conditioners are expected to last as long as their lower efficiency counterparts. Room air conditioners have lifetimes between 5 and 15 years, with an average of 11 years.

3.3. Conservation Programs

The National Appliance Energy Conservation Act (NAECA) of the United States mandates both minimum efficiency standards for room units and continuing standards development to determine whether the NAECA minimum standards should be amended.

Several electric utilities have instituted residential rebate programs for increasing the saturation of high efficiency space conditioning and water heating appliances. Room air conditioners have been included in some of these programs. An EPRI report titled "A Compendium of Utility-Sponsored Energy Efficiency Rebate Programs" provides detailed information on these residential rebate programs (EPRI, 1987).

4. Environmental Issues

Use of high efficiency room air conditioners results in improved energy efficiency and reduced energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

The refrigerant used by all room air conditioners is R-22. R-22 is a hydrochloroflurocarbon (HCFC) and demonstrates both ozone depletion potential (ODP) and global warming potential (GWP) (Fairchild and Fischer, 1991). These are significant environmental concerns and a great deal of work is being done to develop a suitable replacement refrigerant. In addition to ODP and GWP, replacement refrigerants must contend with an array of criteria including nontoxicity, nonflammability and chemical stability, and inertness. Research has yet to identify any pure fluid that can be considered a suitable substitute for R-22. Some binary and ternary mixtures have demonstrated promise as being suitable substitutes for R-22, but no prototypes have been developed to demonstrate how they might affect the performance of actual air conditioning systems (Radermacher and Jung, 1990). Some organizations are proposing the complete ban of HCFC production by the year 2005. Though no suitable substitute has yet been developed for R-22, the intensity of work currently being conducted to find replacements for HCFCs may result in the development of a suitable replacement for R-22 by the end of the century.

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VI. HIGH-ALBEDO MATERIALS, COATINGS, AND PAINTS

END-USE: Air Conditioning

SECTOR: Small Commercial, Residential

DESCRIPTION

Performance: With high-albedo (reflective) materials, up to 85% of the incident shortwave radiation can be reflected, thus keeping building and urban surfaces cooler and reducing their warming rates. Compared to conventional materials that reflect between 20% and 30% of the sun's radiation, high-albedo materials can reduce the heat gain in buildings and keep the urban air temperature from rising. The results are significant savings in cooling energy use at building scale and city-wide, as well as reductions in pollutant emissions.

Consumer utility: By keeping building envelopes cooler, high-albedo materials help attain indoor thermal comfort in hot climates. If applied on a city-wide scale, high-albedo materials can keep the urban air temperature lower than otherwise, thus achieving outdoor thermal comfort as well. In addition to saving energy, high albedo paints and coatings increase the life span and structural integrity of roofs, walls, and streets/pavements. Less maintenance is needed.

Development status: High-albedo paints, coatings, membranes and components are readily available.

COSTS

Since there are a large variety of high-albedo strategies, it is not feasible to make a general statement about cost. But we can state, for example, that if painting is performed during regular maintenance of roofs, walls or other surfaces (usually every 10 to 20 years) no additional costs should be incurred by switching from a dark color to a light one. For elastomeric coatings, the cost is in the range of \$3 to \$9 per m^2 with associated application (labor) cost in the range of \$3 to \$6 per m^2. Rubber membranes (Ethylene Propylene Diene Terpolymer Membranes: EPDMs) cost in the range of \$4 to \$7 per m^2 and their installation costs run in the range of \$16 to \$23 per m^2. For paved surfaces, the materials cost range is from \$1.5 to \$20 per m^2.

IMPLEMENTATION

Installation: Depending on whether the high-albedo product is a paint, coating, membrane or component, the installation procedure will vary accordingly. In all cases, no new or special requirements need to be met.

Maintenance: Depending on the type of high-albedo surfacing, the typical life span is between 10 and 50 years. Maintenance requirements during this period are minimal , although periodic cleaning may be needed to retain high albedo.

Conservation programs: No programs have been established yet. Some proposals are being developed to offer incentives, such as utility rebates, for meeting a minimum specified albedo in each climate zone and to incorporate high-albedo in building energy codes.

ENVIRONMENTAL ISSUES

Use of high albedo materials, coatings and paints can result in both direct (building) and indirect (urban-scale) reductions in energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

Volatile organic compounds (VOCs) may be released from paints and coatings, and may require special precautions if urban-scale implementation of high-albedo paints and coatings is considered. Membranes and shingle roofs do not impose this type of possible hazard.

VI. HIGH-ALBEDO MATERIALS, COATINGS, AND PAINTS

1. Description

1.1. Performance Characteristics

Albedo is reflectivity integrated over the solar spectrum. More reflective surfaces will have higher albedo values. High-albedo materials can save cooling energy use directly by reducing the heat gain through a building's envelope and, if applied on a large scale, indirectly by lowering the urban air temperature. Analysis of these direct and indirect effects through computer simulation suggests that urban-scale changes in albedo can reduce peak cooling loads in many American cities by 30% to 50%. The reduction in generating capacity needed to meet cooling demand also translates into reduced pollutant emissions into the atmosphere.

Under clear sky conditions, surface temperatures of conventional materials, such as built-up roofs with gravel, black Ethylene Propylene Diene Terpolymer Membranes (EPDMs), bituminous roofs, and dark asphalt are on the average about 35°-40°C higher than those of high-albedo coatings and surfaces. In the morning and in the late afternoon, the high-albedo materials can be as cool as the air itself. Measured data show that while conventional materials warm up by an average 0.055 °C/(W m^{-2}), the high-albedo surfaces warm up by an average 0.015 °C/(W m^{-2}) (Taha et al., 1992). Thus, for the same amount of insolation, the darker surfaces are three to four times warmer than the high-albedo ones. Figure VI-1 shows surface temperatures for selected surfaces with different albedos, tested side-by-side on one roof in the San Francisco Bay Area.

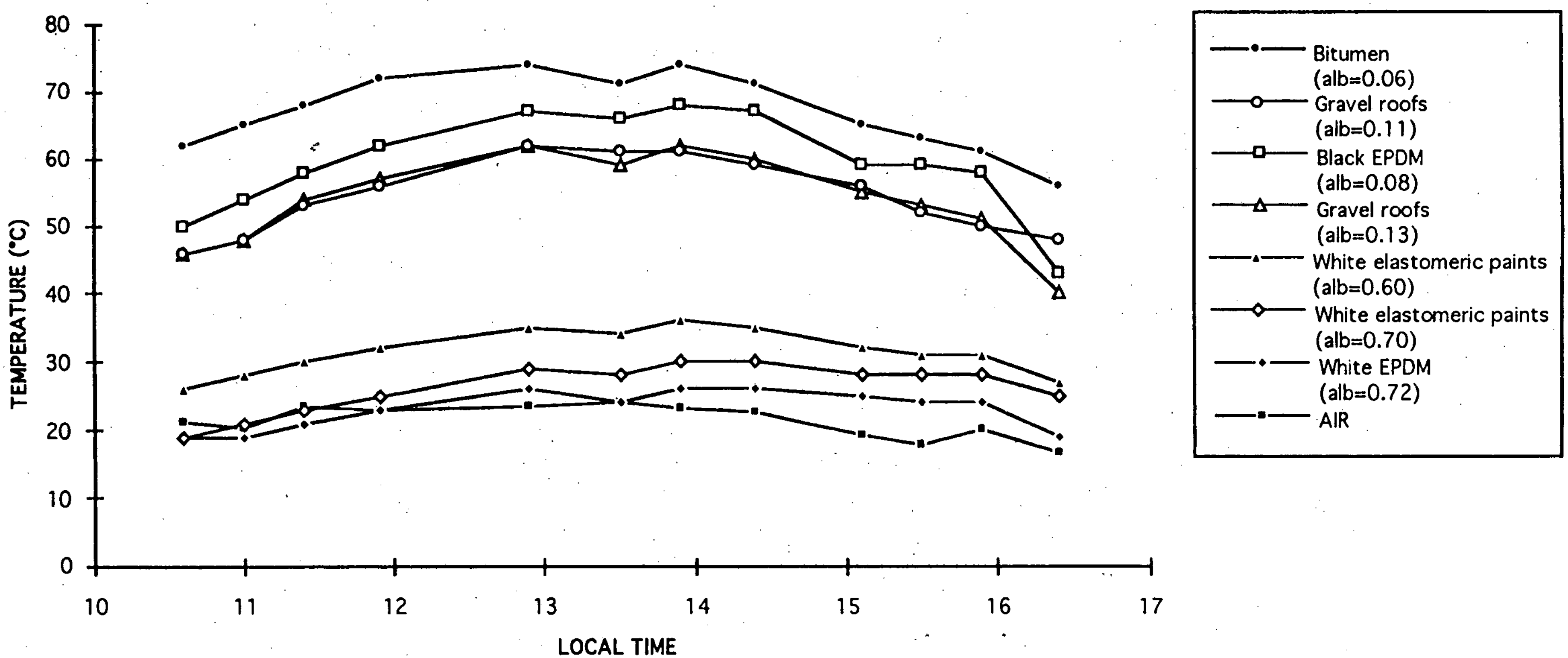
Because higher urban albedos reduce the amount of absorbed solar radiation, building and urban surfaces remain cooler and, in turn, the intensity of longwave radiation from these surfaces is reduced. Ambient air temperatures also stay lower because of reduced convective heat flux, thanks to lower surface temperatures. Microclimate computer simulations for Sacramento, CA, indicate a possible reduction of 4°C in urban air temperature in summer resulting from a change of effective urban albedo from 0.25 to 0.40 (Taha et al., 1988, 1990; Taha, 1990). Reduction in urban air temperatures (i.e. mitigating urban heat islands) and reduction of pollutant emissions are major advantages of large-scale implementation of high-albedo materials.

The indoor microclimate is also affected by albedo modifications because the air temperature under roofs of varying albedos can be significantly different. For example, the air temperature of an attic space under a red cedar shingle roof can be about 16°C lower than that of an attic space under a lower albedo asphalt roof, averaged over ventilated and non-ventilated conditions (Cedar Shake and Shingle Bureau, 1991). Tests on horizontal, R-11 panels show that under clear sky conditions in mid-latitudes, the temperature under a black membrane can be 24 °C higher than under a beige membrane, and 30 °C higher than under a white membrane (Backenstow, 1987).

Similar observations have been made of urban surfaces. Even in cold regions such as Alaska, white-painted roads (albedo = 0.55) can be at the same temperature as ambient air while regular roads (albedo = 0.15) can be 11°C warmer than the air (Berg and Quinn, 1978).

Figure VI-1: ALBEDO AND SURFACE TEMPERATURE OF TEST AREAS

7/15/91



In terms of cooling energy use, whiter surfaces have a significant impact. Although the actual energy savings are building-specific and depend on current weather conditions and operating schedules, measured data show that the range of savings in cooling energy is usually between 20% and 50% (Boutell and Salinas, 1986; Habel and Florence, 1985; Chandra et al., 1991; Akbari et al., 1991). In one case, the cooling load of a residential building in Sacramento was completely offset by changing the albedo of its roof from 0.18 to 0.77 (Akbari et al., 1991). Simulations and theoretical studies have shown that savings up to 70% are possible (Backenstow, 1987; Taha et al., 1988, Akbari et al., 1993). Table VI-1 shows condensed results from simulations for Sacramento, CA.

Table VI-1
Direct and Indirect Effects of Albedo Modifications on Cooling Energy Use in a Residential Building, Sacramento, CA, July 9-12.

	Base Case	Direct Savings		Direct + Indirect Savings	
Building Surroundings	a_b=0.30 a_s=0.25	a_b=0.43 a_s=0.25	a_b=0.90 a_s=0.25	a_b=0.43 a_s=0.40	a_b=0.90 a_s=0.40
kWh/day	25.00	2.7%	19%	49%	62%
Peak kW	7.07	2.5%	14%	24%	35%
Cooling hours/day	14.00	0.0%	7%	33%	44%

a_b is the building albedo
a_s is the albedo of the surroundings
the last row represents the cooling hours during the 3-day period
Source: Taha et al., 1988.

In general, computer simulations of the direct (building scale) effects of albedo indicate that in insulated residential and small commercial buildings, the reduction in cooling energy amounts to 0.3% for every 0.01 increase in albedo, whereas for uninsulated buildings, the savings amount to about 0.5% for each 0.01 increase in building albedo (Taha et al., 1988; Martien et al., 1989). On the other hand, indirect savings (urban scale) resulting from a 0.01 increase in albedo would be 3% (Taha et al., 1988). However, these results should be interpreted cautiously as the simulations were performed with one-dimensional boundary layer climate models and some parameters remain uncertain. Also, the savings stated here are valid within the albedo range from ~0.25 to ~0.45.

Field test data from two sites in Sacramento, California show significant energy savings of 50 to 69% during the summer months. At the first site, white specialty polymer coating was applied to the metal roof and on the southeast wall of a school bungalow with R-19 attic insulation and attic ducts. As a result the albedo increased from 0.34 to 0.70, the cooling energy savings were 50%, and the peak demand reduction was 40% (450W). At the second site, white specialty polymer coating was applied to a gray rolled composition roof on a home that had R-11 attic insulation and no attic ducts. The albedo was increased from 0.18 to 0.73, the cooling energy savings were 69%, and the peak demand reduction was 28% (500 W) (Akbari, et al., 1993).

On a nation-wide basis (U.S.), it is estimated that a large-scale strategy of light-colored surfaces would save 0.25 quads (0.26 exajoules) per year with a payback time of less than a month, and decrease CO_2 emissions by about 10 million tons of carbon per year. In fact, each 1°C of urban air temperature reduction may result in savings of 2% to 3% of the system-wide electric utility load in most major mid-latitude cities (Akbari et al., 1989).

1.2. Consumer Utility

By reflecting most of the incoming solar radiation, high-albedo materials keep building envelopes cool and help attain indoor thermal comfort in hot climates. If applied on a city-wide scale, high-albedo materials can keep the ambient air temperature in urban areas lower than otherwise, thus achieving outdoor thermal comfort as well. In addition to saving energy, high albedo paints or coatings increase the life span and structural integrity of roofs and exposed surfaces by decreasing thermal cycling and UV absorption. Less maintenance is needed.

While the application of high-albedo materials seems to be a relatively easy task, and while there seems to be plenty of room for implementing this strategy in urban areas (Taha et al., 1992), there are some potential problems. For example, there might be glare problems caused by the highly reflecting surfaces which might lead to hazards or visual discomfort. Another potential problem concerns people's preferences which might limit the colors/hues that will be applied on their homes, places of business, and neighborhoods. However, the glare problems could be overcome and avoided if careful planning is sought in advance. The preferences problem could be settled by letting people choose colors (visible spectrum) while the longwave (invisible spectrum) albedo can be controlled to achieve the desired effects.

1.3. Development Status

Light-colored paints, coatings, EPDMs, toppings, aggregates, and emulsions are readily available from appropriate manufacturers. No special or new technology is needed. An albedo 'labeling' program may be initiated to test high-albedo materials and label them for customer use. More measured data on energy use and peak demand impacts are needed to refine proposed utility and government programs.

2. Cost of Equipment

Cities can be easily whitened. Most buildings and flat roofs are painted (or resurfaced) every 10 to 20 years and can be lightened on the next cycle. This procedure should not entail any additional costs as it only involves different color choices, not different materials. For new buildings, albedo requirements can be incorporated into building codes, thus integrating high-albedo materials into a city's energy policy. On streets and parking lots, whiter asphalt can be used at low incremental cost. However, in addition to energy benefits, light-colored roofs and asphalt reflect more UV radiation and will last longer. And because they remain cooler, there is an improvement in pavement performance and reduced rutting. These benefits save money in the long run, as well. A program of white surfaces could pay for itself many times over simply by extending the life span of roofs, streets, and other exposed building/urban surfaces.

This section gives a general idea of the material and labor costs associated with increasing the albedo of building and urban surfaces in the U.S. These crude estimates do not include the cost of preparing a surface for application (such as road bed and substrate preparation and roof construction and layering); they include only the cost of the materials and the labor needed to apply them. Also, the costs vary with time, application procedures, and manufacturer/contractor's assumptions. Thus, these estimates should be used to get a sense of the order of magnitude of these costs, not the exact price.

For paved surfaces, large costs can be associated with whitetopping and replacing the dark asphalt surfaces with ones that have light aggregates. But the use of light aggregates in resurfacing the top layer seems to be one cost-effective option; unless light-colored aggregates are not locally available, there should be no significant additional cost over that of dark materials. For example, white limestone should cost approximately the same as dark grey basalt (Shuler, 1991). Table VI-2 gives further information on paved surfaces.

For roofing, elastomeric coatings have been used in several instances and their costs have been documented. For example, the cost of Superprep from Thermo Materials is $2.15/m^2 and the application cost is about $0.6/m^2 (Habel and Florence, 1985). The contractor cost for Acryshield elastomeric coating from National Coatings Corporation is $2/m^2 for materials if used at a rate of 1 gal/4.5 m^2 (Cordell, 1991). The corresponding labor costs range from $2.7 to $5.4 per m^2. Enerchron, from Helios Energy Products, costs about $10 per m^2 with a labor cost of about $6 per m^2 at the recommended 5 m^2 per gallon for roofs and 10 m^2 per gallon for walls.

Table VI-2*
Cost Estimates for Paved Surfaces[a]
(1989$)

Paving Material	Average cost[b] ($/m^2)	Estimated new albedo[c]	Estimated weathered albedo[d]	Expected life[e] (Yr) (average)	Annualized cost[f] ($/m^2)/yr
Resurfacing Paved Surfaces (uppermost layer only)					
Regular asphalt (~2.5 cm)	$2.3	0.05-0.10	0.15-0.20	4	$0.68
Regular chip seal (~1.3 cm)	$1.2	0.15-0.20	0.15-0.20	4	$0.35
Regular slurry seal (~1.0 cm)	$1.2	0.05-0.10	0.15-0.20	4	$0.35
Asphalt/light aggregates (~2.5 cm)	$2.6	0.05-0.10	0.30-0.40	4	$0.77
White chip seal (~1.3 cm)	$1.5	0.40-0.50	0.30-0.40	4	$0.44
Repaving Surface (entire depth)					
Regular asphalt (~18 cm)	$16.4	0.05-0.10	0.15-0.20	22	$1.47
Concrete whitetopping (~13 cm)	$18.9	0.70-0.80	0.40-0.60	22	$1.70
Asphalt/light aggregates (~18 cm)	$16.7	0.05-0.10	0.30-0.40	22	$1.50

Based on data from Martien et al., 1989.

a) Assumptions: Estimates for resurfacing an existing asphalt urban street in good structural condition. The estimates include the costs of materials and labor only, and do not include the cost associated with road bed preparation.
b) Sources: Means, 1989; Reese, 1989; International Slurry Seal Association, 1989; Portland Cement Association , 1989.
c) Sources: Threlkeld, 1970; Oke, 1987; Griggs et al., 1989; Reagan and Acklam, 1979.
d) Sources: Estimates based on Threlkeld, 1970; Oke, 1987; Griggs et al., 1989; Reagan and Acklam, 1979. Note that the weathering estimates are highly variable and uncertain.
e) Source: Portland Cement Association, 1986; Portland Cement Association, 1989; Riverside Cement, 1989.
f) The real interest rate is assumed to be 7%.

Carlisle SynTec membrane costs are $3.87/m^2 for black EPDMs and $5.8/m^2 for white EPDMs. For the black EPDM, the installed costs are $20.4/m^2 and $26.9/m^2 for mechanically fastened and fully adhered systems, respectively. For the white EPDM, these costs are respectively $25.8 and $32.3 per m^2 (Gillenwater, 1991). Of course, these costs include only the membrane system. Table VI-3 gives additional cost information for roofs.

Table VI-3
Cost Estimates for Roofs[a]
(1989$)

Roof Material	Average installed cost[b] ($/m²)	Estimated new albedo[c]	Estimated weathered albedo[d]	Expected life[e] (Yr) (average)	Annualized cost[f] ($/m²)/yr
Steep Roofs					
Regular, dark asphalt shingles	$ 8.7	0.05-0.10	0.15-0.20	20	$0.82
Asphalt shingles w/ light aggregates	$ 8.7	0.35-0.40	0.30-0.35	20	$0.82
Roll asphalt with reflective paint	$10.0	0.80-0.90	0.60-0.70	20	$0.94
Untreated cedar shakes	$18.3	0.30-0.35	0.20-0.25	17	$1.90
Concrete tile	$18.3	0.35-0.40	0.25-0.30	50	$1.34
White concrete tile	$23.7	0.70-0.80	0.60-0.70	50	$1.72
Painting only	$ 3.0	--	--	4	$0.89
Flat and Gently Sloped Roofs					
Dark built-up asphalt	$18.3	0.05-0.10	0.15-0.20	20	$1.47
Light built-up asphalt	$18.3	0.30-0.40	0.25-0.30	20	$1.47
Built-up asphalt w/white-coated gravel	$18.3	0.50-0.60	0.40-0.50	20	$1.47
Built-up asphalt with reflective paint	$18.3	0.70-0.80	0.60-0.70	20	$1.47
Single-ply white polymer roofing	$18.3	0.70-0.80	0.60-0.70	20	$1.47
Painting only	$ 2.5	--	--	4	$0.74

Based on data from Martien et al., 1989.

a) Assumptions: Estimates include materials and labor costs only. They do not include the costs of removing an existing roof. We define steep roofs to be those with greater than a 4 inch rise per foot of run.
b) Sources: Concrete Construction, 1983; Kiley and Mosell, 1989; Means, 1989. For white concrete: Estimate based on increased materials costs as indicated by a manufacturer of white cement.
c) Sources: Threlkeld, 1970; Oke, 1987; Griggs et al., 1989; Reagan and Acklam, 1979.
d) Sources: Estimates based on Threlkeld, 1970; Oke, 1987; Griggs et al., 1989; Reagan and Acklam, 1979. Note that the weathering estimates are highly variable and uncertain.
e) Source: Concrete Construction, 1983 and discussions with roofing contractors and manufacturers.
f) The real interest rate is assumed to be 7%.

Table VI-4 gives information on the cost of conserved energy for selected albedo measures, using a hypothetical house, in Sacramento, CA, as an example. Note that the estimates, particularly those related to the effects of weathering, are variable and still uncertain.

Also, in the case where light-colored aggregates are not locally available, costs may increase due to the need for transportation. And, there can be a 100% increase in cost for replacing standard cement with white cement.

In constructing Table VI-4, it was assumed that a 150-m² house, located in Sacramento, would use ~3000 kWh per year in cooling energy. It was also assumed, based on computer simulations, that the annual cooling energy use of that house would decrease by 0.4% for each 0.01 increase in the albedo of the building and by 3% for each 0.01 increase in the albedo of the surrounds (Taha et al. 1988). In computing the Cost of Conserved Energy (CCE) for indirect (urban scale) effects, it was assumed that the albedo modifications were implemented on only 50% of the available surface area of paved streets and roofs. In this example, vertical surfaces were assumed to have no contribution to modifications in urban albedo. Table VI-4 also indicates the entries that involve direct, indirect, or both effects.

Table VI-4
Cost of Conserved Energy (CCE) for Direct and Indirect Measures

Measure	$\Delta\alpha_i$	$\Delta\alpha_b$	$\Delta\alpha_s$	CCE (¢/kWh)	Effect
Repaint walls white	0.30	0.15	--	~0	direct
Replace dark asphalt shingle with light on steep roof	0.15	0.175	0.017	~0	direct + indirect
Replace dark asphalt shingles with roll roof and reflective coating on steep roof	0.50	0.25	0.055	2.3	direct + indirect
Paint steep roof**	0.50	0.25	0.055	17.0	direct + indirect
Replace dark built-up flat roof with light gravel	0.30	0.15	0.033	~0	direct + indirect
Replace dark built-up flat roof with reflective coating	0.50	0.25	0.055	~0	direct + indirect
Replace dark built-up flat roof with single ply with white polymer	0.50	0.25	0.055	~0	direct + indirect
Paint flat roof**	0.50	0.25	0.055	14.0	
Resurfacing dark asphalt payment with light aggregates	0.20	--	0.028	3.4	indirect
Resurfacing with whitetopping	0.10	--	0.014	~0	indirect
Repaving dark asphalt with light aggregates	0.20	--	0.028	1.1	indirect
Repaving with white cement whitetopping	0.40	--	0.056	4.4	indirect
Repaving concrete with white cement	0.30	--	0.017	6.0	indirect

* Based on data from Martien et al., 1989.
** Non-maintenance, implemented solely for purpose of energy conservation (if done as part of a maintenance program, the CCE would probably be 0).
$\Delta\alpha_i$ is the change in the albedo of a surface component (i), $\Delta\alpha_b$ is the change in the albedo of a building, where we assume equal roof and wall areas, $\Delta\alpha_s$ is the change in the albedo of the surroundings, and CCE = (annualized cost per building) / (Annual savings per building).

3. Implementation Issues

3.1. Installation

There are no special requirements to install high-albedo materials, paints, and coatings. However, local codes and regulations should be observed. Additionally, some localities may not allow home owners to change the appearance (color) of their houses without prior approval from a supervising group or association.

The following are suggestions for increasing the albedo of typical building and urban surfaces:

Building surfaces

•Light-colored aggregate added to the roofing material. A common example is modified bitumen where the black bitumen (layer or tiles) is covered with a granular layer of a light color.

•Light-colored rocks on flat or gently-sloped roofs. This has the advantage that it does not require special materials, provided that the roof is able to withstand the additional load.

•Colored and painted roofs. This procedure may be especially suitable for exposed metal roofs and those finished with flat components.

•Coating with elastomeric coatings or EPDMs. This procedure has the main advantage that it does not require extensive roof preparation: most elastomeric coatings and EPDMs can be directly applied to existing roofs after appropriate cleaning.

•Using light-colored concrete tiles on sloping roofs. This practice, although relatively new to the U.S., has been popular for a long time in Europe, Japan, and Australia (Concrete Construction, 1983). Although the tiles would result in additional expenses in underlayments to insure watertightness, the roof has a typical expected life of well over 50 years compared to an average life of about 10 to 20 years for conventional roofs. The main disadvantage of tiles is their larger loading (about 950 lbs/100 ft^2).

Urban surfaces (streets, sidewalks, parking lots, school yards, and other similar surfaces)

•Using light-colored aggregates in the upper layer of the asphalt in new pavements. Although initially dark, the albedo of the paving will increase after some weathering and road wear, when the aggregates will be exposed. There are also some synthetic binders of light colors that can be used to hold the aggregates instead of the dark asphalt, but their initial costs might preclude their use for major construction or large surfaces (Shuler, 1991). Since the aggregates form about 95% (by weight) of the mixture, using light aggregates seems to be a good strategy provided that the binders' issues are addressed.

•Using a light-colored slurry or chip seal when resurfacing. Slurry seal may be more vulnerable to wear and tear effects and would thus require more frequent maintenance than light-colored aggregates.

•Using concrete rather than asphalt, with a light-colored aggregate and binder.

•Whitetopping. This process involves producing light-colored concrete pavements that are 7 to 10 cm thick, used as an overlay treatment to distressed asphalt.

•Using artificial lighteners in preparing the mixtures of asphaltic concrete and slurry seals.

•Using paints of light colors that are designed specifically to resist weathering, wear and tear, and other environmental effects.

3.2. Maintenance

While most high-albedo strategies (paints, coatings, etc.) do not require special maintenance, they need cleaning and re-coating/resurfacing after wear has reached a certain level. This cycle is usually between 10 and 50 years.

An issue that may affect the performance of high-albedo materials is their dirt pick-up qualities. If these surfaces pick up dirt easily, their albedos may change quickly over time (some light-colored surfaces may become darker and some dark surfaces may be become lighter). Variations of up to 15% in albedo have been associated with such changes. If these changes occur quickly, then higher maintenance costs should be anticipated.

Albedo also changes over time as a result of the effects of weathering and wearing. Building surfaces are exposed to various environmental factors such as solar radiation, humidity, high temperatures, freeze, rain, and dust, whereas other urban surfaces, such as streets, parking lots, and school yards, are subject to wear effects from pedestrian and vehicular traffic in addition to the environmental factors mentioned above.

The effects of soiling, weathering and wear have not been extensively researched, but a few estimates are available. For example, a built-up roof may start with an albedo of ~0.1 when new, but become 0.3 to 0.4 after about six months, and a reflective roof that starts with an albedo of 0.9 can reach values between 0.6 and 0.7 in two years (Courville, 1989; Griggs et al., 1989). The thermolastic coating Solar Shield (from Thermo Materials) has an initial reflectivity of 0.90, but after aging, the reflectivity drops to 0.78. Sloping the roofs minimizes the effects of dirt accumulation, water ponding, and biological growth, and is recommended whenever possible.

For urban surfaces, e.g., streets and parking lots, the change of albedo over time has been monitored in limited laboratory experiments. Accelerated weathering procedures have been used to quantify the impact of weathering on the reflectivity of a selection of surfaces. Table VI-5 presents results from an accelerated weathering test.

Table VI-5
Weathering and Solar Reflectivity of Selected Paints

Paint	Measured Reflectivity		
	Before Weathering	After Weathering	Reduction
Traffic white (standard)	0.82	0.73	-11%
Traffic white (untinted)	0.82	0.74	-10%
Custom blend traffic white	0.75	0.77*	+3%
Traffic white (with pumice)	0.76	0.70	-8%
Tank white	0.75	0.76*	+1%
A100 Latex white	0.82	0.75	-9%
Acrylic emulsion white sealer	0.79	0.76	-4%

Source: Kritz and Wechsler, 1967.
*The authors indicate the apparent increase in reflectivity is within the uncertainty of the measurement technique.

3.3. Conservation Programs

No programs have been established yet. Utilities may, in the future, consider such incentives as rebates for meeting a minimum specified albedo in each climate zone. There are also proposals being developed to incorporate high albedo in building energy codes.

Education and information programs for consumers, utilities, and government agencies are needed to make the public aware of the potential for energy savings with high albedo materials. For example, the decision-makers needs to be informed that white asphalt tile, which makes up a large portion of the residential market, has a low albedo despite its light color.

4. Environmental Issues

Use of high albedo materials, coatings and paints can result in both direct (building) and indirect (urban-scale) reductions in energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

Summer urban "heat islands" (urban areas that are 5° to 8° F warmer than surrounding rural areas) are created by the combined effect of increased darker surfaces and reduced vegetation. The application of high albedo materials on a large scale can have the indirect affect of reducing these heat islands. In areas subject to smog, such as Los Angeles, decreasing the ambient urban temperatures can lead to a corresponding decrease in the number of smog incidences.

Volatile organic compounds (VOCs) may be released from paints and coatings, and may require special precautions if urban-scale implementation of high-albedo paints and coatings is considered. Membranes and shingle roofs do not impose this type of possible hazard.

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VII. SOLAR DOMESTIC WATER HEATERS

END-USE: Water Heating

SECTOR: Residential

DESCRIPTION

Performance: Solar water heater performance is very strongly dependent on climate, type of system, installation and hot water usage. The Solar Rating & Certification Corporation (SRCC) directory indicate fractional energy savings ranging from 37% to 95%.

Consumer Utility: No changes in consumer utility if designed and installed correctly.

Development Status: A wide variety of solar water heated designs have been installed over the past 20 years providing ample field experience for those manufacturers and installers who remain in the business. Since initial costs are high, reliability, longevity and low maintenance are key to the success of a solar water heater, and the best designs have proven their worth over the past few decades.

COSTS

Retail prices for installed residential single family solar water heaters typically range from $1,800 to $2,700. Estimated solar fractions in southern California range from 50% to 80%. Simple payback ranges from 7 to 12 years.

IMPLEMENTATION

Installation: The main components of solar water heating systems are solar collectors and storage tanks. The collectors are typically installed on the roof. Collectors can be of two general types: flat plate or integral collector storage. The storage can be part of the collector, part of the backup heater, or a separate tank. In cooler climates where temperatures get below freezing, some method of freeze protection is required.

Maintenance: The amount of maintenance varies from $35 to $75 per year with the type of system installed.

Conservation Programs: Tax credits were available in the past in many states to encourage solar water heating. Some utilities have offered, or are considering offering, rebates for purchasing solar water heaters.

ENVIRONMENTAL ISSUES

Use of solar domestic water heaters results in reduced emissions from fuel-fired water heaters, improved energy efficiency, and reduced energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

VII. SOLAR DOMESTIC WATER HEATERS

1. Description

Solar domestic water heaters have collectors of two general types: flat plate or integral collector storage. The storage can be part of the collector, part of the backup heater, or a separate tank. Pumps are often used to move the working fluid through the collector and back to storage. Some systems use photovoltaic panels to power the pumps. This reduces the amount of auxiliary energy consumption and controls. Sunlight that warms the collector also powers the pump. If storage is part of the collector, no pumps will be needed. Thermosyphon systems place the storage tank above the collector. The lower density of the heated water causes it to rise into the storage tank. These systems do not require pumps. Another pumpless system uses a percolating working fluid to transfer heat from the collector to the storage tank.

1.1. Performance Characteristics

Solar water heater performance is very strongly dependent on climate, type of system, installation and hot water usage. The Solar Rating & Certification Corporation (SRCC) directory indicates fractional energy savings ranging from 37% to 95%.

Solar water heaters are usually designed to heat one tank-full of water each sunny day. Water can become hot enough to cause scalding temperatures under certain operating conditions. Scald protection valves are recommended for added safety. In flat plate systems, the backup water heating system is commonly built into the solar storage tank.

1.2. Consumer Utility

No changes in consumer utility if designed and installed correctly. An improperly sized system, or one without adequate backup capability, may reduce the amount of available hot water.

1.3. Development Status

A wide variety of solar water heated designs have been installed over the past 20 years providing ample field experience for those manufacturers and installers who remain in the business. Since initial costs are high, reliability, longevity and low maintenance are key to the success of a solar water heater, and the best designs have proven their worth over the past few decades.

2. Cost of Equipment

Typical installed costs of solar water heating systems for single family residences in southern California are listed in Table VII-1. Retail prices for installed residential single family solar water heaters typically range from $1,800 to $2,700. Estimated solar fractions in southern California range from 50% to 80%. Simple payback ranges from 7 to 12 years. These payback periods were calculated relative to electric resistance water heaters using an electricity cost of 8¢ per kWh. The backup water heater for solar water heating is nearly always an electric resistance water heater because it is easier to install than gas backup and in a properly sized system it seldom operates, so the electric cost is low. Gas-fired storage water heaters have large flue losses that electric storage water heaters do not have.

Table VII-1
Costs of Solar Water Heaters

Type of system	Cost	Simple Payback Period
Active	$1,800 - $2,300	7 - 10
Passive	$1,800 - $2,700	8 - 12
Thermosyphon	$1,800 - $2,500	8 - 11

3. Implementation Issues

3.1. Installation

Installation of solar water heaters takes some special training and skills that combine a knowledge of construction, water plumbing, electrical controls, and heat exchangers. Even the best equipment can be disabled in the field by an inexperienced installer. Some types of equipment are inherently easier to install due to pre-packaged plumbing and wiring, modular design, or simple passive operating principles.

The main components of solar water heating systems are solar collectors and storage tanks. The collectors are typically installed on the roof, while the remainder of the system must be connected to the domestic water supply system.

In cooler climates where temperatures get below freezing, some method of freeze protection is required. Either the collector is drained completely, or temporarily warmed by circulating water through it. Other options are to use a closed loop collector with an anti-freeze solution, or to make the collector out of materials that will not be damaged if the water in it freezes.

3.2. Maintenance

The amount of maintenance for a residential single family solar water heater was estimated by the California Solar Energy Industries Association to be from $35 to $75 per year depending on the type of system installed. Lifetimes were estimated to be 15 to 20 years.

A simple preventive maintenance program on storage water heaters can dramatically increase lifetimes. This maintenance program consists of replacing anodes every few years to prevent corrosion and draining the tank once a year to flush out sediment and scale buildup. This maintenance should also be done on solar water heaters.

While water tank maintenance is important, it is not as critical as maintenance of some of the other solar components. The quality of the antifreeze or other fluid, verification of freeze protection, verification of sensor and control functions, lead detection, pump failure, clogged pipes or heat exchangers, fluid level and pressure, expansion tank air pressure and proper automatic valve operation should be checked every few years or at any sign of trouble depending on the type of system. The failure of these components can prevent solar heat collection and cause the system to operate on backup fuel without the user being aware of the failure.

3.3. Conservation Programs

Tax credits were available in the past in many states to encourage solar water heating. Some utilities have offered, or are considering offering rebates for purchasing solar water heaters. Sacramento Municipal Utility District is offering rebates on solar water heating systems.

The South Coast Air Quality Management District is currently considering standards for gas-fired water heaters that may be so strict that some form of solar assist will be necessary.

4. Environmental Issues

Use of solar domestic water heaters results in improved energy efficiency and reduced energy demand. Reduced energy demand has the environmental benefits of reduced emissions from fuel-fired water heaters, reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

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Florida Solar Energy Industries Association, 930 N. Krome Ave, Suite 2A, Homestead, FL 33030, (305)2146-8447, FAX (305)246-8489.

Solar Rating & Certification Corporation, 777 North Capitol St., N.E., Suite 805, Washington, DC, 20002-4226, (202)408-0306, FAX (202)408-8536.

VIII. HEAT PUMP WATER HEATERS

END-USE: Water Heating

SECTOR: Residential

DESCRIPTION

Performance: Essentially the same performance as electric resistance storage water heaters, except that efficiencies are typically 2 to 2.5 times higher.

Consumer Utility: Heat pump water heaters cool and dehumidify the air surrounding the evaporator coil. This can be an advantage where cooling is desirable, a disadvantage when cooling is undesirable. Some heat pump water heaters are designed to recover waste heat from whole house ventilation systems.

Development Status: Heat pump water heaters are commercially available in the U.S. Sales are less than 1% of electric resistance storage water heaters. The Electric Power Research Institute (EPRI) is sponsoring work to reduce first cost of heat pump water heaters.

COSTS

Retail price for heat pump water heaters is typically $850-$1,700, not including installation costs. Payback typically ranges from five to nine years, depending on hot water use and the efficiency of the water heater being replaced.

IMPLEMENTATION

Installation: Heat pump water heaters must be installed in locations with adequate air volume or air circulation to provide the necessary heat source. A condensate drain must also be provided.

Maintenance: Early models of heat pump water heaters had a reputation for being unreliable. Current versions are much more reliable.

Conservation Programs: Some utilities have offered rebates for purchasing heat pump water heaters. Puget Power is in the pilot phase of a large rebate program for heat pump water heaters that recover waste heat from ventilation systems.

ENVIRONMENTAL ISSUES

Use of heat pump water heaters results in improved energy efficiency and reduced energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

Heat pump water heaters use R-22 as the refrigerant for the heat pump. R-22 is a hydrochloroflurocarbon (HCFC) and demonstrates both ozone depletion potential (ODP) and global warming potential (GWP) (Fairchild and Fischer, 1991). These are significant environmental concerns and a great deal of work is being done to develop a suitable replacement refrigerant. In addition to ODP and GWP, replacement refrigerants must contend with an array of criteria including nontoxicity, nonflammability and chemical stability, and inertness. Research has yet to identify any pure fluid that can be considered a suitable substitute for R-22. Some binary and ternary mixtures have demonstrated promise as being suitable substitutes for R-22, but no prototypes have been developed to demonstrate how they might affect the performance of actual air conditioning systems (Radermacher and Jung, 1990). Some organizations are proposing the complete ban of HCFC production by the year 2005. Though no suitable substitute has yet been developed for R-22, the intensity of work currently being conducted to find replacements for HCFCs may result in the development of a suitable replacement for R-22 by the end of the century.

VIII. HEAT PUMP WATER HEATERS

1. Description

1.1. Performance Characteristics

Heat pump water heaters extract heat from the surrounding air to heat water in a storage tank. The Energy Factor [EF] (a measure of efficiency which includes standby losses) of heat pump water heaters ranges from 1.8 to 2.5. This compares to EFs of 0.88 to 0.96 for electric resistance storage water heaters.

Heat pump water heaters cool and dehumidify the air used as a heat source. In some situations this is helpful (e.g. dehumidifying a moist basement or when located in the conditioned area of a house with a large cooling load). Adequate air circulation must be available. One manufacturer recommends that heat pump water heaters not be installed in spaces smaller than 800 cu. ft. unless provisions are made to increase air circulation. In new construction that requires mechanical ventilation, the exhaust air can be used as a heat source for the heat pump water heater.

1.2. Consumer Utility

Heat pump water heaters come in three major configurations: add-on, integral, and ventilating. Add-on heat pumps attach to standard electric resistance storage water heaters. They can be made to fit on top of existing water heaters, or can be installed separately. These models circulate cold water out of the bottom of the tank past the condenser of the heat pump and then back into the tank. Integral heat pump water heaters have the heat pump attached directly to the storage tank. The more efficient models of this type circulate the hot refrigerant through a heat exchanger built into the wall of the storage tank. Ventilating heat pump water heaters are designed to extract heat from a ducted air stream. These models are used to extract heat from the exhaust air of mechanically ventilated houses.

1.3. Development Status

Heat pump water heaters are commercially available in the U.S. Sales are less than 1% of electric resistance storage water heaters.

The Electric Power Research Institute (EPRI) and Crispaire Corporation have recently developed a residential or small commercial heat pump water heater that has an estimated EF of 2.4. This "E-Tech" water heater costs about $395.00 and is touted as much easier to install than existing heat pump water heater (EPRI, 1993).

2. Cost of Equipment

Heat pump water heaters are much more costly than electric resistance water heaters. Representative energy factors, retail costs, and simple payback for both types of heat pump water heaters are listed in Table VIII-1. Payback periods were calculated using an electricity cost of 8¢ per kWh.

Table VIII-1
Costs of Heat Pump Water Heaters

Type of HPWH	Energy Factor	First Cost	Simple Payback
integral	2.2 - 2.5	$1,400 - $1,700	5 - 8 yrs
add-on	1.8 - 2.1	$850 - $1,570	5 - 9 yrs

3. Implementation

3.1. Installation

Since heat pump water heaters are small refrigeration machines, they require trained refrigeration technicians to service (and in some cases, to install) them properly. This is especially important for add-on machines where some components are assembled in the field.

The difficulty of installation varies depending on the type of heat pump water heater and the situation. Installing simple integral systems can be nearly identical to installing a resistance water heater. Installing a ventilating heat pump water heater can be an elaborate procedure that includes duct work.

3.2. Maintenance

The reliability record of some earlier models was very poor. The lack of an infrastructure for repair and service also created problems. Indications are that current models are more reliable.

A simple preventive maintenance program on storage water heaters can dramatically increase lifetimes. This maintenance program consists of replacing anodes every few years to prevent corrosion and draining the tank once a year to flush out sediment and scale buildup. This maintenance also should be done on heat pump water heaters. Replacing the anode costs about $40. Along with water tank maintenance, a properly changed refrigerant loop, a heat exchanger free of sediment and minerals, and properly operating sensors, pumps and controls are critical for successful operation. If the refrigerant system or its controls malfunction, the system may revert to backup heat without the user being aware of it.

3.3. Conservation Programs

Several utility rebate and marketing programs to promote heat pump water heaters were started in the Pacific Northwest during the early to mid-1980s. These programs ended because poor reliability of most models and lack of a service and repair infrastructure were seen as major problems. Any large utility or other programs using heat pump water heaters would want to be assured manufacturers have corrected these problems. Puget Power is in the pilot phase of a large rebate program for heat pump water heaters that recover waste heat from ventilation systems.

4. Environmental Issues

Use of heat pump water heaters results in improved energy efficiency and reduced energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

Heat pump water heaters use R-22 as the refrigerant for the heat pump. R-22 is a hydrochloroflurocarbon (HCFC) and demonstrates both ozone depletion potential (ODP) and global warming potential (GWP) (Fairchild and Fischer, 1991). A great deal of work is being done to develop a suitable replacement refrigerant. In addition to ODP and GWP, replacement refrigerants must contend with an array of criteria including nontoxicity, nonflammability and chemical stability, and inertness. Research has yet to identify any pure fluid that can be considered a suitable substitute for R-22. Some binary and ternary mixtures have demonstrated promise as being suitable substitutes for R-22, but no prototypes have been developed to demonstrate how they might affect the performance of actual air conditioning systems (Radermacher and Jung, 1990). Some organizations are proposing the complete ban of HCFC production by the year 2005. Though no suitable substitute has yet been developed for R-22, the intensity of work currently being conducted to find replacements for HCFCs may result in the development of a suitable replacement for R-22 by the end of the century.

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IX. ENERGY-EFFICIENT MOTORS

END-USE: All Motor-Driven (Refrigeration, Ventilation, Air Conditioning, Pumps)

SECTOR: Commercial, Industrial, Residential

DESCRIPTION

Performance: Energy-efficient motors (EEMs) provide essentially the same performance as the standard motors they replace, except that efficiencies are typically three to eight percentage points higher for 3-phase motors above about 1 kW output, with corresponding savings in power and energy. For small motors (below about 1 kW) the differences can be much higher (savings of 50% or more are possible, especially for certain single-phase motors).

Consumer Utility: EEMs provide the same consumer utility as their standard counterparts. In some cases, the reduced heat and longer life of the energy-efficiency motor increases the utility (less heat added to the space, resulting in less cooling load and more heating load).

Development Status: EEMs are commercially available from most motor manufacturers for three-phase applications from about 1 kW output through several hundred kW; some single-phase motors are available for certain applications. About 20% of the three-phase motors (of 0.75 kW and above) sold in the US are EEMs.

COSTS

The first-cost premium is about 20% to 40% depending on quantity ordered. See Table IX-1 for trade prices (as paid by the typical buyer) of new EEMs, standard motors and rewound motors, as well as adaptor plates and pulleys. See Table IX-2 for simple payback periods, which range from immediate to over 20 years, depending on type of purchase (incremental cost or full replacement cost), on size of motor, on annual operating hours and energy prices.

IMPLEMENTATION

Installation: Energy-efficient motors are the same frame size as new standard motors. They are smaller than older standard motors (from mid-1960s and earlier), requiring the use of adaptor plates and sometimes pulleys or couplings.

The slip can be lower (i.e., EEMs on average run about 1% faster), sometimes requiring adjustments to the driven equipment. In belt-drive applications, adjustable or new pulleys can be used to adjust the speed on the driven equipment. In pumping applications, the impeller can be machined to a smaller diameter. In applications where cycling is used to match output to load, usually no compensation is needed.

Maintenance: Generally, maintenance is reduced due to the higher quality construction of the motors. Lifetime should be considerably longer than standard motors (up to twice as long).

Conservation Programs: Typically, rebates are used to make the incremental cost of the EEM minimal (or negative).

ENVIRONMENTAL ISSUES

Use of energy-efficient motors results in improved energy efficiency and reduced energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

There are solid waste issues associated with the use of energy-efficient motors because motor replacement programs will generate scrap motors for disposal.

IX. ENERGY-EFFICIENT MOTORS

1. Description

1.1. Performance Characteristics

Energy-Efficient Motors (EEMs), also known as "High-Efficiency Motors" and "Premium Efficiency Motors," have essentially the same performance as the standard motors they replace, except that efficiencies are typically 3 to 8 percentage points higher for three-phase motors ranging in output power from about 1 kW to about 150 kW, respectively. For small motors (below about 1 kW), the differences can be much higher. For example, replacing small shaded-pole motors with permanent-split-capacitor (PSC) motors can save 50% or more of the power and energy used for the application (usually small fans). See Table IX-1 for three-phase motors under typical loading conditions (75% of rated load).

When making decisions regarding purchase of EEMs, it is important to get the actual nominal efficiency of the motors to make comparisons, using a consistent efficiency test procedure (the US NEMA MG1-12.54 or Canadian CSA C390 are preferred due to their greater accuracy, but the European IEC-34.2 or the Japanese JEC-37 can also be used). The actual nominal efficiency is preferable to the National Electrical Manufacturers Association (NEMA) nominal efficiency (sometimes referred to as the nameplate efficiency) because it more accurately reflects the average efficiency of a motor model. General labels ("energy-efficient; high-efficiency") are essentially meaningless. Washington State Energy Office (WSEO) has a very useful database; otherwise consult motor manufacturers for catalog information.

1.2. Consumer Utility

Electric motors provide the drivepower for a wide variety of end-uses, including refrigeration, ventilation, air-conditioning, water pumping, and a host of industrial processes. EEMs provide the same consumer utility as their standard counterparts. In some cases, the reduced heat and longer life of the high-efficiency motor increases the utility (less heat added to the space).

1.3. Development Status

Energy-efficient motors are commercially available from most motor manufacturers for three-phase applications from about 1 kW output through several hundred kW. Single-phase motors are available for certain applications including PSC motors for small fans and certain pump motors. About 20% of the new motors sold in the U.S. of 0.75 kW and larger are EEMs.

2. Cost of Equipment

The increased quantities of higher-quality materials in energy-efficient motors, as well as their more limited production, leads to higher prices than standard motors. The cost premium is about 20% to 40% depending on quantity ordered. See Table IX-1 for trade prices (as paid by typical buyer) of new EEMs, standard motors and rewound motors, as well as adaptor plates and adjustable pulleys. As shown in Table IX-2, the simple payback period for EEMs varies from immediate to over 20 years, depending on the application (incremental cost compared to a new standard motor or compared to a rewound standard motor or full replacement cost for a retrofit), on the motor size and on the annual operating hours. Other factors include the load profile (how many hours per year at what fraction of rated load) and the price of electricity.

Table IX-1
Costs and Performance of Open Drip-Proof Energy-Efficient Motors, Standard Motors, and Rewinds

A	B	C	D	E	F	G	H	I	J	K	L	M
hp	avg. cffic. new ODP std. %	avg. effic. new ODP EEM %	new-motor ODP kW savings (75% load)	average cost ODP std. $	average cost ODP EEM $	avg. effic stock & rewound ODP %	ODP retrofit & rewind kW savings (75% load)	rewind cost ODP $	labor cost retrofit $	baseplate adapter cost, U to T frame $	baseplate adapter cost, pre-stnd. to T frame $	adjustable sheave cost $
1	76.3	83.6	0.064	132	164	74.3	0.084	209	132	12	37	10
2	78.5	84.6	0.1	159	198	76.5	0.14	233	132	12	37	10
3	80.6	87.8	0.17	144	184	78.6	0.22	276	132	18	61	25
5	83.2	88.2	0.19	179	231	81.2	0.27	318	132	18	56	25
7.5	85.3	89.9	0.26	240	327	83.3	0.38	356	132	21	70	45
10	86.3	90.4	0.3	300	388	84.3	0.45	418	132	21	69	45
15	87.2	91.7	0.47	397	527	85.2	0.7	475	221	28	100	65
20	88.1	92.4	0.59	497	647	86.1	0.89	580	221	28	127	65
25	88.9	93.0	0.69	590	762	86.9	1	717	221	39	127	76
30	89.4	93.0	0.74	688	874	87.4	1.2	817	221	39	127	76
40	90.2	93.8	0.96	869	1111	88.2	1.5	969	363	50	164	98
50	90.9	93.9	1	1021	1278	88.9	1.7	1116	363	71	164	98
60	91.4	94.6	1.2	1282	1583	89.4	2.1	1230	363	92	177	115
75	91.9	94.8	1.4	1608	1925	89.9	2.4	1425	363	92	273	115
100	91.9	94.8	1.9	2090	2494	89.9	3.3	1530	856	102	custom	154
125	92.3	94.8	2	2465	2991	90.3	3.6	1729	856	custom	custom	custom
150	92.7	95.1	2.3	3209	3933	90.7	4.3	2019	856	custom	custom	custom
200	93.5	95.6	2.6	3909	4949	91.5	5.2	2299	856	custom	custom	custom
250	94.6	95.7	1.8	4674	6986	92.6	4.9	2769	856	custom	custom	custom

NOTE: Columns B and C are the averages of the full load nominal efficiencies of the motors supplied by eight manufacturers (WSEO, 1990). Column D is calculated from B and C, assuming 75% load. Columns E and F are trade prices. Column G is two percentage points lower than column B (one point for rewind damage and one point because standard motors were less efficient in the past than they are today). Column H is calculated from C and G. Column J is from NEES 1990. Columns K, L and M are from Gilmore 1990. Column L pertains to motors built before industry-wide U-frame sizes were developed in 1952.

Source: Nadel, et al., 1991. Prices in $US. ODP = open drip proof, EEM = energy-efficient motor
Motors are 4-pole (~1800 rpm). hp is rated output = 0.746 kw.

Table IX-2
Energy-Efficient Motors Cost-Effectiveness

		Simple Payback Period (Years)		
		Hours per year operation		
	kW output	2000	4000	6000
EEM vs. New Std. Motor (incremental cost)	0.8	3.1	1.6	1.0
	7.5	1.8	0.9	0.6
	75.0	1.3	0.7	0.4
EEM vs. Rewind (incremental cost)	0.8	0.0	0.0	0.0
	7.5	0.0	0.0	0.0
	75.0	1.8	0.9	0.6
EEM as Retrofit (full replacement cost)	0.8	22.1	11.1	7.4
	7.5	7.1	3.6	2.4
	75.0	6.4	3.2	2.1

Assumptions: 1800 rpm ODP motors running at 75% of rated outputs
Electricity price = $0.08 per kWh
Motor and labor costs and performance from Table IX-1
(for 1 hp, 10 hp and 100 hp motors)

Since enactment of the Energy Policy Act in the U.S., which makes most standard motors illegal starting October 1997, production of EEMs has increased. As a result, prices will most likely decrease.

3. Implementation

3.1. Installation

Energy-efficient motors are the same frame size as new standard motors. They are smaller than older standard motors (from the mid-1960s and earlier), requiring the use of adaptor plates and sometimes pulleys or couplings.

The slip can be lower (i.e., EEMs on average run about 1% faster), sometimes requiring adjustments to the driven equipment. In belt-driven applications, adjustable or new pulleys can be used to adjust the speed on the driven equipment. In pumping applications, the impeller can be machined to a smaller diameter. In applications where cycling or motor speed variation is used to match output to load, no compensation is needed.

3.2. Maintenance

Generally, maintenance is less than that of standard motors due to the higher quality construction of the EEMs. Lifetime should be considerably longer than standard motors (up to twice as long, depending on the environment and application).

3.3. Conservation Programs

Typically, rebates are used to make the incremental cost of the EEM minimal (or even negative). Utility costs of over 10 programs in the U.S. and Canada ranged from $0.001 to $0.007 per kWh saved.

4. Environmental Issues

Use of energy-efficient motors results in improved energy efficiency and reduced energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

There are solid waste issues associated with the use of energy-efficient motors because motor replacement programs will generate scrap motors for disposal. Recycling of motor materials, especially copper and high quality steel, is possible.

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X. ADJUSTABLE-SPEED DRIVES

END-USE: All Motor-Driven (Refrigeration, Ventilation, Air Conditioning, Pumps)

SECTOR: Commercial, Industrial, Residential

DESCRIPTION

Performance: Adjustable speed drives (ASDs) provide the capability of varying the speed of electric induction motors to match the load required by their end-use systems and result in typical energy savings of 20 to 50% for pump, fan, and compressor applications. While significant energy is saved by running a motor at a slower speed with an ASD, when running at full-speed an ASD/motor system will use about 5% more energy than the motor alone running at full speed.

Consumer Utility: ASDs improve consumer utility from motor-driven end-uses. Longer equipment life, quieter operation, and better control (improved comfort from HVAC systems; improved product quality or reduced emissions in industry) are sometimes more of a motivation to install ASDs than the energy savings.

Development Status: The increased integration of ASD circuitry, expanding markets, and competition are lowering ASD costs, even while the performance and reliability are improving. ASDs are commercially available from several manufacturers for 3-phase applications from about 1 kW output through tens of thousands of kW, as well as drives for specialized appliances (such as variable-speed air conditioners, heat pumps, and furnaces) Up through a few hundred kW of motor output, pulse-width modulation (PWM) drives dominate, due to lower cost and good performance. For large ASDs, the choice of technology depends on such factors as the type of motor, size, speed range, and control requirements.

COSTS

See Table X-1 for trade prices (as paid by the typical buyer) of ASDs. The simple payback period for ASDs varies tremendously depending on ease of installation, the load profile (how many hours per year at what fraction of rated load), and the price of electricity. Common payback periods range from one to five years.

IMPLEMENTATION

Installation: ASDs can generally be used with existing motors. The physical size of ASDs has been decreasing over the years, making for easier installations.

Maintenance: Most ASDs contain air filters (used for the fan-forced cooling air) which must be periodically cleaned. Otherwise the drives require no regular maintenance. Due to the fact that ASDs start and stop their loads at controlled rates and run them at lower average speeds, maintenance on the driven equipment is generally reduced; motor life may also be extended in applications where the motor runs cooler.

Conservation Programs: Typically, rebates are used to reduce the cost of the ASD. A few utilities in the U.S. and Canada have rebates specifically for ASDs; several others have generic rebates (based on kWh or kW saved) that can be used to subsidize ASD applications.

ENVIRONMENTAL ISSUES

Use of adjustable speed drives results in improved energy efficiency and reduced energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

X. ADJUSTABLE-SPEED DRIVES

1. Description

1.1. Performance Characteristics

Adjustable-Speed Drives (ASDs), also known as "Variable Frequency Drives" and "Adjustable Frequency Drives," are electronic devices that enable electric induction motors to be operated over a continuous range of speed. Note that there are also mechanical devices, sometimes called adjustable-speed drives, that are installed between the motor and the driven load, which serve to vary the speed of the load while the motor speed remains constant. Electronic ASDs (here simply called ASDs) are the dominant speed-control technology. Since the loads on most motor-driven end-uses change over time, the ASD allows the motor output to match the end-use requirements, saving power and energy whenever the system operates below its peak load. Most ASDs are solid-state devices that operate by converting the fixed-frequency alternating-current (AC) electricity supplied by the utility to direct current (DC), and then synthesizing an AC output of controllable frequency. Since the speed of induction motors is directly related to the frequency of power supplied to them, ASDs can control their speed. The most common applications for ASDs are pumps, fans, and compressors, where savings of 20 to 50% are common.

ASDs do not save energy by themselves. The load on the end-use system must be lower than the peak load (at least at times), and there must be a control system that determines the load on the end-use system and provides an input signal to the ASD so that it in turn can control the motor. While the reliability of recent ASDs is quite good, a bypass panel is needed for critical applications to ensure that the motor and its end-use can continue to function even if the ASD fails. Especially for large drives, or where ASD-controlled motors are a large fraction of the electrical load in a facility, the harmonics produced by the drive can cause power quality problems which may require isolation transformers or filters to mitigate. Harmonics can create resonance problems where power factor correction capacitors are present, sometimes resulting in damage to the capacitors. Operation at very low speeds (typically below 20% of nominal) can overheat the motor. (Nadel et al., 1991)

While significant energy is saved by running a motor at a slower speed with an ASD, when running at full-speed an ASD/motor system will use about 5% more energy than the motor alone running at full speed.

1.2. Consumer Utility

ASDs improve the consumer utility from motor-driven end-uses. Longer equipment life, quieter operation, and better control (improved comfort from HVAC systems; improved product quality or reduced emissions in industry) are sometimes more of a motivation to install ASDs than the energy savings.

1.3. Development Status

The increased integration of ASD circuitry, expanding markets, and competition are lowering ASD costs, even while the performance and reliability are improving. There are several million ASDs now installed throughout the world, still a small fraction of the number of potential applications. ASDs are commercially available from several manufacturers for 3-phase applications from about 1 kW output through tens of thousands of kW. Drives for residential appliances (such as variable-speed air conditioners, heat pumps, and furnaces) are typically designed for the specific appliance and are matched to the type (permanent-magnet or induction) and size of motor used. Up through a few hundred kW of motor output, pulse-width modulation (PWM) drives dominate, due to lower cost and good performance. For large ASDs, the choice of technology depends on such factors as the type of motor, size, speed range, and control requirements.

2. Cost of Equipment

Table X-1 provides trade prices (as paid by typical buyer) of ASDs, both for commercial and industrial applications. Industrial drives are built to withstand the more rugged physical and electrical environment of industry. Variable-torque drives are assumed (Nadel et al., 1991).

Table X-1
Summary of ASD Capital Costs for Commercial and Industrial Applications

Size (motor kW output)	Commercial ASD Cost ($)	Industrial ASD Cost ($)
4.0	2,100	2,700
7.5	2,800	3,600
15.0	3,800	4,800
30.0	5,800	6,100
75.0	11,000	14,000
110.0	16,000	20,000
300.0	--	38,000

Costs for installing the drives range from a few hundred dollars per drive (in new construction) to over $5,000 where controls need to be modified and where the reduction of harmonics is necessary. The manufacturer's cost of residential ASDs, due to their mass production, can be as low as $35 per kW of motor output (Nadel et al., 1991).

The simple payback period for ASDs varies tremendously depending on the application. On the hardware side, the drive rating and ease of installation affect the cost. On the operation side, the load profile (how many hours per year at what fraction of rated load) is critical to the potential savings, and the price of electricity is obviously important as well. Twenty to fifty percent energy savings are common, with payback periods from one to five years (Baldwin, 1989; Nadel et al., 1991).

Consult ASD manufacturers for catalog and pricing information. The Electric Power Research Institute (EPRI) has a useful compilation of ASD manufacturers and their products (Püttgen and Singh, 1991).

3. Implementation

3.1. Installation

ASDs can generally be used with existing motors. The ASD itself can be located away from the motor, which can allow installations where space near the motor is limited or where ambient conditions are too hostile for electronics. There are also special enclosures to allow installation outdoors or in dirty environments. The physical size of ASDs has been decreasing over the years, making for easier installations. ASDs up to a few tens of kW of motor output are now available to fit into standard "motor control center" panels, facilitating their installation in new and renovated facilities.

3.2. Maintenance

Most ASDs contain air filters (used for the fan-forced cooling air) which must be periodically cleaned. Otherwise the drives require no regular maintenance. Due to the fact that ASDs start and stop their loads slowly and run them at lower average speeds, maintenance on the driven equipment is generally reduced. The reduced motor loading can reduce the motor temperature, thereby prolonging its life. It can also increase motor temperature because the motor's fan turns more slowly.

3.3. Conservation Programs

Typically, rebates are used to reduce the cost of the ASD. A few utilities in the U.S. and Canada have rebates specifically for ASDs; several others have generic rebates (based on kWh or kW saved) that can be used to subsidize ASD applications.

4. Environmental Issues

Use of adjustable speed drives results in improved energy efficiency and reduced energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

5. References

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6. Contacts

Power Electronics Applications Center (PEAC), 10521 Research Drive, #400, Knoxville, TN, 37932 (615) 675-9505.

Samotyj, Marek, Electric Power Research Institute (EPRI), 3412 Hillview Avenue, Palo Alto, CA 94303, (415) 855-2980.

XI. ENERGY-EFFICIENT REFRIGERATORS

END-USE: Domestic Refrigeration

SECTOR: Residential

DESCRIPTION

Performance: Energy-efficient refrigerators and freezers are equivalent in performance to typical models. Capacities of typical models vary widely among nations. U.S. models tend to be larger than those in Europe, Japan and developing countries.

Consumer Utility: Energy-efficient refrigerators and freezers provide the same consumer utility as standard models. Reduced internal loads will reduce air conditioning load in countries with warm climates but increase heating loads in cool climates.

Development Status: In developed countries, there is usually a wide range of efficiencies available for the same capacity. Prices are usually not directly related to the efficiency choices. In developing countries, the most energy-efficient technologies are often not available.

COSTS

The first-cost premium for a 28% decrease in energy use is about 13%. See Table XI-1 for retail prices and simple payback periods (as paid by the typical US buyer) of more efficient refrigerator-freezers.

IMPLEMENTATION

Installation: Installation costs will not be affected by the implementation of more efficient designs.

Maintenance: There are no expected impacts on maintenance or lifetime from improving equipment efficiency.

Conservation Programs: Typically, rebates are used to motivate consumers to purchase energy-efficient refrigerators. The rebates depend on how much less energy is used by the model purchased compared to some reference energy use level. In California, the reference energy use is that prescribed by the 1990 Federal energy efficiency standards. A significant barrier to implementation has been the lack of efficient refrigerator design and manufacturing capability. To address this issue, a national competition (known as the Super-Efficient Refrigerator Program) sponsored by a consortium of utilities has recently awarded its $30 million "golden carrot" to Whirlpool Corporation for development of a prototype 22 cubic foot side by side refrigerator freezer that consumes less than 700 kWh/year, 30% less than the 970 kWh/year allowed under the 1993 U.S. standards.

ENVIRONMENTAL ISSUES

Use of energy-efficient refrigerators results in improved energy efficiency and reduced energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

Use of CFCs in refrigerants and insulation is rapidly being phased out in the U.S.

XI. ENERGY-EFFICIENT REFRIGERATORS

1. Description

1.1. Performance Characteristics

Energy-efficient refrigerators and freezers perform the same functions as typical models. Capacities of typical models vary widely among nations. U.S. models tend to be larger than those in Europe, Japan, and developing countries. Comparison of efficiencies among the U.S., Japanese, and European models is difficult because different measurement procedures are used in each of the three locations.

1.2. Consumer Utility

Energy-efficient refrigerators and freezers provide the same consumer utility as standard models. Reduced internal loads for more efficient models will reduce cooling loads in countries with warm climates but increase heating loads in cool climates.

1.3. Development Status

In developed countries, there is usually a wide range of efficiencies available for the same capacity. Prices are usually not directly related to the efficiency choices. In developing countries, the most energy-efficient technologies are often not available. The U.S. has established minimum energy efficiency standards and the European Community is also considering standards.

2. Cost of Equipment

Table XI-1 shows simple payback periods and consumer prices for each design option for an 18 ft^3 top-mount auto-defrost refrigerator-freezer. The price of electricity in 1993 is estimated to be $0.075/kWh in 1988 dollars. Both incremental and cumulative paybacks are given. The cumulative paybacks are computed relative to design option three (foamed door), which is the base case efficiency level predicted for 1993 new top-mount auto-defrost refrigerator-freezers in the U.S. We have chosen this baseline for the cumulative payback period calculation in order to take into account projected efficiency improvements in the marketplace beyond the 1990 minimum efficiency standard. Therefore, cumulative paybacks are not applicable (NA) to the first two design options. In 1991, option 7 was selected for the 1993 efficiency standard for this product class. The cumulative payback period is 4.2 years for this efficiency level.

Most of the design options are self-explanatory. Actual compressor performance data were obtained from compressor and refrigerator manufacturers. The foam insulation thermal conductance value for the baseline model is approximately 0.127 Btu in/ft^2-h-F (equivalent to a resistance value of R-8). This value assumes the use of a non-CFC foam such as HCFC-123 or HCFC-141-b, and the conductivity is 2% higher than the value for a CFC-11 based foam.

It is estimated that the cost of the CFC-11 foam substitute will be 2.5 times greater than the present cost (1993$) of CFC-11. Additionally, the cost of a CFC-12 refrigerant substitute is also estimated to be 2.5 times that of CFC-12. The resulting baseline manufacturer cost is approximately $4.00 higher for a non-CFC 18 ft^3 refrigerator than for one with CFCs available. Simulations were also performed for a scenario where CFCs were available (US DOE, 1988).

Table XI-1
Retail Prices and Payback Periods of Design Options:
18 ft^3 Top-Mount Auto-Defrost Refrigerator-Freezer (No CFCs)

Level*	Design	Energy Use *(kWh/yr)*	Consumer Price *($87)*	Incremental Simple Payback (yrs)**	Cumulative Simple Payback (yrs)
0	Baseline	955	521.7	NA	NA
1	0 + Enhanced Heat Transfer	936	521.9	0.2	NA
2	1 + Foam Refrigerator Door	878	525.1	0.7	NA
3	2 + 5.05 COP Compressor	787	532.3	1.0	1.0
4	3 + 2 inch Doors	763	540.6	4.4	1.7
5	4 + Efficient Fans	732	559.5	7.7	3.0
6	5 + 2.6"/2.3" Side Insulation	706	577.0	8.5	3.8
7	5 + 3.0"/2.7" Side Insulation	690	587.1	8.3	4.2
8	5 + Evacuated Panels	577	656.2	7.9	5.5
9	8 + Two-Compressor System	508	760.7	19.2	8.1
10	9 + Adaptive Defrost	490	794.0	23.4	8.8

* Level 0 = 1990 standard, Level 7 = 1993 standard.

** Energy savings are calculated assuring an electricity price of 7.5¢/kWh.

The fan motor power is chosen to be 8 W for the more efficient evaporator and condenser fan motors. After more efficient fans, there is a branch in the choice of the next design option. Either increased side insulation or evacuated panels are chosen.

The evacuated panel thermal conductance value of R-18 per inch (0.055 Btu in/ft^2-h-F) is assumed to apply to the walls of the cabinet and not to the doors. It is a composite of foam insulation (for structural rigidity) and evacuated panel. Any of three technologies for evacuated panels could be used to achieve this thermal conductivity value. These approaches are: compact vacuum, aerogel and powder-filled evacuated panels. The first approach creates a hard vacuum between rigid steel plates with glass spacers. A 0.25" thick test panel has been produced with an R-10 (R-40 per inch) insulation value. Silica aerogel is a low density form of porous silica glass. Measurements show that R-20 per inch is presently achievable at a pressure of about 75 torr[2]. The last approach, powder-filled evacuated panels, has progressed furthest. General Electric has produced limited quantities of these panels for installation in about 1,000 refrigerator-freezers. A 0.05 thermal conductivity or R-20/inch was achieved at a pressure of about 20 torr. Because of unsatisfactory and inconsistent results, G.E. has withdrawn evacuated panel insulation from currently manufactured refrigerator-freezers.

A two-compressor system employs two separate evaporators and two compressors; one for the refrigerator and one for the freezer. This allows for a higher evaporator temperature in the refrigerator and a higher COP than for the freezer refrigeration system. For adaptive defrost, defrosting is done when needed rather than through a timer control. Energy consumption is reduced by almost 50%; from 955 to 490 kWh/yr for level 10 in Table XI-1. This design incorporates 2" of foam insulation in the doors, a 5.05 EER compressor, evacuated panels in the planar walls, a two-compressor system and adaptive defrost.

2. 760 torr equals one atmosphere.

3. Implementation

3.1. Installation

Installation costs will not be affected by the implementation of more efficient designs.

3.2. Maintenance

There are no expected impacts on maintenance or lifetime.

3.3. Conservation Programs

Typically, rebates are used to motivate consumers to purchase energy-efficient refrigerators. The rebates depend on how much less energy is used by the model purchased compared to some reference energy use level. In California, the reference energy use is that prescribed by the 1990 Federal energy efficiency standards. A significant barrier to implementation has been the lack of efficient refrigerator design and manufacturing capability. To address this issue, a national competition (known as the Super-Efficient Refrigerator Program) sponsored by a consortium of utilities has recently awarded its $30 million "golden carrot" to Whirlpool Corporation for development of a prototype 22 cubic foot side-by-side refrigerator freezer that consumes less than 700 kWh/year, 30% less than the 970 kWh/year allowed under the 1993 U.S. standards.

4. Environmental Issues

Use of energy-efficient refrigerators results in improved energy efficiency and reduced energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

All uses of CFCs (including in refrigerants and insulation) are prohibited after January 1, 1996. Refrigerant and insulation CFCs will be replaced with HCFCs, which have a lower ozone depletion potential (ODP). For example, the ODP of CFC-11 is 1.0 while the ODP of HCFC-141-b is 0.12.

5. References

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XII. DAYLIGHT CONTROL GLAZING

END-USE: Fenestration

SECTOR: Commercial, Residential

DESCRIPTION

Performance: Daylight control glazing utilizes directionally selective materials to reject or redirect incident solar radiation as a function of the geometric relationship between the radiation and the material. To enhance daylight use, they may redirect the incoming sunlight to spread it more usefully within the space. In principle, they could additionally serve solar control needs; for example, they might reflect all energy striking the surface above some critical angle of incidence, to increase the shading coefficient of the glazing in the summer months. Angle-dependent technologies currently include prismatic glazings, louvers, and holographic films.

Consumer Utility: Daylight control glazings optimize the use of daylight while reducing glare. The result can be savings in electric lighting energy and peak electrical demand.

Development Status: Prismatic glazings are currently only available from one European manufacturer, although other types are in development throughout the world. Enclosed louver products are a specialty item available from a few window manufacturers. Integrated louvers and holographic glazings are not yet available.

COSTS

Costs are unavailable but are likely to be higher than standard glazings. Such comparisons, however, may not be appropriate since these materials may be used in different applications.

IMPLEMENTATION

Installation: Applications include specialized daylighting and/or glare control optimization. Care must be taken in the design of these windows for best performance. An important difference between these glazings and conventional systems is the separation here between two of the window functions: to provide view and to provide useful light. Separate vision windows may need to be provided when using redirecting glazings for daylighting.

Maintenance: May require more cleaning than standard glazings, otherwise maintenance is not a significant concern.

Conservation Programs: None exist.

ENVIRONMENTAL ISSUES

Use of daylight control glazing results in improved energy efficiency and reduced energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

XII. DAYLIGHT CONTROL GLAZING

1. Description

1.1 Performance Characteristics

Daylighting design that depends on vertical apertures in a single wall as the illumination source (the most common situation) must often overcome two inherent difficulties: the penetration depth of useful daylight is limited to generally one and one-half times the height of the window; and the brightness of the single window compared to the relative darkness of other room surfaces causes visual discomfort due to contrast glare. Glazing designed for the control of daylight addresses one or both of these issues.

Daylight control glazing utilizes directionally selective materials to reject or redirect incident solar radiation as a function of the geometric relationship between the radiation and the material. To enhance daylight use, they may redirect the incoming sunlight to spread it more usefully within the space. If the angle-dependent transmissivity of such glazings could be fine-tuned for each building application and orientation, useful solar control could be achieved. The transmittance properties could theoretically respond as a function of solar incidence angle. For example, a window coating might be tuned to reflect all energy striking the surface above some critical angle of incidence. It may be possible to produce such effects with oriented coatings, holographic films or through materials embedded within the glazing substrates. These function much like refractive optical systems (e.g., linear Fresnel prisms) normally seen at a much larger scale. There is potentially an opportunity to combine angle-selective technologies with chromogenic materials for further control of the system (see Section XV Switchable Glazing). Current technologies in this category include:

Prismatic glazings: Prismatic glazing systems use the principles of light refraction through dielectric materials to redirect light. Incoming light can be redirected toward more useful destinations, such as onto the ceiling instead of into an occupant's eyes. Systems generally reflect light coming from undesirable angles and transmit (by refraction) light coming from any other angle. In other words, they have a cut-off range and a transmission range. The cut-off range prevents the transmission of direct sunlight into the interior, thus providing the sunshielding effect. In the transmission range, the optical refraction of the prism changes the direction and intensity of the incident light. Daylight striking the window is usually directed up towards the ceiling in the interior.

Enclosed louvers within the window assembly: Reflective louvers intercept direct sunlight before it can strike a work surface or an occupant, and instead redirect it onto the ceiling towards the rear of the room. The redirected sunlight transforms the ceiling into a large, diffuse light source. The aim is to improve penetration of light deep within the space and to create an overall sense of greater brightness (brightening the surfaces of a room results in perceived greater illuminance levels regardless of actual illuminance levels). Horizontal louvers are best suited to south facing windows.

Integrated louvers: Integrated louvers, similar to venetian blinds, have fixed microblinds embedded in the 1/4 inch width of a single piece of glass. This is a research prototype only and not commercially available.

Holographic films on glazings: Glazing materials which utilize holographic optics might contribute to substantially increased daylight levels up to 40 feet or more into the interior of the building from the window wall than with traditional fenestration systems. Holographic devices use diffractive structures to control light transmission and outgoing direction. To date, the holographic daylighting devices developed as laboratory prototypes consist of photopolymers or embossed films applied to glass. Incoming light is redirected as a function of angle of incidence and wavelength of the incoming light.

Current development strategy is to fabricate large polyester sheets, containing an embossed diffractive structure, that can be attached to the upper portion of any visibly transparent aperture facing orientations that range from southeast to southwest (northern hemisphere). Direct sunlight falling on the device will be diffracted towards the ceiling deep into the room, which will reflect glare-free, diffuse light onto the work surfaces. Undesirable direct sunlight is thus not admitted into the space, being transformed instead into redirected useful diffuse light. Current prototypes are partially transparent; while this has the advantage of permitting some vision through the glazing, these holographic prototypes are thereby not perfectly efficient. The view through is darkened somewhat but remains undistorted. At this stage in the research and development cycle, there is a great deal of uncertainty in performance, technical details, and practicality of architectural applications.

Two other angle-dependent technologies not covered here are glass block, which is typically used for aesthetic reasons alone and is not a promising technology for fine control, and glazings with angle-selective structures embedded within the glass substrates (no prototypes are currently in existence).

1.2 Consumer Utility

Daylight control glazings optimize the use of daylight while reducing glare. The result can be a savings in electric lighting energy and attendant cooling energy and peak electrical demand.

1.3 Development Status

Most of the products described in this section are still under development. Prismatic glazings are currently only available from one European manufacturer, although other types are in development throughout the world. Integrated louver products are a specialty item available from a few window manufacturers. Holographic glazings are not yet commercially available.

2. Cost of Equipment

Costs are unavailable, but are likely to be higher than standard glazings. Even if costs were available, comparisons to standard glazings may not be appropriate since these materials have a different function.

3. Implementation

3.1 Installation

Applications include specialized daylighting and/or glare control optimization. Care must be taken in the design of these windows for best performance. An important difference between these glazings and conventional systems is the separation between two functions of the window: to provide view and to provide useful light. Separate vision windows may need to be provided when using redirecting glazings for daylighting.

3.2 Maintenance

Daylight control glazing may require more cleaning than standard glazings. Otherwise, maintenance is not a significant concern.

3.3 Conservation Programs

No programs are currently known to exist.

4. Environmental Issues

Use of daylight control glazing results in improved energy efficiency and reduced energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

5. References

See Table XII-1.

6. Major Manufacturers

See Table XII-2.

Table XII-1
Glazing References and General Bibliography

Windows and Daylighting Group, Lawrence Berkeley Laboratory.
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Table XII-2
Major Glazing Manufacturers

AFG Glass Inc.
75 Doney Crescent
Concord, Ontario L4K 1P6
Canada

Alpen
5400 Spine Road
Boulder, CO 80301
USA

Cardinal IG
12301 Whitewater Drive
Minnetonka, MN 55343
USA

Flachglas AG
Auf der Reihe 2, P.O. Box 100851
4650 Gelsenkirchen
Germany

Ford Glass
4 Parklane Blvd., Suite 464
Dearborn, MI 48126
USA

Guardian Industries
14600 Romine Road
Carleton, MI 48117
USA

Interpane Coatings, Inc.
Deerfield, MI 49238
USA

LOF Co.
811 Madison Avenue
Toledo, OH 43695
USA

Monsanto Company
800 N. Lindbergh Blvd.
St. Louis, MO 63167
USA

Nippon Sheet Glass
8, 4-chome, Dosho-machi
Higashi-ku, Osaka
Japan

Pilkington Glass, Ltd.
Alexandra Works
St. Helens WA10 3TT
England

PPG Industries, Inc.
One PPG Place
Pittsburgh, PA 15272
USA

Saint-Gobain
Exprover S.A.
Avenue de Tervuren, Bte 4
B-1150 Brussels
Belgium

Southwall Technologies
1029 Corporation Way
Palo Alto, CA 94303
USA

Spectrum Glass Products, Inc.
P.O. Box 408
520 E. Railroad Street
Clinton, NC 28328
USA

Viracon, Inc.
800 Park Drive
Owatonna, MN 55060
USA

XIII. INSULATING GLAZING

END-USE: Fenestration

SECTOR: Commercial, Residential

DESCRIPTION

Performance: The least efficient window consists of a single piece of glass in an aluminum frame, providing minimal resistance to conductive heat flow, with resultant effects on energy use and occupant comfort. The variety of technologies aimed at improving the insulating value of a basic window include insulating glass units (IGUs), low-emissivity coatings (low-E), gas or transparent insulation fills, evacuated units, "superwindows" and insulating frames. While generally targeted for cold climates, insulating glazing can provide benefits in warm climates as well. Comfort factors (radiant body heat loss, down drafts) and condensation can be as important as energy savings in any climate. The key glazing performance characteristic measuring insulating ability is the *U-value* or *R-value*. Single-pane glass has a typical R-value of 1.0. The improved glazing assemblies discussed in this section range from R-2 to R-10.

Consumer Utility: Insulating glazing reduces energy costs and increases occupant comfort compared to basic glazing. Benefits are realized in life cycle savings, occupant satisfaction and the potential of reducing or eliminating secondary commercial baseboard heating systems or other heating plants.

Development Status: Standard IGUs have long been available from all window manufacturers and are the most common window choice for U.S. and Canadian residential applications. Low-E coated glazings are available from every major glass and window manufacturer. Gas filled IGUs are available from most manufacturers. Aerogel and other transparent insulation fills and evacuated windows are not yet available in commercial products. Superwindows (with whole window R-values of 5 or above) have recently emerged on the market through a few window manufacturers.

COSTS

In general, insulating glazing is significantly more expensive than single-pane glazing, however, payback periods are often short. First costs can be offset by savings in downsized HVAC equipment or by utility rebates.

IMPLEMENTATION

Installation: Applications include: a) extreme hot or cold climates for all building types; b) residential and small commercial buildings in all but the most temperate climates; and c) any application where comfort or condensation may be an issue. Insulating glazing is thicker and heavier than single-pane applications. Otherwise, installation of windows is no different than with a single-pane unit.

Maintenance: Maintenance and durability are generally not a problem. Insulating units need to keep moisture out which may require better sealants and greater manufacturing quality control.

Conservation Programs: Many incentive programs, building codes and standards in the U.S. and in Canada encourage the use of insulating windows, particularly for residential construction. Utility rebates, generally paid per square foot of glazing, often eliminate the added first cost.

ENVIRONMENTAL ISSUES

Use of insulating glazing results in improved energy efficiency and reduced energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

XIII. INSULATING GLAZING

1. Description

1.1 Performance Characteristics

Glass is highly conductive, which means single-pane windows offer little resistance to heat transfer due to a temperature difference between inside and outside. In addition, typical window frames and other assembly components are made of conductive metals with no thermal breaks. The window has traditionally been the weak point of the building envelope in terms of conductive heat transfer. This is generally a concern more for heating loads than cooling, thus many glazing advancements have been aimed primarily at heat loss reduction. However, buildings in extremely warm climates can also benefit from insulating glazing.

In addition to the energy use impacts of conductive heat transfer, important comfort factors motivate the use of insulating glass. When a poor window separates a heated space from a colder environment outside, the surface temperature of the window is much lower than for other objects in the space. People sitting near the window will radiate body heat to this cold surface, which gives a feeling of chill regardless of the room air temperature. The greater the difference between body temperature and glass temperature, the more uncomfortable the individual will feel. The cold surface will also initiate a "down draft" convective loop when circulating room air loses heat upon contact with the window and falls due to its subsequently greater density. This draft increases the sense of chill. If there is moisture in the room air, a further effect of the cold window may be condensation on the glass. When room air drops in temperature upon contact with the cold glass, it may reach its dewpoint and fail to keep its water content in vapor form. Water condenses into liquid drops on the glass, which can cause damage to interior finishes, among other problems. Condensation and down drafts are concerns only in cold climates. Radiant body heat transfer can be a comfort concern in cold or hot climates; in a hot climate, a warm piece of glass will radiate heat to a nearby occupant, causing a feeling of warmth regardless of air conditioning in the space. The energy use ramification of radiant heat transfer discomfort is a greater tendency for occupants to overcondition the space. For example, occupants will set a heating thermostat higher than necessary in reaction to the chill described above.

The key glazing performance characteristic measuring insulating ability is the *U value*. U value is the rate of thermal transmission through a material or assembly and is expressed as $Btu/h{\cdot}ft^2{\cdot}°F$ or $W/m^2{\cdot}°K$. Lower U values indicate a reduction in conductive heat loss. This characteristic is also often expressed as the *R value*, or resistance to heat transfer, which is the reciprocal of the sum of all the U values in an assembly and thus higher numbers indicate greater resistance to heat flow. Single-pane glass has a typical R value of 1.0. The improved glazing assemblies discussed below range from R-2 to R-10. For comparison, a typical insulated wall in new residential construction in the U.S. is R-12. The walls in existing residential construction and in commercial buildings typically range from R-2 to R-8. All U or R values discussed in the text are for the *center* of the glazing unless otherwise noted. For reference, we also give whole window values in italics in Table XIII-1. Other elements of the window assembly degrade the overall performance, and therefore increase the U value (reduce the R value) of the whole window, however, this performance degradation varies as a function of the edge and frame conditions.

The key glazing performance characteristic measuring solar heat gain control is the *shading coefficient* (SC). SC measures how well a particular glazing inhibits the transfer of solar heat. Shading coefficients for common products typically range from 1.0 to 0.2. Windows with lower shading coefficients inhibit solar heat transfer more effectively than those with higher SCs.

Shading coefficient addresses energy transfer through the entire solar spectrum, which ranges from the ultraviolet through the visible and the short wave infrared wavelengths. Solar energy is split approximately evenly between visible and infrared wavelengths, with a very small percentage of ultraviolet radiation. Glazing materials vary in their transmittance depending on the wavelength of energy striking the material. This means two glazings with very different properties could have the same shading coefficient. For example, one glazing might be transparent to visible wavelengths and block all infrared energy (and would appear clear), while an equal shading coefficient could be achieved with a totally black glass (blocking all visible wavelengths but transparent to infrared). The glazing performance characteristic measuring the transparency of glass to visible wavelengths is the *visible transmittance* (T_{vis}). The comparison between shading coefficient and visible transmittance is given as the ratio T_{vis}/SC, also known as *glazing luminous efficacy* (K_e). This term, which is borrowed from the field of electric lighting, indicates how effective a glazing is for both shading and lighting. In other words, it is a measure of the trade-off of light transmittance (and view clarity) for reductions in solar heat gain. A high ratio indicates that a glazing achieves solar control primarily by blocking the invisible portions of solar energy and preserving transmission of visible light. Most standard solar control products ignore any losses in visible transmittance. Newer products preserve both light and view while maximizing solar control. These are known as *spectrally selective* glazings because they preferentially block IR and UV radiation.

Technologies to decrease thermal energy flow through windows fall into two general categories: (a) increasing the resistance of the window assembly (by replacing conductive materials with less-conductive ones or adding materials and/or layers); and (b) lowering the emissivity of the glazing (reducing its ability to absorb and re-radiate heat). Specific technologies are discussed below.

Insulating glass units (IGUs): These assemblies normally consist of two panes of glass (sometimes three), separated by an air gap and sealed. Trapping air between two panes of glass doubles the thermal resistance of the product (R-2 for a standard IGU). This solution is simple enough that the majority of windows in the U.S. are now insulating glass. These units appear equally transparent as single glazing, however, they are significantly heavier and thicker. Single panes are commonly used at 0.25 inch thickness; a typical IGU consists of two 0.25 inch panes with a 1/2 inch air gap, for a total assembly of 1 inch.

Low-E coatings on glass: Low-emissivity coatings, often referred to as "low-E," consist of very thin, transparent layers of metals and oxides deposited on glass or plastic which inhibit the ability of the coated material to transfer heat through radiation. Low-E coatings work much like the inside of a thermos bottle to reflect long-wave infrared radiation back to its source. They were originally designed to improve window insulation performance in cold climates, allowing solar heat (near-infrared energy) into the space while room heat (far-infrared energy) re-radiated from warm indoor surfaces is not allowed to escape back outside. Uncoated glass is highly absorptive to far infrared energy, and it re-radiates the absorbed heat both indoors and out; energy radiated to the outdoors is a heat loss for the space. By contrast, low-E coatings reflect rather than absorb room heat, reducing overall heat transfer. These coatings are functional in warm climates as well, where far infrared radiation from warm surfaces outside is not admitted through the glass.

There are two general manufacturing processes for low-E coatings. Pyrolytic coatings are normally applied to glass as part of the float production process. These coatings are very durable (they are called "hard coats") but do not have optimal optical characteristics. The "soft coat" sputtered coatings, applied after glass production in a vacuum chamber, have better performance but must be protected from the environment (applied to one of the sealed inside surfaces of an IGU, for example). Low-E coatings can be combined with tints, other coatings, and gas fills. Hard coat low-E coatings can be used with single-pane glass; however, the insulating effects of these coatings are most effective when the coating faces a sealed air space. While a single-pane low-E coated window will show a small improvement in U-value, it should only be used in dry and temperate climates to minimize the increased likelihood of condensation (a low-E coated single pane will have a colder surface temperature than an uncoated pane). For a double-pane insulating glass unit with a low-E coating, R-2.9 is typical. Pyrolytic coatings may have noticeable color or haze effects. Sputtered coatings are virtually color-free and without haze.

Low-E coating on suspended plastic film: A patented product known by its trademarked name "Heat Mirror" is a special application of low-E technology combined with the principles of an IGU. The assembly consists of two panes of glass and a low-E coated thin plastic sheet stretched and suspended in the space between the panes, which creates a second air gap. Indistinguishable in weight, size and appearance from a conventional two-pane clear IGU, the R value is increased to 4.0. A unit with larger air gaps, resulting in a thicker assembly than with a conventional IGU, achieves R-4.5.

Gas fills: The insulating value of double and triple glazed systems is attributed to the air trapped between glass layers. To further increase the insulating properties of such systems, air is replaced by low-conductance gases. Argon, a colorless, non-toxic inert gas, is most commonly used. Argon is 30% less thermally conductive than air, due to its greater molecular mass (molecules move more slowly and thus energy-exchanging collisions are less frequent). Better performance can be achieved with more expensive gases such as krypton and sulfur hexafluoride. Gas-filled units must be hermetically sealed in order to contain the injected gas over long periods of time. They are widely used in Europe and the U.S. Gas fills provide the greatest benefit when used in conjunction with low-emissivity coatings. An argon-filled IGU has a resistance of R-2.22. An argon-filled IGU with a low-E coating has a resistance of R-4.

TIM fills: Transparent insulation materials (TIM) permit opaque, insulated facade elements to admit light and/or solar heat without sacrificing thermal properties of the envelope. Transparent insulation can be used to significantly inhibit heat loss across transparent/translucent building openings, or it can be used in combination with a darkened, heat-absorbing surface to turn the fenestration system into a passive solar heater. The material would typically be sandwiched in the air gap of an IGU. Two main types of TIM exist, although products are not widely available.

Aerogel is a type of TIM that has been known for more than 50 years. Widespread architectural application of aerogel is not expected in the near future but its potentially favorable thermal characteristics have engendered widespread interest.. Aerogel can achieve R-20 per inch of thickness. Aerogel is a microporous silica matrix that traps air in tiny holes. It is transparent because the holes are smaller in diameter than visible light wavelengths, although there is some haze due to scattering. Research for window applications has been underway since the late 1950s. Currently, two kinds of prototypes are available: 1) highly transparent "tiles" usually 2 cm thick and currently prototyped in dimensions up to 60 x 60 cm^2; 2) granules of varying diameter (1-10 mm), for a cheaper product but with strong light scattering. Both would typically be used as fill in a double-pane glazing assembly. Both systems can be improved with a soft vacuum (0.1 atmosphere) or special gas fills. Current research attention on aerogel is directed towards appliance insulation (e.g., refrigerators).

Honeycomb or capillary structure transparent materials are another form of fill technology. Some European prototype fenestration units using these materials have been designed to act as passive heating devices. These units absorb solar radiation and re-radiate it indoors, so that the inner wall surface acts like a large low-temperature wall heater.

Evacuated windows: The fill strategy with the lowest conductance per unit thickness would be the use of a hard vacuum between low-E coated glass. However, the long-term integrity of seals and the structural stability of the unit (keeping it from collapsing due to pressure differences) has proven difficult to master in a cost-effective manner. Research is continuing in this area. Theoretically, R-20 could be achieved with an IGU of less than 1 inch total thickness.

Superwindows: Three of the above principles have been combined for the highest R-value product currently available. An assembly consisting of three layers of glazing, two low-E coatings, and two gas fills results in a superwindow with a center of glass R-value between 6 and 10. In the patented product currently available, a version of a superwindow is created where a low-E coating is applied to each of two plastic sheets, which are individually suspended in the space between two panes of glass. The resulting three air gaps are filled with argon. The assembly thus consists of two low-E coatings and three gaps with argon fills. In addition, the spacer between the glass panes is made of non-metallic insulating material (see frames and spacers below). Due to their ability to gain solar heat as well as provide insulation against heat loss, superwindows have proven to be net-energy gainers, even on north facing walls (Arasteh, 1989).

Better frames and spacers: With significant improvements in glazing accomplished, the edge of the IGU and the window frame become the thermal weak points of the assembly. Conductive metals are often used to frame the unit and to maintain the space between panes. For a typical window, total heat loss breaks down to 50% due to the glass, 25% due to frame conductance and 25% due to edge (spacer) conductance. Window R and U values are often given for the center of the glass, without considering frame and edge losses. For example, an IGU with a center-of-glass U value of 0.49 (R-2), has a total-window U value of 0.87 (R-1.15) when used in an aluminum frame with an aluminum spacer. Improvements include thermal breaks in metal frames, greater use of wood and clad wood sash and frames, or the substitution of lower conductance frame materials like vinyl. For the example IGU above, total-window U value in an aluminum frame with thermal breaks is 0.62 (R-1.6), in a wood frame with a wood spacer 0.47 (R-2.1) and in a vinyl frame with a fiberglass spacer 0.44 (R-2.3).

1.2 Consumer Utility

Insulating glazing serves the purposes of reducing energy costs, reducing noise transmission, and increasing occupant comfort compared to basic glazing, providing a greater consumer utility. Benefits are greatest in residential buildings in cold climates. The consumer trade-off is a thicker window assembly (which won't influence construction costs or wall design in most cases) and a more expensive first cost for the product compared to single-pane glazing in a standard aluminum frame. Pay-off is in life cycle savings, occupant satisfaction, and the potential of reducing or eliminating secondary commercial baseboard heating systems. Insulating glazings that employ a low-E coating, especially if it is on plastic film, often reduce ultraviolet transmission, which causes fading of upholstery and other interior finishes and can damage artwork.

1.3 Development Status

Standard two and three pane insulating units have long been available from all window manufacturers and are the most common window choice for U.S. and Canadian residential applications. Low-E coatings first became available in 1981 and have steadily increased in market share ever since. As of 1991, they have captured over 30% of the U.S. residential market and a smaller but growing share of commercial windows as well, one of the most rapid industrial acceptances for a new building technology. Low-E coated glazings are available from every major glass and window manufacturer. Gas filled IGUs are available from most manufacturers. Aerogel, other transparent insulation fills and evacuated windows are not yet available in commercial products. "Superwindows" have recently emerged on the market through a few window manufacturers.

2. Cost of Equipment

Costs vary by technology, market region, size of order and other factors. In general, insulating glazing is significantly more expensive than single-pane glazing, however, in cold climates payback periods are usually short. First costs can be offset by savings in downsized HVAC equipment or by utility rebate programs. See Table XIII-1 for comparative costs and benefits.

3. Implementation

3.1 Installation

Applications include: a) extreme hot or cold climates for all building types; b) residential and small commercial buildings in all but the most temperate climates; and c) any application where comfort or condensation may be an issue.

Insulating glazing is thicker and heavier than single-pane applications (typically 1 inch versus 0.25 inch). Otherwise, construction is no different than with a single-pane unit.

3.2 Maintenance

Maintenance and durability is generally not a problem. Insulating units need to keep moisture out which may indicate a need for better sealants and greater manufacturing quality control. Occasionally, the seal of an insulating unit can fail, and fogging in the unit can occur. This requires that the unit be replaced. With gas-filled units, gas leakage without an additional fogging problem does not require replacement, however, the value of the gas is lost. Seal failures are rare in all cases.

3.3 Conservation Programs

Many incentive programs in the U.S. and Canada encourage the use of insulating windows, particularly for residential construction. These programs reduce the added first cost for the measure. Rebates are generally paid per square foot of glazing. Some energy codes in the U.S. and Canada, in addition to ASHRAE Standard 90.1, either require or encourage insulating glazing for certain applications.

4. Environmental Issues

Use of insulating glazing results in improved energy efficiency and reduced energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

5. References

See Table XII-1 in chapter XII (Daylight Control Glazing).

6. Major Manufacturers

See Table XII-2 in chapter XII (Daylight Control Glazing).

Table XIII-1
Generic Glazing/Window Comparisons

PRODUCT	$/SF[1]	U-Value[2]	R-Value[3]	SC[4]	T_v[5]	K_e[6]	Benefit[7]
Base case							
1. Single pane clear glazing in aluminum frame	6.43	1.09 *1.26*	0.92 *0.79*	0.98 *0.90*	0.89 *0.71*	0.91 *0.79*	Least expensive product available but in almost all cases has a higher life cycle cost than most other products.
Insulating Glass							
2. Standard 2-pane IGU clear, aluminum frame	9.62	0.48 *0.80*	2.1 *1.25*	0.82 *0.79*	0.80 *0.63*	0.98 *0.80*	Doubles the insulating value of standard single pane while also improving comfort and reducing condensation probability due to warmer glass surface temperature. Most cost effective in heating-dominated situations; life cycle cost is negative in these cases. Can be cost effective in hot climates for air conditioned buildings, although payback period may be longer than in cool climates. Can be significantly more comfortable in hot climates due to cooler glass surface temperature.
2a. Standard 2-pane IGU clear, wood frame	16.85	0.48 *0.48*	2.1 *2.1*	0.82 *0.66*	0.80 *0.60*	0.98 *0.91*	Higher whole-window R-value than with aluminum frame. Same benefits as above. Frame improvement most cost effective in cold climates; somewhat effective in moderate climates; probably not cost effective in cooling-dominated situations. Wood frame may be chosen over aluminum for aesthetic reasons.

Table XIII-1
Generic Glazing/Window Comparisons

PRODUCT	$/SF[1]	U-Value[2]	R-Value[3]	SC[4]	T_v[5]	K_e[6]	Benefit[7]
3. Low-E coating 2-pane IGU clear, aluminum frame	11.64	0.31 *0.64*	3.2 *1.56*	0.74 *0.71*	0.68 *0.54*	0.98 *0.76*	Low-E coating triples the insulating value over a single pane and increases by 50% over a standard double pane. This performance is similar to a triple pane unit for less width and less weight. Aluminum frame will reduce the overall insulation (see below). Another benefit is more comfortable glass surface temperatures than single or double glazing, improving occupant comfort and reducing condensation probability. Other benefits include high Tv and low SC, which could result in cooling and lighting savings. Low-E products available in a wide range of Tv and SC values. Low-E coatings can also reduce ultraviolet transmission. Cost effective in cold climates; may or may not be cost effective in other climates.
3a. Low-E coating 2-pane IGU clear, wood frame	18.87	0.31 *0.36*	3.2 *2.77*	0.74 *0.59*	0.68 *0.51*	0.98 *0.86*	Higher whole-window R-value than with aluminum frame. Same benefits as above. Frame improvement most cost effective in cold climates; somewhat effective in moderate climates; usually not cost effective in cooling-dominated situations.
4. "Heat mirror" IGU, clear, wood frame	22.37	0.25 *0.29*	4.0 *3.44*	0.49 *0.39*	0.61 *0.46*	1.24 *1.18*	The additional air space in this specialized low-E unit increases the insulating value four times over a single pane and 25% over a standard low-E unit. Has all the same other low-E benefits discussed in #3. This product available in other Tv and SC values. Also significantly reduces ultraviolet transmission more than other low-E products due to the plastic layer. Probably cost effective in cold climates; may or may not be cost effective in other climates.
5. Argon gas fill 2-pane IGU, wood frame	17.48	0.45 *0.46*	2.2 *2.2*	0.82 *0.66*	0.80 *0.60*	0.98 *0.91*	Very small insulating improvement over a standard double pane. Gas fills work best when used in combination with a low-E coating. Usually not cost effective without a coating.

Table XIII-1
Generic Glazing/Window Comparisons

PRODUCT	$/SF[1]	U-Value[2]	R-Value[3]	SC[4]	T_v[5]	K_e[6]	Benefit[7]
6. Low-E + argon fill 2-pane IGU, clear, wood frame	19.50	0.25 *0.30*	4.0 *3.33*	0.74 *0.59*	0.68 *0.51*	0.98 *0.86*	Gas fill combined with a low-E coating increases the insulating value four times over a single pane and 25% over a standard low-E unit. Has all the same other low-E benefits discussed in #3. Performance is similar to the Heat Mirror for a slightly lower cost.
7. Aerogel fill 2-pane IGU	?	0.10	10.0	?	?	?	Would improve insulating value 10 times over single pane and 5 times over standard double pane for the same weight as a double pane; insulating and comfort benefits comparable to an insulated wall, with the added benefit of light transmission. Disadvantage is haze or light diffusion; material is not completely transparent. Cost unknown and cost effectiveness questionable as only extremely cold climates appear to significantly benefit from very high R value windows.
8. Evacuated 2-pane IGU	?	0.05	20.0	0.82	?	?	The highest R value currently known of in window R&D, this insulating value would exceed even a well-insulated wall for potentially the same weight and potentially similar appearance of a standard double pane. A major obstacle is structural integrity of the unit due to atmospheric pressure. Visible transmittance is unknown because current R&D prototypes maintain integrity with a grid of glass supports throughout the unit. These glass beads could also create a thermal bridging effect, significantly decreasing performance. Cost will likely be high due to manufacturing complexities, and cost effectiveness is questionable as only extremely cold climates appear to significantly benefit from very high R value windows.

Table XIII-1
Generic Glazing/Window Comparisons

PRODUCT	$/SF[1]	U-Value[2]	R-Value[3]	SC[4]	T_v[5]	K_e[6]	Benefit[7]
9. Superwindow IGU, wood frame	32.39	0.12 *0.20*	8.1 *4.9*	0.62 *0.51*	0.52 *0.40*	1.19 *0.78*	The only currently available product uses 2 low-E coatings on 2 suspended plastic films for a 4-layer/ 3-gap unit. Highest R value commercially available, with further comfort improvements over a standard low-E window. Possibly cost effective in cold climates only. Other options at lower costs are just beginning to enter the market.
10. Vinyl frame for standard 2-pane IGU.	13.33	0.48 *0.46*	2.1 *2.17*	0.82 *0.65*	0.80 *0.60*	0.98 *0.92*	Improves the whole-window U value over the center-of-glass value (instead of degrading it) for this type of glazing.
10a. Vinyl frame for low-E 2-pane IGU.	15.35	0.31 *0.32*	3.2 *3.2*	0.74 *0.58*	0.68 *0.58*	0.92 *0.88*	Better whole window U value than with other frames.
10b. Vinyl frame for low-E plus argon 2-pane IGU.	15.98	0.25 *0.28*	4.0 *3.6*	0.74 *0.59*	0.68 *0.51*	0.92 *0.86*	Better whole window U value than with other frames.
Solar Control							
11. Gray tint single pane, alum frame	7.72	1.09 *1.25*	0.92 *0.80*	0.71 *0.71*	0.45 *0.36*	0.63 *0.51*	Reduces shading coefficient. Always cost effective in air conditioned cooling dominated buildings. However, this is a standard approach with only modest performance. Usually outperformed by the other entries below. All color classes of tints share the feature of only modest shading coefficient values, due to absorption and reradiation of solar energy. Furthermore, gray and bronze tints tend to reduce a higher fraction of visible energy than solar infrared, yielding a darker tint for a given level of solar control than with blue or green colors (Ke>1 means glazing is favoring daylight - see #13). Helps reduce glare over clear glazing.

Table XIII-1
Generic Glazing/Window Comparisons

PRODUCT	$/SF[1]	U-Value[2]	R-Value[3]	SC[4]	T_v[5]	K_e[6]	Benefit[7]
12. Reflective coating single pane, alum frame	9.00*	0.90 *1.03*	1.11 *0.97*	0.28 *0.33*	0.14 *0.12*	0.50 *0.36*	Drastically reduces shading coefficient over clear glass and significantly outperforms tints for solar control, due to reflection of solar energy rather than absorption. Always cost effective in air conditioned cooling dominated buildings. However, this is a standard approach with a high penalty in visible transmission losses (this class of solar control has the lowest Ke values). These glazings can appear very dark and/or mirrored. Helps reduce glare over clear glazing.
13. Spectrally selective tint single pane, alum frame	8.70*	1.09 *1.26*	0.92 *0.79*	0.58 *0.60*	0.66 *0.52*	1.14 *0.87*	Reduces shading coefficient while maintaining high visible transmittance. Cost effective based on shading coefficient savings alone, but further cost benefit is available via daylighting (high visible transmittance permits elecric lighting to be reduced). May also be chosen for view clarity or appearance. Helps reduce glare over clear glazing.
14. Spectrally selective low-E coating 2-pane IGU, aluminum frame	18.00*	0.30	3.33	0.52	0.70	1.35	Almost the best available product for low shading coefficient together with high visible transmission (very high Ke values). Low-E coating has further benefit for heating and comfort concerns. Probably cost effective when used with daylighting controls in an air conditioned building. Probably cost effective under these circumstances in both cooling and heating dominated buildings provided that daylighting can offset a significant amount of energy. May also be chosen for view clarity or appearance. May help reduce glare over clear glazing.
15. Selective tint + selective coating 2-pane IGU, aluminum frame	20.00*	0.29	3.4	0.38	0.60	1.58	Best available product for low shading coefficient together with high visible transmission (highest Ke values available). Same benefits as above and similar cost effectiveness estimate. May also be chosen for view clarity or appearance. Helps reduce glare over clear glazing.

Table XIII-1
Generic Glazing/Window Comparisons

PRODUCT	$/SF[1]	U-Value[2]	R-Value[3]	SC[4]	T_v[5]	K_e[6]	Benefit[7]
16. Silk screen white frit line pattern 50% coverage on clear IGU	9.40*	n/a	n/a	.48	.39	.81	Significantly reduces shading coefficient without color or mirror effects. Performance values and appearance characteristics vary widely depending on pattern, frit color, and glass color. Price would be higher for custom patterns. At this price, cost effective in cooling dominated air conditioned buildings.
17. Retrofit film on single pane clear	1.70 B	0.69	1.45	0.43	0.50	1.16	Glue-on reflective film reduces shading coefficient for relatively low cost. Also improves U value. Wide range of products available. Durability is an issue, however payback periods are usually less than five years. Reduces UV transmission. Helps reduce glare over clear glazing.
Daylight Control							
18. Prismatic device	?	?	?	?	?	?	Possibly increases daylighted area by sending light more deeply into the perimeter spaces. Cost effectiveness is unknown. Benefit in glare reduction and lighting quality.
19. Holographic device	?	?	?	?	?	?	R&D testing has indicated the possibility of doubling the area of daylighted perimeter space, with benefits in both electrical lighting and cooling savings, especially at peak demand periods. Many performance and manufacturing issues have yet to be resolved, and cost effectiveness is not yet clear. A successful product would benefit glare reduction and overall lighting quality.

Table XIII-1
Generic Glazing/Window Comparisons

PRODUCT	$/SF[1]	U-Value[2]	R-Value[3]	SC[4]	T_v[5]	K_e[6]	Benefit[7]
Switchables							
20. Thermochromic	?	?	?	varies	varies	varies	Could reduce cooling or heating loads by optimizing solar gain. However, may do so at the expense of daylighting savings. Cost effectiveness unknown.
21. Photochromic	?	?	?	varies	varies	varies	Could reduce lighting loads by optimizing daylight transmission. However, may do so at the expense of cooling loads. Cost effectiveness unknown.
22. Liquid crystal	60.00	0.58	1.72	0.66 on 0.65 off	0.67 on 0.60 off	1.0 on 0.92 off	The only product currently available yields little or no energy savings. Primary use is for privacy control. Manufacturer may soon discontinue this product.
23. Electrochromic	25.00*	?	?	varies	varies	varies	Superior energy performance over any existing glazing product is predicted, both in energy and in peak electricity demand. Payback is estimated by an R&D firm at 5 years, with optimistic economic assumptions and for a warm climate application.

Footnotes

1 Average generic product cost (not installed cost) as quoted by manufacturers to a builder constructing 50 typical U.S. homes, in 1991 U.S. dollars, per square foot of the product. Figures will vary depending on many project-specific factors. Cost comparison relationships between various products will vary over time, particularly as leading-edge technologies gain market share. Unless otherwise noted, costs were compiled by Charles Eley Associates for the California Energy Commission, as reported in the CEC report "Life-Cycle Cost Analysis; Building Envelope Energy Conservation Measures, Low-Rise Residential Buildings."

2. Winter nighttime **center-of-glass** value. Units are Btu/hr·ft^{2}·°F. Values in *italics* are **whole window** U-values, calculated by Window 4.0 for a 3'x4' window, which takes into account the affect of the frame. Spacer effects are not included here.

3. Reciprocal of the U value. Units are Hr·ft^{2}·°F/ Btu. For **center of glass**. Values in *italics* are **whole window** R-values, based on U-value calculated by Window 4.0 for a 3'x4' window, which takes into account the affect of the frame. Spacer effects are not included here.

4. Shading coefficient, given as a percentage, calculated as solar heat gain for this glazing divided by solar heat gain for 1/8 inch clear glass. **Glazing** only. Values in *italics* are **whole window** SC values, calculated by Window 4.0 for a 3'x4' window, which takes into account the affect of the frame.

5. Visible transmittance, the percentage of solar energy in the visible spectrum (approximately 380-720 nm) that is transmitted. **Glazing** only. Values in *italics* are **whole window** TV values.

6. Glazing luminous efficacy, the dimensionless ratio of visible transmittance to shading coefficient (K_e=T_{vis}+SC). Values in *italics* are calculated with the **whole window** SC and TV values.

7. Benefit is summarized in broad terms and includes some general indication of cost benefit when possible. It is not possible to provide more detailed life cycle or payback estimates for windows in a general manner; cost benefit analysis for window technologies must be performed on a case by case basis, due to the number of variables affecting building performance, and the range of values those variables can take.

* R&D estimate.

? Unknown and unable to estimate.

B From 1991 Means Construction Data, Western Edition.

Appendix

Specific products used as models for the generic glazing data (performance characteristics only; costs are from generic tables in the Eley/CEC reference and do not correlate with the brand names below).

1. LOF clear 1/4" uncoated.

Insulating: all without tint or add'l coatings, 1/4" glass and 1/2" air gap or equiv.

2. Cardinal clear IGU
3. Cardinal LoE-178 #2 IGU with air
4. Southwall (high transmittance) HM77, with 1/8" glass and 3/8" air spaces, for total of 1" assembly and a better comparison to standard 1/4" glass/1/2" air IGU.
5. Cardinal clear IGU, with argon
6. Cardinal LoE-178 IGU with argon
7. 1/2" of aerogel in an IGU. Hypothetical.
8. Hypothetical.
9. Southwall Superglass 1" clear.
10. Vinyl frame with fiberglass spacer. NOTE: the $4.50 delta cost over stnd IGU may be vastly overpriced, due to biases in quotes for the CEC report.

Solar Control

11. LOF gray 1/4" monolithic
12. Cardinal SS-114 monolithic (silver on clear, stainless steel sputtered coating, high reflectance)
13. LOF Evergreen 1/4" monolithic
14. Cardinal LoE2-171 (clear), air fill, 1/4" glass with 1/2" gap
15. Cardinal LoE2 270 (green), air fill, 1/4" glass with 1/2" gap
16. Viracon clear IGU with 50% white frit line pattern.
17. 3M Scotchtint Plus All Season Window Film IN50BR (Bronze).
18. N/A
19. Hypothetical product.
20. Suntek Cloud Gel.
21. Hypothetical product.
22. Taliq Varilite Vision Panel with 1" clear IGU. Taliq is no longer in business?
23. Hypothetical product.

XIV. SOLAR CONTROL GLAZING

END-USE: Fenestration

SECTOR: Commercial, Residential

DESCRIPTION

Performance: Buildings with significant cooling loads generally need to reduce heat admitted through the windows. The largest contributor to this heat transfer is direct solar radiation. An important additional component is energy re-radiated by the glass as it warms up. The total energy transfer is known as *solar heat gain*. Glazing solar control strategies include tints, coatings, films, opaque patterns and integrated louvers. The key glazing performance characteristic measuring solar heat gain reduction is the *shading coefficient* (SC). Shading coefficients for common products typically range from 1.0 to 0.2.

Consumer Utility: Solar control glazings reduce cooling costs while benefiting occupant thermal comfort. Reduced cooling loads can result in lower HVAC system equipment costs and less need for additional exterior or interior shading devices. Solar control glazings additionally can assist in reducing brightness glare of the glazing.

Development Status: Tints and reflective coatings have long been available from every glass manufacturer in a wide range of aesthetic appearances. Spectrally selective tints and spectrally selective low-E coatings have entered the market more recently and are available from several manufacturers. Solar control retrofit film is widely available. Integrated louvers are available from a few specialized window manufacturers. Silk screened glazing is also a specialty item available from a few manufacturers.

COSTS

Costs vary by technology, market region, size of order and other factors. In general, solar control glazing is more expensive than basic glazing, however, payback periods are usually short or not a concern. First costs are usually offset by savings in downsized HVAC equipment.

IMPLEMENTATION

Installation: Applications include: a) commercial buildings in almost all climates; b) residential buildings in temperate, warm or hot climates; and c) any application where comfort or glare may be an issue. Solar control glazings are no different in terms of application than a clear glazing. However, there is an aesthetic aspect to tints and reflective coatings (a color or mirror effect).

Maintenance: Maintenance and durability of tints and coatings is generally not a concern. Multi-layered units may require better sealants and improved manufacturing quality control.

Conservation Programs: Many incentive programs, building codes and standards in the U.S. encourage the use of solar control, particularly for commercial construction. Utility rebates, generally paid per square foot of glazing, often eliminate the added first cost.

ENVIRONMENTAL ISSUES

Use of solar control glazing results in improved energy efficiency and reduced energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

XIV. SOLAR CONTROL GLAZING

1. Description

1.1 Performance Characteristics

Buildings with significant cooling loads generally can benefit from reducing heat admitted through the windows. Heat passes through a window in three ways: conduction/convection due to a temperature difference between inside and outside; heat absorbed by the window re-radiated into the space; and solar radiation directly transmitted through the glass. The first two mechanisms can be inhibited with the use of an insulating technique (see Insulating Glazing section). However, direct solar radiation is by far the largest contributor to heat gain through the windows. The total heat transfer due to both solar energy directly transmitted through the window and the secondary component of re-radiated energy from the warmed glass is known as ***solar heat gain***. Solar heat gain is inhibited through solar control strategies.

This section treats solar control as accomplished within the glazing material or enclosed in the window unit. Another common approach to solar control, using exterior or interior shading devices, is not covered here. White miniblinds have been found to have shading coefficients of up to 0.44 (Cutter Information Corporation, 1992).

There are several different approaches to glazing solar control:

Tints: Tinted glass, also known as "heat absorbing" glass, utilizes energy absorbing materials dispersed throughout glass, that reduce the shading coefficient and give color to the glass. These materials absorb in all wavelengths of the solar spectrum. There are several standard tint compositions that appear generally bronze, gray, blue or green in color. Blue and green glasses tend to transmit a relatively high fraction of visible light versus infrared (K_e = 0.8-1.0), whereas gray and bronze are the opposite (K_e = 0.4-0.8). All of these glazings are commonly used, although often not effectively for performance optimization. Shading coefficients for tints typically range from 0.5 to 0.8. Both the shading coefficient and the K_e of a tint can be improved if the tint is used in the exterior pane of an insulating unit, since the absorbed energy will be re-radiated outdoors.

Reflective coatings: Reflective glazings ("mirror" glass) utilize a surface coating that may be deposited any number of ways to reflect and absorb incident energy. Glass surface coatings were developed for superior solar control over tints, with the more effective coatings working principally by reflecting rather than absorbing incident solar energy. Less absorbed energy means less heat is re-radiated into the space. Like some standard tints, typical reflective coatings do not distinguish between the visible and infrared portions of sunlight. The mirror-like appearance of these glazings when viewed from the exterior is the indication that most visible light is being reflected away. Reflective coatings are commonly used and they can be deposited on either clear glass or tinted substrates. The properties are highly dependent on the materials used for the coatings and the process by which they are deposited. These, in turn, vary widely depending on whether the coating must survive in an exposed environment or whether it will be protected in the air space of a double glazed unit. The higher performance coatings generally are metallic films and require some protection within a sealed glass unit. Shading coefficients for reflective coatings typically range from 0.12 to 0.6. Reflective coatings for commercial buildings create glare for their neighbors and are not permissible in some cities. Reflective coatings are generally the poorest in daylight selectivity (K_e = 0.5).

Spectrally selective tints: The natural selectivity for visible light of the blue and green family of tints (this includes aqua) has been exploited and extended in some new products recently available on the market with $K_e > 1.0$. Spectrally selective tints, used on their own in single- or multi-pane assemblies, are limited in efficacy improvement potential and may not move much beyond the current K_e maximum of 1.18 for commercial single-pane tinted products. Further daylight selectivity can be achieved through the addition of sputtered low-E coatings, which are usually used in insulating glass units (although lower performance pyrolytic low-E coatings may be applied to single-pane glazing). The application of conventional reflective coatings to tinted glazings generally reduces K_e.

Spectrally selective low-E coatings: These are currently the best commercially available glazing technology for solar control without the loss of useful daylight. Original low-E coatings, developed for cold climate applications, have been modified for use in cooling conditions. The first low-E coatings were designed to be highly transparent throughout the solar spectrum and more reflective in the energy region of longwave infrared, where room temperature heat radiates. Selective low-E coatings also reflect shortwave infrared energy, thereby also blocking direct solar radiation. These coatings can be considered a new type of reflective glazing; since they reflect primarily in the invisible infrared, these transparent coatings achieve a high degree of reflectivity without a mirror effect and without color. The shading coefficient is lowered even more when a selective low-E coating is used together with a selective tint. Depending on the coating and degree of tint, shading coefficients may go as low as 0.2 and K_e as high as 1.58. Selective low-E coatings are the soft-coat sputtered type and require protection within an IGU or laminated glass unit.

Enclosed louvers: The solar control protection offered by traditional venetian blinds can be duplicated within the glazing assembly. Very small louvers are contained within the 1/2 inch air gap in a two-pane window. The louvers are usually fixed in place. A thicker product is available with operable louvers.

Integrated louvers: Integrated louvers, similar to venetian blinds, have fixed microblinds embedded in the 1/4 inch width of a single piece of glass. This is a research prototype only and not commercially available.

Silk screens: A ceramic pattern can be applied to the glass surface, through a silk screen process, to make part of the glazing more opaque without leaving an overall tint. The result is a reduction of overall shading coefficient.

Solar control retrofit films: The shading coefficient of an existing glazing can be increased by gluing solar control film to it, for example to convert clear glass to tinted or reflective glass. Tinted and/or aluminized polyester solar control films for retrofit were first introduced in the early 1960s and have been a common retrofit. Various metals can be used to control color or reduce shininess. Newer coatings have improved in spectral selectivity, and films are also available with lower performance low-E coatings.

1.2 Consumer Utility

Solar control glazings reduce cooling costs while increasing occupant thermal comfort. Reduced cooling loads can result in lower HVAC system equipment costs and less need for additional exterior or interior shading devices. Solar control glazings additionally can assist in reducing brightness glare due to the window. Solar control glazings, especially those which employ a low-E coating on plastic film, often reduce ultraviolet transmission, which causes fading of upholstery and other interior finishes and can damage artwork.

1.3 Development Status

Tints and reflective coatings have long been available from every glass manufacturer in a wide range of aesthetic appearances (interior and exterior apparent color, interior and exterior mirror effects, degree of visible transparency, etc.). Spectrally selective tints and spectrally selective low-E coatings have recently entered the market and are available from several manufacturers. Solar control retrofit film is widely available. Integrated louvers and silk screened glazing are available from a few specialized window manufacturers.

2. Cost of Equipment

Costs vary by technology, market region, size of order and other factors. In general, solar control glazing is only slightly more expensive than clear single-pane glazing. However, payback periods are usually very short or not a concern. First costs are usually more than offset by savings in downsized HVAC equipment. In addition, utility rebate programs also offset product cost. See Table XIII-1 for comparative costs and benefits.

3. Implementation

3.1 Installation

Applications include: a) commercial buildings in almost all climates; b) residential buildings in temperate, warm or hot climates; and c) any application where comfort or glare may be an issue. Solar control glazings are no different in terms of application than a clear glazing. However, there can be the appearance of color or a mirror effect.

3.2 Maintenance

Maintenance and durability of tints and coatings is generally not a concern. Glue-on retrofit films occasionally require replacement. Multi-layered units need to keep out moisture, which may require better sealants and improved manufacturing quality control.

3.3 Conservation Programs

Many incentive programs in the U.S. encourage the use of solar control, particularly for commercial construction. These rebates often eliminate the added first cost for the measure. Rebates are generally paid per square foot of glazing. Some energy codes in the U.S., in addition to ASHRAE Standard 90.1, either require or encourage solar control glazing for certain applications.

4. Environmental Issues

Use of solar control glazing results in improved energy efficiency and reduced energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

5. References

See Table XII-1 in chapter XII (Daylight Control Glazing).

6. Major Manufacturers

See Table XII-2 in chapter XII (Daylight Control Glazing).

XV. SWITCHABLE GLAZING

END-USE: Fenestration

SECTOR: Commercial, Residential

DESCRIPTION

Performance: Switchable glazings incorporate optically active materials whose solar-optical properties change in response to variations in temperature, incident light, and/or applied electrical current. These glazings switch from a transparent state to tinted or opaque upon the appropriate stimulus. The use of switchable glazings in commercial buildings should reduce the peak electricity demand and the cooling, lighting, and total electricity consumption associated with windows, in comparison with all other window technologies currently available. There are four major categories of switchables: electrochromic, liquid crystal, thermochromic, and photochromic. The most promising of these are electrochromic coatings, which can be actively controlled to modulate sunlight using an applied voltage. The maximum benefits can be obtained when the glazings are used in conjunction with dimmable electric lighting controls.

Consumer Utility: These glazings address occupant needs for comfort, privacy and performance as well as utility load management requirements. Switchable glazings may eliminate the need for window treatments such as blinds or drapes for privacy, solar control and glare. The dynamic nature of these glazings is a departure from traditional static windows. However, in most aspects, these glazings are otherwise nearly equivalent to the conventional windows they replace.

Development Status: Most switchable glazings are currently only laboratory technologies. However, a few high performance products will likely be introduced commercially within the next few years. Two types of products currently available have only modest energy saving ability.

COSTS

Switchable glazings are likely to be significantly more expensive than traditional products until adequate market share is gained. Product developers expect switchables to eventually become competitive with traditional insulating glazing units, especially if elimination of traditional solar control mechanisms (blinds, etc.) is included in the calculation. Current developer projections estimate an optimistic payback of five years. Developers estimate a payback of three years if first cost savings are taken in reduced HVAC equipment, or if utility incentive programs offset added costs.

IMPLEMENTATION

Installation: Installation of electrochromics is generally equivalent to that for standard windows, with the additional significant aspect of electric control. These windows must be connected to a power supply and must be provided with override switches or other forms of manual control. This can be further complicated if window control is tied in with the building comfort systems.

Maintenance: Product life is unknown at this time.

Conservation Programs: None currently in existence.

ENVIRONMENTAL ISSUES

Use of switchable glazing results in improved energy efficiency and reduced energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

XV. SWITCHABLE GLAZING

1. Description

1.1 Performance Characteristics

Switchable glazing materials fall into two general categories: (1) passive materials stimulated by environmental factors (e.g., temperature or light), and (2) active materials stimulated by an electrical signal from the occupant, building automation system, etc.

Passive materials

Thermochromic glazing: solar-optical properties change from a clear, high transmittance state to a darker or cloudy, diffusive, low transmittance state as the glazing temperature rises. Some thermochromics are inorganic, thin-film coatings such as vanadium oxide, while others are polymeric gels sandwiched between window glazing layers.

Photochromic glazing: solar-optical properties vary with incident solar radiation, darkening as the intensity of radiation increases. The most common photochromics are silver halides incorporated into the matrix of the glazing, which have been used in sunglasses for years.

Active Materials

Liquid crystal glazing: electrically activated device where suspended liquid crystal molecules modify their alignment or their light absorbing properties upon changes in level of applied current. The material is clear when the power is on, cloudy when off. Because they require continuous power to maintain their clear state, these materials are not a highly attractive energy saving technology.

Electrochromic glazing: solar-optical properties change due to insertion and removal of ions in the electrochromic layer of a multilayer product, upon a change in an electric field. Electrochromic materials can be maintained at any grade of tint between transparent and fully darkened. They require voltage only to change condition.

Currently, studies indicate that electrochromics hold the most promise for reducing electricity use and peak demand in buildings over conventional window systems. Electrochromics can (depending on control method) dynamically modify their visible transmittance and shading coefficient, and can be driven by either lighting or cooling needs. Performance is optimized when electrochromics are used together with dimmable electric lighting controls. They further have the potential to be linked with the building's automation system and to adjust continuously to changing exterior environmental conditions, occupant preferences and utility needs (e.g., real time pricing).

In any climate or application where window-related electricity consumption and peak demand are high, electrochromics will show efficiency benefits. The savings improve as cooling or lighting loads increase. As window size increases, the relative benefits of electrochromic windows over their static counterparts increases, regardless of climate. Energy and demand savings for north orientation applications are modest; the most significant benefit in these cases is improved glare control.

1.2 Consumer Utility

Switchable glazings, especially electrochromics, will provide significant benefits in terms of improved thermal and visual comfort for building occupants, although these benefits are difficult to quantify.

1.3 Development Status

Most switchable glazings are currently only laboratory technologies. However, a few products may be introduced commercially within the next five years. An acrylic skylight thermochromic product is available with a modest switching effect (transmittance change of 15%). In photochromics, both glass and plastic products are under development. Manufacturers have not yet found a method for economically scaling up this long-standing technology to the required sizes for building windows. A liquid crystal product is currently available, however, its primary purpose is for privacy, with possible negligible or negative energy savings. Electrochromics are still in development, however, these are expected to be available within the next several years.

2. Cost of Equipment

Cost is difficult to estimate prior to commercialization. It is likely that switchables will be significantly more expensive than a traditional product. Some information on costs is provided in Table XIII-1.

Developers are aiming for an electrochromic product at an incremental cost of $15/sf more than standard double glazing. However, in the case of electrochromics, the energy benefits should pay off fairly quickly, with an payback of five years in a warm climate. If first cost savings in HVAC equipment downsizing and the elimination of sun control devices such as shades or blinds are included (which typically cost $5-10/sf plus periodic maintenance), the payback time may drop to three years. In addition, utility rebates could further reduce the added first costs of these products. Any consideration of payback should give attention to the non-quantifiable benefits of improved occupant comfort and building market value.

3. Implementation

Switchable glazings can serve more than one purpose at once, optimizing comfort, energy performance, lighting needs and privacy or view factors. They are probably most appropriate for cooling-dominated, daylighted applications or for applications where visual comfort (glare control) is critical.

3.1 Installation

Installation of electrochromics is generally equivalent to that for standard windows, with the additional complication of electric control. These windows must be connected to a power supply and must be provided with override switches or other forms of manual control. This can be further complicated if window control is tied in with the building comfort systems.

3.2 Maintenance

Product life and maintenance issues are unknown at this time.

3.3 Conservation Programs

Because these products are still in development, there are currently no utility programs for their application. At this time, electrochromics show the most promise for energy use and peak demand reduction. Incentive programs could provide significant cost offsets for electrochromics and would be appropriate for both the commercial and the residential sector.

4. Environmental Issues

Use of switchable glazing results in improved energy efficiency and reduced energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

5. References

See Table XII-1 in chapter XII (Daylight Control Glazing).

6. Major Manufacturers

See Table XII-2 in chapter XII (Daylight Control Glazing).

XVI. TREE PLANTING

END-USE: Heating and Cooling

SECTOR: Residential

DESCRIPTION

Performance: In addition to their aesthetic value, trees also have an added value for saving energy, both in heating and cooling climates. These savings accrue because trees block the sun in the summer and block the wind in the winter. Case studies in recent years have documented dramatic differences in cooling energy use between houses on unlandscaped and landscaped sites. Computer studies have shown that trees are also beneficial in cold climates because their wind-shielding benefits more than balance their shading penalties.

Consumer Utility: Tree planting increases property values and provides increased comfort.

Development Status: Available.

COSTS

Typical cost to establish a tree in the U.S. is $50 to $100, depending on local conditions and tree type. The $100/tree cost, plus the assumption that three trees are planted per house, imply simple payback times of less than four years for homes built before 1973, and less than 5.4 years for homes built during the 1980s.

IMPLEMENTATION

Installation: In heating-dominant locations, trees should be planted in the direction of the prevailing winter winds to reduce air infiltration. If possible, avoid planting trees on the south side of the house that would block winter sunshine. Even a deciduous tree bereft of leaves in the winter will block up to 40% of the incident sunshine.

In cooling-dominant locations, trees should be planted on the sunny sides of the house and close enough to shade the windows and walls. Trees on the west side are particularly effective because they can keep the low rays of the setting sun from streaming in the windows.

Maintenance: In temperate climates, deciduous trees drop leaves which may need to be collected and disposed of or composted. Compost from leaves can be used for fertilizer, which may offset some or all of the costs of collecting the leaves. If selected properly for their location and climate, trees will need watering only for the first 5 to 10 years. Trees usually live 50 to 150 years.

Conservation Programs: Electric utilities in California now offer rebates for tree planting in cooling load dominated climates.

ENVIRONMENTAL ISSUES

Trees sequester carbon and reduce pollutant emissions from power generation. If leaves are not composted, they may take up significant landfill space. Planting many trees can alter the local environment and lower summertime temperatures through evapotranspiration. This will counteract the urban heat island phenomenon, make it more comfortable for humans, and reduce air-conditioning demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

XVI. TREE PLANTING

1. Description

1.1 Performance Characteristics

Many horticulturists and landscape architects have noted that in addition to their aesthetic value trees, shrubs, and lawns also have an added value for saving energy, both in heating and cooling climates. Case studies in recent years have documented dramatic differences in cooling energy use between houses on unlandscaped and landscaped sites (Laechelt and Williams, 1976; Buffington, 1979; Parker, 1981).

Below, we show calculations from a detailed study of the effect of trees on residential energy use (Huang et al., 1990). This analysis uses a sophisticated building energy simulation model (DOE-2.1D) to estimate heating and cooling energy savings for older buildings (those built before 1973) and new buildings (built in the 1980s). The seven cities chosen for the DOE-2.1D simulations represent the range of climate conditions found in the U.S., with heating degree-days ranging from 220 to 8000 and cooling-degree days from 600 to nearly 4000.

Of the seven cities, Minneapolis was chosen to represent cold locations with long severe winters; Chicago and Pittsburgh represent temperate locations with cold winters and short but hot summers; Washington represents temperate locations with moderate winters and humid summers; Miami represents hot-humid locations; Phoenix represents hot-arid locations; and Sacramento represents temperate locations with hot arid summers.

Both shading and wind-shielding effects of trees affect the heating and cooling energy requirements of buildings. Current understanding is sufficient to model the shading effects. However, models to simulate the wind-shielding effect of trees are still very general. The model used in this study correlates the windspeed to the overall percentage cover of trees and buildings within a neighborhood. Although this model distinguishes between summer and winter conditions, it does not differentiate the wind-shielding effects of nearby trees from those due to the average neighborhood tree density.

The results show that during the heating season, the wind-shielding benefits of trees are always greater than the penalties of reduced solar gain from tree shading. However, the heating energy savings are not particularly large since windspeeds in residential neighborhoods are substantially reduced already by the buildings. For the less tightly built pre-1973 houses in the predominantly heating locations of Chicago, Minneapolis, Pittsburgh, and Washington (Table XVI-1), the reductions in heating energy use from three trees per house are from 8 to 16 MBtu, or 4% - 8% of the total heating bill. This represents savings of around $40 to $100 a year. For the tighter 1980s houses (Table XVI-2), the savings are reduced by one half to two thirds, resulting in savings from 3% to 11%. For the three cooling-dominant locations (Miami, Phoenix, and Sacramento) the savings in heating energy use are negligible.

During the cooling season, wind shielding is detrimental since it decreases convection of heat away from the building, which causes higher temperatures on building surfaces exposed to the sun and more conductive heat gain into the building. This cooling energy increase was also reported in another computer study of the impact of vegetation on residential building energy use (McPherson, 1987). The increased heat gain due to higher surface temperatures is evident in the pre-1973 houses in hot sunny locations. At the reduced windspeeds of 30% tree canopy cover, wind-shielding increase cooling energy use by 240 kWh in Phoenix and 206 kWh in Sacramento.

Table XVI-1
Energy and Cost Savings for pre-1973 Houses in 7 Different Climates

		1 Tree			*2 Trees*			*3 Trees*			
		10%tree canopy (energy savings, () = increase)			20% tree canopy (energy savings, () = increase)			30% tree canopy (energy savings, () = increase)			SPT 3 trees (30%) assuming $100/tree cost
Location	Base case (not savings)	wind only (Δ)	wind + shade (Δ)	(%Δ)	wind only (Δ)	wind + shade (Δ)	(%Δ)	wind only (Δ)	wind + shade (Δ)	(%Δ)	(years)
Chicago, IL (1400 sq. ft. house)											
Heating (MBtu)	**193.4**	9.6	8.0	4.2	15.7	11.5	6.0	20.1	15.6	8.1	
Cooling (kWh)	**2447**	14	194	7.9	29	373	15.2	35	492	20.1	
Final E (MBtu)	**201.4**	9.6	9.0	4.5	15.7	12.5	6.2	20.1	17.6	8.8	
Energy costs ($)	**1275**	50	64	5	83	103	8.1	107	138	10.8	2.2
Miami, FL (1400 sq. ft. house)											
Heating (MBtu)	**14.6**	0.2	0.1	0.7	0.4	0.3	2.1	0.4	(0.1)	(0.5)	
Cooling (kWh)	**11062**	124	705	6.4	181	1172	10.6	219	1951	17.6	
Final E (MBtu)	**51.6**	0.2	2.1	4.1	0.4	4.3	8.3	0.4	5.9	11.5	
Energy costs ($)	**1053**	12	62	5.9	18	104	9.9	22	170	16.1	1.8
Minneapolis, MN (1400 sq. ft. house)											
Heating (MBtu)	**166.4**	7.3	6.1	3.7	12.1	8.5	5.1	15.4	11.3	6.8	
Cooling (kWh)	**1825**	0	123	6.7	(16)	273	15	(22)	359	19.7	
Final E (MBtu)	**172.4**	7.3	7.1	4.1	12.1	9.5	5.5	15.4	12.3	7.1	
Energy costs ($)	**997**	39	39	3.9	64	61	6.1	81	81	8.1	3.7
Phoenix, AZ (1400 sq. ft. house)											
Heating (MBtu)	**69**	0.8	0.9	1.4	1.4	2.0	2.9	1.7	1.5	2.1	
Cooling (kWh)	**13058**	(78)	618	4.7	(148)	1031	7.9	(240)	1682	12.9	
Final E (MBtu)	**113**	0.8	2.9	2.6	0.4	5.0	4.4	0.7	7.5	6.6	
Energy costs ($)	**1654**	(5)	67	4.1	(9)	114	6.9	(16.)	178	10.8	1.7
Pittsburgh, PA (1600 sq. ft. house)											
Heating (MBtu)	**192.2**	6.2	4.2	2.2	10.3	6.0	3.1	13.1	8.2	4.2	
Cooling (kWh)	**1728**	(46)	182	10.5	(70)	316	18.3	-(94)	417	24.1	
Final E (MBtu)	**197.2**	5.2	4.2	2.1	(9.3)	7.0	3.6	12.1	9.2	4.6	
Energy costs ($)	**1024**	29	29	2.8	48	44	4.3	61	59	5.8	5.1
Sacramento, CA (1400 sq. ft. house)											
Heating (MBtu)	**103.9**	2.8	1.8	1.7	5	3.6	3.4	6.2	2.4	2.3	
Cooling (kWh)	**3865**	(79)	230	6	(151)	382	9.9	(206)	681	17.6	
Final E (MBtu)	**116.9**	2.8	2.8	2.4	5	5.6	4.8	6.2	5.4	4.6	
Energy costs ($)	**915**	4	35	3.8	5	61	6.7	4	91	9.9	3.3
Washington, DC (2000 sq. ft. house)											
Heating (MBtu)	**187.5**	8.7	7.7	4.1	14.4	10.3	5.5	18.3	13.9	7.4	
Cooling (kWh)	**4020**	10	272	6.8	3	545	13.6	(1)	753	18.7	
Final E (MBtu)	**200.5**	8.7	8.7	4.3	14.4	12.3	6.2	18.3	15.9	7.9	
Energy costs ($)	**1629**	63	74	4.5	104	112	6.9	131	152	9.3	2.0

(1) Final E = Final Energy. Electricity measured as site energy at 3412 Btus/kWh.

Table XVI-2
Energy and Cost Savings for 1980s Houses in 7 Different Climates

		1 Tree			*2 Trees*			*3 Trees*			
		10% tree canopy (energy savings, () = increase)			20% tree canopy (energy savings, () = increase)			30% tree canopy (energy savings, () = increase)			SPT 3 trees (30%) assuming $100/tree cost
Location	Base case (not savings)	wind only (Δ)	wind + shade (Δ)	(%Δ)	wind only (Δ)	wind + shade (Δ)	(%Δ)	wind only (Δ)	wind + shade (Δ)	(%Δ)	(years)
Chicago, IL (2000 sq. ft. house)											
Heating (MBtu)	**107.6**	7.6	6.3	5.8	12.2	8.9	8.2	15.6	11.7	10.9	
Cooling (kWh)	**2126**	7	151	7.1	10	289	13.6	9	394	18.5	
Final E (MBtu)	**114.6**	7.6	7.3	6.4	12.2	9.9	8.6	15.6	13.7	12	
Energy costs ($)	**799**	38	49	6.1	63	79	9.9	80	106	13.3	2.8
Miami, FL (1600 sq. ft. house)											
Heating (MBtu)	**3.7**	0.2	0.2	4.6	0.3	0.3	8.5	0.4	0.2	6.2	
Cooling (kWh)	**8658**	190	506	5.8	314	876	10.1	390	1365	15.8	
Final E (MBtu)	**32.7**	1.2	2.2	6.6	1.3	3.3	10.1	1.4	5.2	16	
Energy costs ($)	**780**	18	46	5.9	30	79	10.1	36	121	15.5	2.5
Minneapolis, MN (2000 sq. ft. house)											
Heating (MBtu)	**97.1**	4.6	3.6	3.8	7.5	4.4	4.5	9.5	5.9	6.1	
Cooling (kWh)	**1543**	(7)	126	8.2	(12)	231	15	(30)	286	18.5	
Final E (MBtu)	**102.1**	4.6	4.6	4.5	7.5	5.4	5.3	9.5	6.9	6.7	
Energy costs ($)	**609**	24	27	4.4	39	37	6.1	49	48	7.9	6.3
Phoenix, AZ (1600 sq. ft. house)											
Heating (MBtu)	**13.7**	0.5	0.5	3.4	0.9	0.9	6.4	1.1	0.7	5	
Cooling (kWh)	**7992**	44	364	4.6	62	641	8	46	900	11.3	
Final E (MBtu)	**40.7**	0.5	1.5	3.6	0.9	2.9	7.1	1.1	3.7	9.1	
Energy costs ($)	**876**	8	39	4.5	11	69	7.9	10	95	10.8	3.2
Pittsburgh, PA (1600 sq. ft. house)											
Heating (MBtu)	**77.6**	2.8	1.5	1.9	4.6	1.7	2.2	5.8	2.4	3.1	
Cooling (kWh)	**1301**	(22)	146	11.2	(39)	235	18.1	(54)	302	23.2	
Final E (MBtu)	**81.6**	2.8	2.5	3.1	4.6	2.7	3.3	5.8	3.4	4.2	
Energy costs ($)	**440**	13	14	3.2	21	19	4.3	27	26	5.9	11.5
Sacramento, CA (1600 sq. ft. house)											
Heating (MBtu)	**44.5**	1.9	1.1	2.6	3.2	2.3	5.1	4.1	1.5	3.3	
Cooling (kWh)	**2756**	(13)	160	5.8	(40)	278	10.1	(66)	441	16	
Final E (MBtu)	**53.5**	1.9	2.1	4	3.2	3.3	6.1	4.1	3.5	6.5	
Energy costs ($)	**520**	6	23	4.4	9	42	8.1	10	57	11	5.3
Washington, DC (2200 sq. ft. house)											
Heating (MBtu)	**81.6**	5.4	4.5	5.6	8.7	5.7	7	11.1	7.6	9.3	
Cooling (kWh)	**3007**	16	193	6.4	12	381	12.7	8	519	17.3	
Final E (MBtu)	**91.6**	5.4	5.5	6	8.7	7.7	8.4	11.1	9.6	10.5	
Energy costs ($)	**796**	39	45	5.7	64	67	8.4	80	90	11.3	3.3

(1) Final E = Final Energy. Electricity measured as site energy at 3412 Btus/kWh.

Trees substantially reduce peak heating and cooling power requirements. In heating seasons, the wind-shielding effect of trees results in a lower infiltration rate and, hence, a lower heating power requirement. During the cooling season, both the wind-shielding and shading effects of trees contribute to lower peak cooling power consumption. Huang et al. (1990) show that for pre-1973 houses, the electric peak power savings are about 0.5 kW to 1.3 kW for planting three trees (30% foliage cover). The savings are similar for the 1980s houses, ranging from 0.5 kW to 1.5 kW for three trees. Peak heating power reductions are of less interest to utility companies, since they occur in the early morning hours.

Huang et al. (1990) indicate that planting trees around a house reduces both heating and cooling loads. During the winter, the wind-shielding effect of trees more than compensates for the decreased solar gain and makes a recognizable, albeit limited, contribution in reducing winter heating energy use. During the summer, the impact of tree shading in reducing summer cooling energy use is many times larger than the negative effects of reduced windspeed, and can typically lower cooling costs by up to 20%.

Previous work investigated the potential of trees for reducing cooling energy use and increasing comfort by cooling entire neighborhoods through evapotranspiration (Huang et al., 1987). This study suggests that the evaporative effect of trees on building cooling loads may be substantially larger than other effects, such as shading. There is indirect evidence for this effect in urban meteorological studies showing that urban areas near city parks are generally cooler than other neighborhoods (Landsberg, 1981; Oke, 1987). Using a simple meteorological model, the Huang study showed that the climate modifications from increased tree coverage might reduce building cooling loads more than tree shading alone. However, due to the complex nature of the urban microclimate and tree physiology, the potential effect of evapotranspiration needs to be further studied and better documented.

1.2 Consumer Utility

Trees block the sun and cool the air (through evapotranspiration). Quality of life and ability to remain comfortable are improved through tree planting. In addition to their energy savings and environmental benefits, trees have been shown to increase property values.

1.3 Development Status

Trees of most varieties are commonly available through local garden stores or mail order houses.

2. Cost

Gas and electricity prices vary depending on the location and year. To analyze the net cost savings associated with the changes in building energy use resulting from tree planting, we used 1986 local utility prices for each city as recorded by the National Association of Home Builders Research Foundation for the ASHRAE-90 residential energy standards committee (Johnson 1986). These utility prices are average rates computed for typical residential space conditioning use, taking into account rate schedules and marginal costs charged by different utility districts. The 1986 prices for natural gas and electricity for the seven cities are given in Table XVI-3.

Table XVI-3
Average Fuel Prices for Gas and Electricity in 1986

Location	Gas ($/MBtu)	Electricity ($/kWh)
Chicago, IL	$5.10	$0.1185
Miami, FL	$5.74	$0.0877
Minneapolis, MN	$5.36	$0.0583
Phoenix, AZ	$2.78	$0.1015
Pittsburgh, PA	$4.93	$0.0447
Sacramento, CA	$4.44	$0.1175
Washington, DC	$7.20	$0.0697

In pre-1973 houses, planting three trees around a house can reduce space conditioning energy use in the cold climates by 4% - 8%, corresponding to savings of $60 to $140 per year. In the hot climates, the corresponding energy reductions are 13% - 20%, and the annual savings $90 - $170. Peak power savings are 4% - 15% for heating and 6% - 22% for cooling.

The cost to plant a 5-10 foot tree in a residential area is between $50 (without labor costs) and $100 (with labor costs) per tree in the U.S. (R.S. Means, 1992). In the most expensive case ($100/tree), Table XVI-1 shows that the simple payback time (SPT)[3] for planting three trees next to a pre-1973 house ranges from 1.7 years in Phoenix to 5.1 years in Pittsburgh, with all cities but Pittsburgh having a simple payback time of less than four years.[4] For 1980s houses (Table XVI-2), the SPTs are higher because the houses are better insulated and have more efficient heating and cooling equipment. The simple payback times for planting three trees assuming costs of $100/tree range from 2.5 years in Miami and Chicago to 10.5 years in Pittsburgh, with all cities but Pittsburgh having simple payback times of less than 5.4 years.

These simple calculations ignore potential costs from leaf disposal, and also ignore the increased property value usually associated with having trees in residential areas. If the leaves are composted, net benefits may accrue to the homeowner, because the compost can be used for fertilizer. Little is known about the magnitude of these effects.

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3. Simple payback time is equal to the capital cost of an efficiency option divided by the expected annual energy savings. The SPT is a crude measure of the time it will take for a given investment to pay for itself. It does not account for the time value of money.

4. We use the energy cost savings associated with wind plus shading effects in the SPT calculations.

3. Implementation

3.1 Installation

Tree species must be carefully selected for suitability to climate, and landscaping should be designed to maximize the effect of the trees. Labor needed for initial installation is typically 1/2 hour to 1 person-hour, depending on the size of the tree. Little is known on total labor requirements over the life of a tree.

3.2 Maintenance

Deciduous trees drop leaves, which must be collected and composted or otherwise disposed of. If selected properly for their location and climate, trees will need watering only for the first 5 to 10 years. Compost from leaves can be used for fertilizer, which may offset some or all of the costs of collecting the leaves.

3.3 Conservation Programs

Numerous utility companies have implemented tree planting programs varying from informational brochures on tree selection and planting to donating trees and sponsoring neighborhood plantings. Utilities in California are now giving rebates to customers who plant trees in residential areas. The Pacific Gas and Electric Company (in Northern California) gives $5 rebates towards the purchase of trees for those customers who live in hot weather areas.

4. Environmental Issues

Trees sequester carbon and reduce pollutant emissions from power generation. If leaves are not composted, they may take up significant landfill space.

Planting many trees can alter the local environment and lower summertime temperatures through evapotranspiration. This will counteract the urban heat island phenomenon, make it more comfortable for humans, and reduce air-conditioning demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

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6. Contacts

American Forestry Association. Neil Sampson, Executive Vice President. (202)667-3300.

U.S. Environmental Protection Agency. Office of Policy Analysis, Climate Change Division, 401 M Street, SW (PM-221), Washington, DC 20460. (202)260-8825

XVII. ADVANCED INSULATION

END-USE: Heating and Cooling

SECTOR: Commercial, Residential

DESCRIPTION

Performance: Flexible panels filled with gases (air, argon, or krypton) can be sized and shaped for cavities found in conventional construction. Gas Filled Panels (GFPs) can also be used in composite with rigid polymer foam insulations for applications such as insulated sheathing and foam core panels. These panels offer higher R-values per inch than conventional building insulation. The most likely initial application is in manufactured housing.

Consumer Utility: In manufactured housing, interior space is at a premium. GFPs offer R/thickness values significantly higher than standard practice, which allows the use of thinner walls for a given R value. In addition to saving space, higher R/thickness values also conserve costly structural lumber and offer reduced weight.

Development Status: Not commercial, but prototypes and license rights are available.

COSTS

Costs for argon-filled GFPs. are comparable to CFC blown foam insulation for equivalent insulation levels. Costs for air-filled GFPs are greater than glass fiber insulation for a given wall thickness, but such GFPs allow attainment of significantly greater R-values for a given wall thickness.

IMPLEMENTATION

Installation: Similar to conventional insulation products.

Maintenance and durability: GFPs should require little maintenance once installed. Product lifetimes are a function of barrier material gas transmission rates and sealing quality.

Conservation Programs: None.

ENVIRONMENTAL ISSUES

Use of advanced insulation can result in improved energy efficiency and reduced energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

Argon-filled GFPs can achieve insulation values similar to that of CFC blown foams, without the use of CFCs (which are believed to harm the earth's ozone layer and contribute to global climate change). Gas fills are inert and harmless. Other environmental effects depend on the character of the barrier/baffle materials and their associated durability.

XVII. ADVANCED INSULATION

1. Description

1.1 Performance Characteristics

Gas-Filled Panels, or GFPs, are a high-performance and environmentally-benign insulating material. GFPs employ a low-emissivity baffle structure inside a barrier envelope containing gas at atmospheric pressure. The baffle structure is an assembly of thin polymer sheets that minimize solid conduction and effectively eliminate radiative and convective heat transfer. High-performance GFPs use gases with thermal conductivities lower than that of air. Gases such as argon or krypton are hermetically sealed within the baffle and retained at atmospheric pressure with the use of high-performance gas barrier materials. Gas-filled panel technology evolved by applying the principals used in high-performance window glazings to opaque insulation (Arasteh et al., 1989; Arasteh et al., 1990).

Improving building energy efficiency typically involves higher levels of thermal performance for envelope insulation; this requires either thicker insulation or higher performance (R-value per inch) products. Increasing the thickness of building components to accommodate more insulation can be inconvenient and costly. Insulation with greater R-value per unit thickness can thus avoid changing building techniques and improve energy efficiency.

The highest performance building insulations currently in use are two-part, thermoset polymer foams blown with chlorofluorocarbons (CFCs); these have performance levels around R-7.2/in. (50.0 m-K/W). CFCs are to be phased out by 1996 because of their detrimental effect on the earth's ozone layer. This phase-out will force the use of alternative blowing agents that have higher thermal conductivity and may not fully solve the ozone depletion problem. The performance of foams blown with alternative agents will be around 0 to 25% depending on which blowing agents are used and on the success of techniques to decrease radiative heat transport. These high-performance thermoset polymer foams, and widely used but lower performance glass fiber insulations, may become problematic for use in buildings because of rising environmental concerns over recyclability and toxicity of building materials. Non-CFC blown thermoplastic foams (such as polystyrene) may avoid environmental problems, however their performance levels are typically R-5.0/in. (43.7 m-K/W) or less.

Gas Filled Panel research focuses on investigating the three components of GFPs (baffle, barrier, and gases) and on fabricating functional prototypes for refrigerator/freezers (R/F). Approximately 200-300 separate baffles and 150 GFPs have been produced since research began in late 1989. This technology summary presents results of GFP research to date that are relevant to the use of GFPs in building applications. GFP designs for buildings are likely to differ from designs for R/F applications because of differences in installation, stiffness requirements, and optimal performance per thickness.

Panel Components

Gas Filled Panels are comprised of three primary components: (1) baffles, (2) barriers, and (3) gas fills. The resulting hermetic panel devices can have a variety of thermal, geometrical, and mechanical properties. Each of these three components is discussed and relevant results of current research on panels for R/F applications are presented. Note that for patent and proprietary reasons, specifics of baffle geometries and dimensions are not disclosed here.

Baffle Component

A baffle functions to suppress radiation and convection, enabling the performance potential of low-conductivity gases to be realized. "Compartmentalizing" the gas contained within the panel minimizes convective heat transfer. Compartmentalizing is accomplished by constructing the baffle out of solid, thin sheet material assembled into a three-dimensional form, creating multiple layers and cavities. The dimensions of the layers and cavities are selected so that convection is minimized within a cavity or compartment. Low-emissivity cavity surfaces eliminate significant radiative heat transfer. Low-emissivity surfaces are inexpensive and available in the form of roll stock, vacuum metalized thin polymer films. Such films typically have an aluminum coating 100 to 500 angstroms thick with an emissivity of about 0.04. Solid conduction through the baffle structure can decrease insulating performance; this effect is minimized by employing solid conduction paths that are long relative to the panel thickness. Baffles can use a variety of different geometries, material types and thicknesses resulting in different mechanical properties and thermal performances.

We distinguish between stiff and flexible baffles. Self-supporting and supportive baffles are termed stiff, and "inflatable" self-locating baffles are termed flexible. Panels with flexible baffles can be lightweight (0.4 lb./ft3 [6.4 kg/m3]), collapsible, and expandable. Panels with stiff baffles maintain their shape when handled, are heavier (2 lb./ft3 [32.0 kg/m3]), and require vacuum purging when gas filled. Research on GFPs for applications in composite with rigid foam has focused on stiff baffles in order to help maintain panel geometry during the foaming operation. Research at LBL focused on maximizing baffle stiffness without compromising thermal performance while using only conventional, low-cost materials such as papers and simple thermoplastic films. Baffles with some stiffness and good thermal performance were developed, but we found that GFPs are unlikely to be as stiff as rigid closed-cell polymer foams.

Barrier Component

The barrier component is comprised of gas-barrier polymer films that are wrapped or formed to create a hermetic panel of desired size and volume. Effective barrier materials are critical for the long-term thermal performance of GFP insulation. The film must act as an effective barrier to gas diffusion; diffusion is "two-way" with air gases driven into the panels and the desired low-conductivity gases driven out of the panels. The film should be a good barrier to moisture permeation and have low thermal conductivity, be non-degradable, durable, non-extensible, sealable, and flexible or formable. The film must also be relatively low cost and easily run on fabrication equipment.

Candidate Barrier Films

A gas filled approach to insulation is viable because of recent advances in polymer barrier film technology within the food packaging industry. A variety of barrier materials and film configurations are commercially available that could be used for GFPs. We distinguish two approaches to gas barriers: vacuum coatings and polymer barrier resins. Vacuum coatings include very thin layers of deposited materials such as aluminum, silicon oxide, and manganese oxide. Polymer barrier resins include: ethylene vinyl alcohol (EVOH) and polyvinyl alcohol (PVA or PVOH). Polyvinylidene chloride (PVdC) has potential applications for GFPs as a moisture barrier. Ethylene Vinyl Alcohol (EVOH) is a copolymer of ethylene and polyvinyl alcohol so EVOH without ethylene is PVA. EVOH is available with ethylene content ranging from 26% to 48%; lower ethylene contents provide a greater gas barrier. However, the higher the percentage of ethylene in EVOH, the easier it is to process and the less it is affected by moisture. Both EVOH and PVA can be oriented to increase crystallinity and their barrier performance.

In general, mono-layer films of a single polymer will not be able to meet the demands of GFPs, so combinations of different polymers will be used to create one multilayer film structure that has an adequate gas barrier, is strong and can be sealed. Multilayer films can be produced by either lamination or coextrusion. For example, an EVOH-based coextruded film may have the structure: nylon/adhesive/EVOH/adhesive/EVOH/ adhesive/ polyethylene. One commercially available PVA-based laminated film has the structure: oriented polyester/adhesive/PVdC/oriented PVA/PVdC/adhesive/ polyethylene.

Barrier Film Performance Capabilities

The gas barrier performance requirements for such insulation applications are within the capabilities of commercially available materials and existing technologies (Griffith and Arasteh, 1992). The performance characteristics of all likely barrier films over long periods of time is largely unknown.

Gas Fill Component

Thermal conductivity through the gas is the primary mode of heat transfer in a GFP. R-values of GFPs depend strongly on the type of gas fill. Gases with relatively higher molecular weight typically have lower thermal conductivity. Monatomic gases (such as krypton or xenon) have lower conductivity than polyatomic gases of equal (and typically higher) molecular weight because of the additional rotational and vibrational energies associated with molecules. Although the thermal conductivity of a gas is important, other characteristics of the gas must also be acceptable. Gases cannot be flammable or toxic, nor can they condense at temperatures (at about atmospheric pressure) within ambient temperature ranges. Gases must be stable and cannot react problematically with other components of the panel. If is desirable for the gases to have little or no ozone depletion potential or greenhouse warming potential. The components and processes used to produce a gas should also be relatively benign.

Information on all commercially available gases was compiled using the methodology described in Griffith and Arasteh (1992) to assess what gases could be used for GFPs. For each gas in Table XVII-1, we used a non-ideal k-value of 0.0092 Btu-in/hr-ft2-F (0.0013 W/m-K) to estimate the level of performance attainable with a flexible GFP designed for maximum R-value. For air this corresponds to a performance level of R-5.25/in (36.4 m-K/W) compared to a measured performance level of R-5.2/in. (36 m-K/W). Because of their environmentally benign nature, argon and krypton are preferred gases with projected GFP performance capabilities of R-7.6/in. (52.7 m-K/W) and R-13.4/in. (93.0 m-K/W), respectively. Current krypton production capacity presents a problem for its use as an alternative for large scale applications currently using CFC blown foams. However, large quantities of krypton exist in the total atmosphere at a concentration of 1.14 parts per million. Argon is inexpensive and abundant as it is 0.93% of the atmosphere. A number of chlorinated and fluorinated hydrocarbons could be employed in GFPs but their potential for environmental harm is a problem. Note that the relatively good performance of air-filled GFPs makes for a soft failure mode should the barrier component fail.

Table XVII-1
Thermal Performance and Cost Estimates of Gases for GFPs

Gas	Ideal Still Gas Thermal Resistivity		Projected GFP Thermal Resistivity		Approximate Gas Cost	
	hr-ft2-F/Btu-in	(m-K/W)	hr-ft2-F/Btu-in	(m-K/W)	$/ft2-in	($/m3)
air	5.5	(38.2)	5.25	(36.4)	0.000	(0.0)
argon	8.1	(56.2)	7.6	(52.7)	0.003	(1.3)
CO2	8.7	(60.4)	8.0	(55.5)	0.010	(4.2)
N2O	8.9	(61.8)	8.2	(56.9)	0.025	(10.6)
CF4	9.0	(62.5)	8.3	(57.6)	0.400	(170.0)
SF6	10.3	(71.5)	9.4	(65.2)	0.150	(63.5)
HFC-134a	10.3	(71.5)	9.4	(65.2)	0.400	(170.0)
HCFC-22	13.1	(90.9)	11.7	(81.2)	0.040	(16.9)
CFC-12	15.3	(106.2)	13.4	(93.0)	0.100	(42.4)
krypton	15.3	(106.2)	13.4	(93.0)	1.200	(508)
xenon	25.6	(177.7)	20.8	(144.4)	22.4000	(9500)

(1) thermal performance measured at 77 deg. F (25 deg. C)

GFP Applications for Buildings

Gas-Filled Panel technology can yield a variety of products useful for building envelope insulation applications. Table XVII-2 lists examples of panel configurations, and applications as well as performance and cost estimates. Typical panel sizes are given; "L" indicates variable or continuous lengths. GFP configurations are presented in Table 2 to illustrate potential products from Gas-Filled Panel technology; most of these have not been developed or tested as of this writing because research has focused on Refrigerator/Freezer applications. R-value projections are estimates based on measured GFP performances and still-gas thermal conductivity values. Preliminary cost estimates are "cost to manufacture" based on material component costs and simple multipliers for added production expenses.

Table XVII-2
Potential Applications, Projected Performance, and Cost Estimates for GFPs in Buildings

GFP Embodiment Designation	Example Application	Typical Panel Size	Projected R-Value	Cost Estimate
		inch (m)	hr-ft2-F/Btu (m2-K/W)	$/ft2 ($/m2)
1 Flexible Argon Expansion "Batt"	Wall Cavity, 2x4 Studs	15 x 3 x L (0.38 x 0.08 x L)	22 (3.9)	0.80 (8.60)
2 Flexible Argon Expansion "Blanket"	Attic, Floor 2x6 Joists	48 x 5.5 x L (1.22 x 0.14 x L)	38 (6.7)	1.05 (11.30)
3 Flexible Air Expansion "Batt"	Wall Cavity, 2x4 Studs	15 x 3.5 x L (0.38 x 0.09 x L)	18 (3.2)	0.50 (5.40)
4 Flexible Air Expansion "Blanket"	Attic, Floor 2x8 Joists	48 x 7.5 x L (1.22 x 0.19 x L)	38 (6.7)	0.85 (9.10)
5 Stiff Air Baffle	Wall Cavity 2x4 Stud	15 x 3.5 x L (0.38 x 0.09 x L)	18 (3.2)	1.00 (10.80)
6 Stiff Argon	Foam Core Composite Panels	15 x 3 x 15 (0.38 x 0.08 x 0.38)	22 (3.9)	1.50 (16.10)
7 Stiff Argon	Foam Composite, Rigid Panels	15 x 1 x 15 (0.38 x 0.03 x 0.38)	7.4 (1.3)	0.70 (7.50)
8 Stiff Krypton	Foam Core Composite Panels	15 x 2 x 15 (0.38 x 0.05 x 0.38)	26 (4.6)	3.30 (35.50)
Glass fiber batt	Wall Cavity 2x4 Studs	15 x 3.5 x L (0.38 x 0.09 x L)	11 (2.0)	0.14-0.18 (1.5-1.9)
CFC blown foam	Wall Cavity 2x4 Studs	15 x 3.5 x L (0.38 x 0.09 x L)	24 (4.2)	0.70-1.75 (7.5-18.8)

(1) Cost estimates for gas filled panels are "cost to manufacture" based on material component costs and simple multipliers for added production expenses (see Griffith and Arasteh 1992 for details).
(2) Costs of Glass fiber and CFC blown insulation are taken from Griffith et al. 1991, Table 2.

Flexible Expansion GFP Embodiments

Items (1) through (4) in Table XVII-2 are based on a GFP design referred to as a flexible expansion GFP. These panels employ thin baffle materials resulting in panels that are very lightweight: densities can be around 0.4 lb/ft3 (6.4 kg/m3). Performance projections are based on R-5.2/in (36.1 m-K/W) for air fill and R-7.4/in. (51.4 m-K/W) for argon fill. The added cost of argon panels arises from the use of high-performance gas-barrier materials, not from the cost of argon. The panels can be collapsed and evacuated to aid in shipping, handling, and gas filling. The "batt" GFPs are sized similar to glass-fiber batts with an interference fit in the width (15 in. width for 14.5 in. cavity). GFP "batts" have flanges for fastening to studs. "Blanket" embodiments could be configured to fit onto joists, centered on common distances. Products could be distributed in collapsed, continuous roll form and subsequently cut and sealed to length. With correct installation such panels could serve as vapor retarders, eliminating the need for such a component in addition to insulation. Panels are flexible and can deflect around cavity obstructions.

Stiff Air Baffle

Stiff baffle components, item (5) of Table XVII-2, could be used without a barrier component. Such air filled insulation material could be produced in a variety of thicknesses and be cut and installed in the same fashion as conventional insulations. Performance is projected at up to R-5.2/in. (36.1 m-K/W) or about the same as thermoplastic rigid foam insulations. The material would be self supporting, mildly stiff and have a density of about 2.0 lb/ft3 (32 kg/m3).

Stiff Argon and Krypton GFPs

Stiff GFPs, items (6), (7), and (8) in Table XVII-2, are currently being developed for Refrigerator/Freezer appliance applications and may also be useful in conjunction with foam for panelized building systems and rigid foam insulated roofing and sheathing products. Modular panels of convenient shapes and sizes would be used in composite with non-CFC foam. Foam would serve as the structural element in the GFP/foam composite; GFPs would boost performance and reduce quantities of foam that would otherwise be required.

1.2 Consumer Utility

In manufactured housing, interior space is at a premium. GFPs offer R/thickness values significantly higher than standard practice, which allows the use of thinner walls for a given R value. In addition to saving space, higher R/thickness values also conserve costly structural lumber and reduce weight. As shown in Table XVII-2, R values of R-18 to R-22 (English units) can be achieved in buildings using 2x4 studs. Conventional glass fiber or mineral wool insulation would require the use of 2x6 studs to achieve comparable R values.

1.3 Development Status

Prototypes of this product are available, but no commercial products are on the market. The GFP technology is available for license from Lawrence Berkeley Laboratory's Technology Transfer Office (see address below).

2. Costs

Table XVII-2 compares the estimated costs of GFPs to glass fiber batts and CFC blown insulation. Glass fiber batts installed in the standard 2x4 stud configuration cannot achieve R-values that approach even those of the air-filled GFPs. The air-filled expansion batt GFP in this configuration costs $0.30 to $0.40/square foot more than glass fiber, but delivers an R-value that is 64% higher than that of the glass fiber insulation. The CFC blown insulation can achieve R-values comparable to that of the argon-filled GFPs, at a cost that is comparable to that of the argon GFPs (at the low end of the blown CFC cost range) and much higher than that of the argon GFPs (at the high end).

3. Implementation

3.1 Installation

GFPs should be well suited for applications in manufactured housing, since they can be installed relatively easily. GFPs by nature are individual hermetic plastic enclosures of discrete shapes and sizes. Products will tend to be uniform and modular, thus lending themselves best to closer tolerance construction and repeated cavity geometries found in modular and panelized manufactured housing. This sector of the industry can also place a higher premium on weight and component thickness and may be faster to adopt new types of building materials.

The large scale manufacture of GFPs will not require the development of any substantially new materials processing technologies. The use of finished, roll stock material components makes the assembly of the panels relatively simple. Existing machinery from the food packaging industry such as thermoformers, impulse heat sealers, and bag making and wrapping machines can be used to manufacture GFPs at high line rates. Complete machines, known as form, fill and seal equipment, routinely used in the food packaging industry, can rapidly encapsulate the baffle with a barrier material, vacuum flush, gas back fill, and seal the panel into a final product.

Prototypes tested to date have been filled with a simple gas-filling apparatus. Fill percentages using this apparatus are generally in the 85%-98% range. Advanced gas-filling methods using vacuum chambers are expected to yield GFPs with fill fractions of 98%-100%; these gas fill percentages have been met in both the window and food industries using vacuum chamber equipment.

3.2 Maintenance

GFPs should require little maintenance once installed. Product lifetimes are a function of barrier material gas transmission rates and sealing quality. Barrier materials used in prototypes to date are taken from applications in the food packaging industry. Further development of these barrier materials are expected to produce barriers with even lower transmission rates, which should make them more desirable for use in GFPs. While GFPs should be designed for high lifetime gas retention rates, it should be noted that a failure of the barrier material will degrade the performance of a GFP to no less than that of an air GFP, R 36 m-K/W (R 5.2 hr-ft^2-F/Btu-in). On the other hand, the failure of the barrier material in some vacuum insulations may degrade performance to significantly lower R-values.

3.3 Conservation Programs

No programs exist--product is still in prototype stage.

4. Environmental Issues

Use of advance insulation can result in improved energy efficiency and reduced energy demand. Reduced energy demand has the environmental benefits of reduced consumption of fuels used in power plants, reduced emissions from existing power plants, and reduced need for construction of new power plants.

Argon-filled GFPs can achieve insulation values similar to that of CFC blown foams, without the use of CFCs (which are believed to harm the earth's ozone layer and contribute to global climate change). Gas fills are inert and harmless. Other environmental effects depend on the character of the barrier/baffle materials and their associated durability.

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