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Cost Effective Building Envelope Options for Reducing Cooling Loads in Commercial Buildings

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ABSTRACT

This paper explores 23 different commercial building envelope options for energy savings and cooling load reduction in five locations with varying climates in the United States (Chicago, Los Angeles, Miami, Phoenix and Washington D.C.). These options include insulation increases, use of shading devices, use of window films, double-pane windows and “superwindows”, sealing of infiltration leaks, and application of "cool" exterior wall paints and roof coatings. The annual energy savings, maximum demand reduction, utility savings and payback periods are examined for each option.

Maximum energy savings potential was found from options which increase the insulation of buildings in cold climates, and from use of “superwindows” to replace single-pane windows. Unfortunately, the most energy-efficient options were not the most cost-effective. Options with the lowest payback periods were window films, window shades and planting of trees. Fewer than 30% of the options studied had payback periods shorter than 10 years. However, many options become more viable when combined with a necessity for replacement, maintenance, or a desire to improve the comfort or appearance of a building.

INTRODUCTION

In response to the United States' moratorium on production of CFC refrigerants in January of 1996, many chillers used to cool commercial buildings will need to be replaced or retrofitted. This necessity is an good opportunity to improve the overall energy efficiency of any building, with hope of being able to downsize the new or retrofitted chiller for even more energy savings in the future. This overall systems approach to chiller replacement is called an "integrated chiller and building retrofit" and involves making cooling and delivery system improvements in conjunction with cooling load reductions.

Most comprehensive commercial building retrofits improve the heating and cooling plant and delivery systems by installing new fans and motors, variable speed drives, energy management systems, improved cooling towers, changing system temperatures, and making use of "free cooling" mechanisms such as heat recovery wheels and evaporative cooling. But load reduction strategies are almost exclusively dedicated to upgrading to energy-efficient lighting, or by making a few high energy use appliances more efficient. Reducing cooling loads by improving the building envelope is seldom performed. This paper explores various building envelope options and estimates their energy savings and financial feasibility.

Available building envelope options run from the time-tested but recently forgotten shade tree, to new high-technology options such as spectrally selective window films. Twenty-three commercially available envelope options are studied in this work, including:

- Increased insulation levels
  - R30 roof insulation
  - R11 wall insulation and R19 roof insulation
  - R19 wall insulation and R20 roof insulation
- Shading devices used with single- and double-pane windows
  - planting of young trees
  - shade from mature trees
  - external awnings
  - internal window blinds
- Window options used with single- and double-pane windows
  - clear window film
  - bronze or gray window film
  - spectrally selective window film
  - double-pane window installation
  - "superwindow" installation
- Miscellaneous envelope options
  - sealing of infiltration leaks
  - "cool" walls, painting exteriors white
  - "cool" roofs, coating roofs with white coatings

Many studies have been done to evaluate the effect of increasing insulation levels, but most of these focus on residential buildings. Penn (1992) recommends that the attic of a residence be insulated first, followed by the walls and floors. In the "Consumer Guide to

Home Energy Savings" Wilson and Morrill say that insulation of residential spaces should pay for itself within five years, depending on the climate and on the type of fuel used for heating and cooling.

In addition to adding home insulation, sealing of infiltration leaks is commonly recommended as a way to save energy and improve the comfort of a residence (Wilson and Morrill, 1995). These leaks are found around doors and windows, baseboards, cabinets, fireplaces, electrical outlets, pipes and recessed lighting.

Shading devices get less credit for contributing to building energy savings. In the recent revival of the use of "green" solutions to provide building cooling there has been some work done in examining the effect of trees and landscaping on residential energy use (McPherson and Simpson, 1995; Huang, Akbari and Taha, 1990). Window blinds and awnings are promoted for use with high-tech systems which automatically manipulate these shading devices to deliver the correct amount of light with the least amount of heat.

New window technologies have recently emerged which promise great energy savings. Window films have been in use for 15-20 years but the most energy-efficient films also block desirable visible light as well as the undesirable heat from infra-red radiation. Recent breakthroughs in film development have resulted in spectrally selective films which block infra-red rays but transmit visible light (Frost, Arasteh and Eto, 1993). Advances in window development have also come up with the "superwindow", a double-pane window filled with argon gas, with spectrally selective coatings and thermally efficient frames (Kosko, 1991; Davids, 1990; Jackson, 1994).

The "electrochromic" window (not studied in this report) promises to save even more energy when it becomes commercially available (Sullivan et al., 1996). This window will have glazing which can change optical properties in response to light and solar radiation levels.

Reflective, or “cool”, roof and wall coatings have been studied in both commercial and residential buildings and have been found to save significant amounts of energy (Konopacki et al., 1997; Parker & Barkaszi, 1994; Akbari et al., 1993; Akbari et al., 1992).

Many studies explore these options for different locations, building types and using various methods of analysis. Unfortunately, no one resource comprehensively analyses all options available to commercial buildings consistently in different climates. This work attempts to fill that gap by modeling the energy use of a commercial building in five locations using 23 different building envelope options. Cost estimates are also gathered for the purchase and installation of each of these options. The annual energy savings and payback periods of each option will be estimated. The most energy efficient and financially attractive building envelope retrofits will be listed.

ANALYSIS

Building energy modeling is performed to evaluate the effects of various envelope options. A building model is run in five locations representing different climate zones: Chicago (heating-dominated), Los Angeles (temperate), Miami (hot and humid), Phoenix (hot and dry), and Washington D.C. (mixed heating and cooling). The envelope options studied are: varying insulation levels in walls and roof; use of shading devices, i.e. awnings, trees, window blinds; use of window films and "superwindows"; sealing infiltration paths; and using "cool" coatings on the building walls and roof.

An energy analysis is performed using DOE 2.1E, a building energy modeling code developed at Lawrence Berkeley National Laboratory and in widespread use for energy analysis (Winkelmann et al., 1993). A square, three-story office building is modeled measuring 170 feet wide by 170 feet deep by 36 feet high, for a total of 86,700 square feet of space on three floors. The building is represented by five zones: a square core zone of 140 feet by 140 feet, and four rectangular perimeter zones of 15 feet by 155 feet. The building is assumed to have 6 feet wide by 4 feet high windows around the entire perimeter on all three floors, 28 windows per floor per wall for a total of 336 windows over 8064 square feet. The wall construction consists of, from outside to inside, 1 inch stucco, 1/2 inch plywood, permeable felt building paper, insulation of various R-values, and 1/2 inch drywall. The roof layer consists of 3/8 inch built-up roofing, 1/2 inch plywood, a 5 foot attic space, insulation of various R-values, and 1/2 inch drywall.

This building is first run with R7 wall insulation, R11 roof insulation, and single-pane windows, and the heating and cooling equipment is sized for this configuration in each of the five building locations. Equipment capacities are kept constant for each location in each successive run with various envelope options. A gas furnace is used for heating in all locations with 1.35 BTUs of heat delivered for each BTU of gas energy burned. An electric chiller is used for cooling with a coefficient of performance of 2.78. The heating setpoint is 68 F, the cooling setpoint is 78 F. Electric supply air fans use 0.0003 kW per cfm of air delivered to the building, and are turned off at night and on weekends.

Lighting is assumed to use 1.4 watts per square foot. Lighting schedules vary from 100% usage on weekdays from 8 am to 4 pm, down to 10% usage at night and on weekends. Lighting schedules remain constant regardless of any window shading or films used. Electrical equipment is assumed to use 0.7 watts per square foot throughout the building, with a schedule of use similar to that for lighting. One person per 100 square feet of floor space, with zero occupancy on nights and weekends is assumed.

Utility rates are programmed into the DOE-2 model for each building location. These rates include energy charges, demand charges (both often at varying for the amount and time of use), monthly customer charges, energy cost adjustments, surcharges and taxes. Electric rates come from the CSA Electric Rate Database (January 1995), and gas rates from the American Gas Association Rate Service (May 1996).

Modeling assumptions for the various envelope options are discussed below. The options are added to the energy model one at a time and are not studied cumulatively. The insulation options studied are all compared to a base case building with R7 wall insulation, R11 roof insulation and single-pane windows. All other envelope options are compared to a more typical base case of R11 walls, R19 roof , and single- and/or double-pane windows.

Comparisons of total building energy use savings, maximum demand reduction, utility cost savings, and payback period are made for each envelope option.

Insulation Level Variation

Different insulation options are studied and their energy use compared to the base case of R7 wall insulation and R11 roof insulation. Three cases are studied: increase of roof insulation to the R30 level; increase of wall insulation to R11 and roof to R19; increase of wall insulation to R19 and roof to R30.

When retrofitting an existing building, insulation will most likely be blown into cavities between wall struts and into the attic. Labor costs of drilling and patching holes in walls to blow insulation through amount to $0.50 per square foot. To upgrade walls to R11 from R7 costs about $0.45 per square foot in materials, for a total including labor of $15,445. To upgrade to R19 costs $0.70 per square foot, or $19,590. Costs of material and labor to upgrade roof insulation to R19 is $0.50 per square foot, for $14,450. To increase roof insulation to R30 from R11 costs $0.80 per square foot including labor, for $23,120 (Brunk Industries, Oakdale, California).

Use of Shading Devices

Three different shading devices are considered in this study: trees, awnings and window blinds. The shading options are compared to two base cases with R11 walls and R19 roof and either single-pane or double-pane windows.

Six deciduous trees are assumed to be planted on the east, south and west sides of the building, for a total of 18 trees. These trees are assumed to block 80% of the sun's energy when in leaf from April through October, and to block 30% of the sun's energy from November through March (McPherson & Simpson, 1995). Young trees are assumed to be 16 feet tall and each cover a circle 10 feet in diameter from a height 6 feet off the ground, for a coverage of about 30% of a 170 foot long by 10 foot high wall section. Mature trees are assumed to be 31 feet high, with 25 foot diameters 6 feet off the ground, covering 70% of the area of a 170 foot by 25 foot wall section. All trees are planted 15 feet away from the building walls with about 30 feet between trees.

The price of young, 16-foot trees, planted in ready-to-go soil (no concrete to break up), is $450 per tree, $8,100 for 18 trees (Professional Tree Care Company, Berkeley, California). The cost of mature, 31-foot trees is assumed to be triple that of a young tree, or $1,350 per tree, or $24,300 for 18 trees.

Awnings are assumed to be hung just above the windows on all three floors of the east, south and west sides of the buildings. Awnings are assumed to be 4.2 feet long (the third side of a 3 foot by 3 foot Pythagorean triangle) and to tilt out from the walls at a 45 angle. The awnings are assumed to be fixed in place all year and transmit no sunlight.

Awning prices vary considerably depending on the materials chosen. They range in price from $59,900 for installed awnings on three sides of the building, to $105,840 when fire resistant materials are used (Maze Awnings and Canvas Products, Oakland, California; Sunset Companies, Livermore, California). The cost value used assumes a midpoint price of $82,870.

Horizontal "mini-blinds" are assumed to be placed in all windows. Window blinds are modeled as window transmission coefficients with 80% of solar energy transmitted from December through March, and 60% of solar energy transmitted from April through November. Costs of blinds vary from $53 per 6 foot long by 4 foot high vinyl blind (total $17,810 for 336 blinds) to $85 for a comparable metal blind ($28,560 total) (Consumer Shades, San Leandro, California; Burris Window Shades, Oakland, California). The midpoint, $23,180, is chosen for cost analysis. Other types of blinds, such as vertical blinds, have similar transmission coefficients and costs.

Window Options

Various window films, single and double pane windows, and "superwindows" are studied as envelope options. These options were modeled as one of the many glass types incorporated in DOE2.1E. Window options are applied to all windows on each side of the building.

Simple single-pane and double-pane windows are modeled in DOE2.1E as glass types 1000 and 2000, respectively. The windows are modeled without specifying frames or frame areas.

Many types of window films can be applied on the inside of existing windows. Films are added in order to strengthen the windows for security reasons or earthquake safety, to block out sunlight, to provide privacy and/or to selectively filter out ultra-violet (damaging to materials) and infra-red (heat) sun rays.

Three different films are compared in this study: clear films, bronze/gray tinted films, and spectrally-selective films. Clear films block out about 70% of solar rays and 80% of visible light. A clear film on a single-pane window is modeled by glass type 1202, and by glass-type 2200 for a double-pane window. Bronze or gray films apply metals like bronze or stainless steel to a clear film to produce a tint and often a reflective sheen on the film surface. These tinted films come in many gradations, but on average block out about 30% of all solar rays and 40% of visible light. Glass type 1407 is used to model a bronze/gray film on a single-pane window, and glass type 2426 is used to model bronze/gray film on a double-pane window. Spectrally selective films block out over

90% of undesirable ultra-violet rays and 45% of infra-red energy, while letting 70% of the visible light through. Spectrally selective films are modeled as glass type 1203 on single-pane windows and as glass type 2660 on double-pane glass.

Frame type variation is not considered for the study of window films. The films are also assumed to have no effect on window U-values. Lighting use inside the building is also constant regardless of the amount of sunlight coming through the windows.

"Superwindows" are highly energy efficient windows which use double-pane glass, low-emissivity coatings to reflect long-wave and infra-red radiation, low-conductivity argon gas between the glass panes, and low-conductivity window frames. These windows have typical U-values of 0.30 Btu/hr/square foot/F, versus 1.0 Btu/hr/square foot/F for single-pane windows and 0.60 Btu/hr/square foot/F for double-pane windows. The "superwindow" is modeled as glass type 2662 in this study.

Prices of clear and bronze/gray window films are about the same, from $2.75 to $3.50 a square foot installed (Burris Window Shades, Oakland California). The average total installed cost of clear and bronze/gray window films for the modeled building is $25,200 (8064 square feet of windows). Spectrally selective films are more expensive at around $6.00/square foot installed, for a total building cost of $48,380 (Daystar Window Tinting, Alameda, California). Simple 4 feet high by 6 feet wide double-pane windows cost $262.50 each, including a 25% installation fee, or a total of $88,200 for 336 windows. "Superwindows" cost $337.50 each, for a total of $113,400 for 336 4 by 6 foot windows including a 25% installation fee (V&W Patio Door and Window Company, Emeryville, California).

Sealing Building and Adding "Cool" Coatings

According to study of commercial buildings, "average" buildings leak at the rate of 0.3 cfm/square foot of wall area, and "tight" buildings at the rate of 0.1 cfm/square foot (ASHRAE Fundamentals, 1993). These values are converted to air-changes per hour for the modeled three-story building, or 1.3 ACH for an average building and 0.4 ACH for a tight building.

Infiltration leaks can be plugged by applying rigid urethane foam around baseboards, windows and trim, recessed lighting, electrical receptacles and switch plates, wire penetrations, and supply and return duct vents (Braun, Hansen & Woods, 1995). It is estimated to take two people two weeks at $50 per hour to plug infiltration leaks in the modeled three-story building with materials costs of $2000, for a total of $10,000.

"Cool" coatings for the exterior walls and roofs are any coating with high solar reflectivity as well as high emissivity. "Cool" coatings include white paints for exterior walls and specially formulated white elastomeric or ceramic coatings for roof surfaces. Metallic paints or coatings are not "cool" coatings, since they tend to have low emissivities which retard their ability to radiate heat away from themselves (Gartland, 1997).

"Cool" walls are modeled as a surface with absorptivity of 0.5. Most standard white paints will absorb 50% of the sun's rays, although paints mixed with titanium dioxide absorb as little as 30% of the sun's energy. Other "medium" colored paints, such as tans, grays, blues and greens, absorb about 80% of the sun's energy, and are modeled as surfaces with absorptivity of 0.8. The cost of painting a commercial building is around $1.10 per square foot (Andy Sahin, Piedmont, California). For the modeled building with 16,400 square feet of non-window surface area, the total cost is $18,060.

The "cool" roof is modeled in this study as a surface with 0.30 absorptivity, compared to a regular black roof with absorptivity of 0.95 (Gartland, 1997). Special roof coatings have been developed which not only have high solar reflectivities, but also contain algaecides and self-washing capabilities to help retain the initial reflectivity of the coating. These coatings can be applied over many existing roof surfaces, with the potential of prolonging the roof indefinitely with repeated reapplications of coating every 10 years (Antrim et al., 1994). Costs of these coatings range between $0.30 and $0.70 a square foot. The midpoint value was chosen for the 28,900 square foot of roof in this study, for a cost of $14,450.

RESULTS

Figures 1 through 12 plot the annual energy savings, demand reduction, utility savings (including both natural gas and electricity costs) and payback period for 23 different envelope options in five different building locations.

Due to assumptions made in modeling the energy use of the building, the energy savings predictions of various envelope options may be conservative. The "cool" roof option underestimates savings since radiative transfer in the attic space and increases in insulation conductivity with temperature are not being modeled. The window film options do not account for changes in window U-value or changes in lighting energy use with various film applications. The payback period for young trees does not take the growth of the tree into account.

Table 1 lists annual energy use, maximum annual electricity demand, and annual utility bill associated with the base cases in Figures 1-12. As expected, as insulation levels and window panes increase, the energy use, electricity demand and utility bills decrease. Chicago is the most energy intensive location due to it's heavy reliance on gas for heating as well as electricity for cooling. The highest electricity demand is seen in Phoenix, where summers are hottest. The highest annual utility bill also occurs in Phoenix, due to high electricity demands and demand charges.

Figures 1 through 12 show that the highest energy savings due to any envelope option occurs in Chicago and Washington D.C. when the envelope conductivity is increased - both in the R19 wall, R30 roof insulation case, and when superwindows are used in place of single-pane windows. Superwindows are also effective energy savers in Phoenix, Miami and Los Angeles when replacing single-pane windows. Next in line in terms of energy savings is use of mini-blinds in Miami and Phoenix for both single and double-pane windows.

The largest demand reductions are also seen in all cities when superwindows replace single-pane windows. Use of bronze/gray window films also reduces electricity demand significantly, but remember that lighting electricity use was held constant in this study. More research needs to be done to see what effect these films have on lighting levels and energy use. The use of mini-blinds and spectrally selective films also causes significant demand reductions in all locations.

Utility bill savings is closely tied to demand reduction: superwindows in place of single-pane windows, bronze/gray films, mini-blinds and spectrally selective films yield the greatest utility savings.

Table 2 lists the payback period for each envelope option averaged over all five locations. The most cost-effective options, based on utility bills alone, are adding window films, installing mini-blinds, and planting trees. Most options are slightly more effective when done for cases where single-pane windows are used in the building, although adding spectrally selective film is more effective on double-pane windows.

These measures generally hold the order listed in Table 2 for all locations. Payback periods of all measures are lowest in Phoenix (2.8 years for bronze/gray film on single-pane windows), then Washington D.C. (3.6 years), Los Angeles (4.0 years), and Miami (4.9 years), and are highest in Chicago (7.5 years). Table 3 lists the options in each city that have payback periods shorter than 10 years. Other than use of window films, mini-blinds and planting of trees, the only other options that have payback periods shorter than 10 years are "cool" roofs in Phoenix and sealing leaks in Washington D.C.

From an environmental standpoint, energy savings is the most important criteria to judge effectiveness of envelope options by, since the energy used is proportional to the emissions generated. Unfortunately, the measures that save the most energy - increasing insulation in climates with cold winters and use of superwindows - have some of the longest payback periods. Another anomaly - use of awnings is a shading technique which saves significantly more energy than planting trees around the building. However, due to it's relatively high cost, awnings come out far behind tree planting on the payback period scale.

Decisions about envelope options are not always made by adhering to a strict scale of payback periods, utility savings or energy savings. There are other factors which may make any of these envelope options attractive in many cases. For example, installation of superwindows in place of perfectly functional double- or even single-pane windows appears to make little financial sense in terms of energy costs and payback periods. But if windows need to be replaced anyway due to problems with condensation, discoloring, or breakage, then superwindows become an attractive option. The cost of installing superwindows over a standard double-pane window is only about $75 a window. With annual utility bill savings of superwindows over double-pane windows in the range of $0.03 to $0.08 per square foot, the payback period of superwindows is reduced to 4 and 10 years, depending on location, from the 17 to 45 year payback period of replacing windows for the sole reason of improving energy efficiency.

Another case where non-energy factors make a measure attractive is the use of cool roof coatings. A cool roof coating may be installed when there is a need for roof maintenance. In many cases the roof coating can be installed over an aging roof surface, protecting it from further degradation and prolonging it's life. The cost of the coating is offset by the money saved in reroofing fees over the life of the roof, and the energy savings that accrues is an added bonus. Similarly, painting a building white during it's normal maintenance round costs no more than painting it a dark color, and the energy saved by reducing the building's cooling load comes for free.

In some cases a desire for more comfort in the occupied space may be the over-riding factor in the use of an envelope option. Often offices on a building's perimeter will overheat on warm summer days, despite the best operation of a properly-sized chiller plant. Efforts to balance air handling systems often result in the perimeter offices being cooled to the proper conditions, with nearby core spaces being too cold. The use of window shading options will be even more attractive in this case.

The choice of shading options will also be guided by personal preference. The two most cost-effective options for reducing perimeter loads are use of bronze/gray films and use of mini-blinds. However, bronze/gray films limit the light into the space at all times - even when it's not desired. Bronze/gray films also give a metallic, reflective look to the windows, which is not always desirable for buildings of certain styles. Mini-blinds are most effective when used to block heat during the summer and transmit it during the winter. The necessity of proper manual control of mini-blinds could make use of spectrally selective films a preferable method of perimeter load control.

Personal preference may also be responsible for addition of trees and other landscaping outside a building. Money spent to beautify a building can also help the building save energy and be more comfortable. Deciduous trees to the east, south and west of a building are most helpful for retarding summer heat. Evergreen trees to the north can block winter winds.

Improvement of comfort in cold climates may also dictate the otherwise economically-unattractive prospect of replacing windows or sealing leaks. Single-pane and even double-pane windows in cold climates may have a significant effect on thermal comfort in perimeter spaces. Warm air cools along the window surface, causing uncomfortable drafts. Infiltration leaks in the building envelope also lead to drafty and uncomfortable spaces.

CONCLUSIONS

The most energy efficient envelope options increase the insulation levels of buildings located in areas of cold winter climate. Replacement of single-pane windows with superwindows is also a large energy saver in all climates.

The greatest monetary savings in utility bills came from replacing single-pane windows with superwindows, adding bronze/gray window films, using mini-blinds for window shading, and adding spectrally selective window films.

The most cost-effective options in terms of payback period are adding window films to existing windows, using mini-blinds (or some type of internal window shade), and planting trees around the sunny sides of a building.

Based on payback period alone, most building envelope options for cooling load reduction are fairly unattractive. All options have payback periods higher than about 3 years. Less than 30% of the 23 options studied in all five locations have payback periods lower than 10 years. The two measures with the greatest potential for energy savings, increased insulation and use of superwindows, have some of the longest payback periods (20-60 years).

Many of these envelope options become more attractive when there is a need for replacement of windows, at times of routine maintenance of roofs and exterior surfaces, a desire for beautification of the building, or a desire to improve the building's comfort.

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Table 1. Base Case Energy Use, Electricity Demand and Utility Bills.

	Annual Energy Use (gas + electricity)	**Maximum Annual Electricity Demand**	**Annual Utility Bill (gas + electricity)**
	(kWhr/square foot)	(kW/square foot)	($/square foot)
R7 walls, R11 roof, 1-pane windows			
Chicago	5.251	0.002875	0.3131
Los Angeles	2.244	0.002727	0.5602
Miami	4.004	0.002811	0.4236
Phoenix	4.028	0.003609	0.7467
Washington D.C.	3.881	0.002766	0.6953
R11 walls, R19 roof, 1-pane windows			
Chicago	4.852	0.002830	0.3100
Los Angeles	2.180	0.002676	0.5545
Miami	3.940	0.002766	0.4182
Phoenix	3.886	0.003527	0.7340
Washington D.C.	3.596	0.002705	0.6801
R11 walls, R19 roof, 2-pane windows			
Chicago	3.924	0.002676	0.2970
Los Angeles	2.019	0.002554	0.5382
Miami	3.733	0.002660	0.4033
Phoenix	3.513	0.003291	0.7000
Washington D.C.	2.974	0.002566	0.6462

Table 2. Average Payback Periods of All Envelope Measures.

Average Payback Period at All Locations (years)	**Envelope Measure Description**
4.6	bronze/gray film - 1-pane
4.8	bronze/gray film - 2-pane
5.6	mini-blind - 1-pane
6.3	mini-blind - 2-pane
10.4	young trees - 1-pane
10.7	young trees - 2-pane
11.3	spectrally selective film - 2-pane
14.4	clear film - 1-pane
14.7	clear film - 2-pane
16.1	spectrally selective film - 1-pane
17.2	"cool" roof
17.3	mature trees - 1-pane
18.0	mature trees - 2-pane
19.1	“superwindows” -1-pane
24.9	awnings - 1-pane
26.6	“superwindows” - 2-pane
28.2	sealed leaks - 1-pane
29.4	awnings - 2-pane
34.3	R30 roof
46.9	R19 walls, R30 roof
57.5	R11 walls, R19 roof
76.3	sealed leaks - 2-pane
156.4	"cool" walls

Table 3. Envelope Options with Payback Periods Shorter than 10 Years (Payback Periods in Parentheses).

Phoenix	**Washington D.C.**	**Los Angeles**	**Miami**	**Chicago**
b/g film, 1-pane (2.8)	b/g film, 1-pane (3.6)	b/g film, 1-pane (4.0)	b/g film, 1-pane (4.9)	b/g film, 1-pane (7.5)
b/g film, 2-pane (3.0)	b/g film, 2-pane (3.8)	b/g film, 2-pane (4.1)	b/g film, 2-pane (5.1)	b/g film, 2-pane (8.1)
mini-blinds, 1-pane (3.4)	mini-blinds, 1-pane (4.2)	mini-blinds, 1-pane (4.7)	mini-blinds, 1-pane (6.6)	mini-blinds, 1-pane (9.1)
mini-blinds, 2-pane (3.9)	mini-blinds, 2-pane (4.5)	mini-blinds, 2-pane (5.2)	mini-blinds, 2-pane (7.8)	
young trees, 1-pane (6.6)	young trees, 1-pane (6.7)	young trees, 1-pane (6.9)		
s.s. film, 2-pane (7.0)	s.s. film, 2-pane (8.0)	young trees, 2-pane (7.5)		
young trees, 2-pane (7.5)	young trees, 2-pane (8.4)	s.s. film, 2-pane (9.7)		
clear film, 2-pane (9.5)	sealed leaks, 1-pane (9.5)			
"cool" roof (9.5)	clear film, 2-pane (9.9)			
clear film, 1-pane (9.5)				