Requiring High Performance Windows in California

Charles Eley, Eley Associates
Bill Pennington, California Energy Commission

ABSTRACT

This paper describes the methods used to update the nonresidential fenestration requirements for the *2001 California Energy Efficiency Standards for Nonresidential and High-Rise Residential Buildings* (standards). Before the 2001 changes, the standards allowed metal frames with single tinted glass along the coast and double tinted glass inland. With the changes, high performance fenestration is required by the prescriptive standards throughout California[1]. The changes were implemented through an emergency rulemaking mandated by Assembly Bill 970 (Statutes of 2000).

California law requires that the standards be cost effective when amortized over the building life. A rigorous life-cycle cost procedure considered the cost of modern fenestration technologies, associated energy savings, views, and typical glass area in buildings. The procedure is summarized below:

- Identify the candidate fenestration products that may be used in vertical and horizontal applications, and collect data on their performance characteristics and cost.
- Develop an energy model that assesses the relative performance of candidate fenestration products and accounts for building type, orientation, and differences in U-factor, solar heat gain coefficient (SHGC), and visible light transmission (VLT).
- Develop a subset of fenestration products intended for reducing U-factor.
- Calculate the life-cycle cost of each U-factor subset. Set the U-factor criteria based on this analysis.
- Establish conditions that would warrant setting different SHGC criteria levels (i.e., climate zone, building type, orientation, and fenestration area).
- For each SHGC condition, calculate the life-cycle cost of each fenestration product in the full set. The product with the lowest life-cycle cost determines the SHGC criteria.
- Review the criteria that results from the above steps and apply professional judgment to provide consistency among similar climates and fenestration area ranges.

Background

In the summer of 2000, California experienced rolling blackouts in the San Francisco Bay area, and electricity bills in San Diego went up by 200-300%. These events signaled the beginning of an energy crisis that continued into 2001 with rolling blackouts becoming a common occurrence throughout the state. High energy prices depleted the state surplus and caused California's largest utility to file Chapter 11 bankruptcy. The state's electrical system continues to be vulnerable to increasing electricity demand, generation supply shortages,

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[1] Single glass can still be used, but only by using the whole building tradeoff procedure and improving the performance of some other building system or component.

transmission constraints, and extremely high wholesale electricity costs caused by an unstable market.

At the close of the 2000 legislative session, the California Legislature responded to the crisis. One piece was Assembly Bill 970 (AB 970), an urgency statute that became effective when Governor Gray Davis signed it on September 6, 2000. The statute, known as the California Energy and Reliability Act of 2000, found that there had been significant growth in the demand for electricity and that new power plant construction and energy conservation had seriously lagged. The act provided a balanced response by providing significant investment in conservation and demand-side management programs. In particular, AB 970 asked the California Energy Commission (CEC) to "*adopt and implement updated and cost-effective standards pursuant to Section 25402 to ensure the maximum feasible reductions in wasteful, uneconomic, inefficient, or unnecessary consumption of electricity"* (Need citation). The Legislature gave the CEC 120 days to do this job.

In response to AB 970, the CEC conducted an emergency rulemaking to develop amendments to the standards, which were adopted by the CEC on January 3, 2001 (119 days after AB 970 was signed by the governor). The AB 970 amendments to the standards focused on reducing peak electricity consumption and demand in the shortest time possible. This paper addresses the AB 970 changes for nonresidential fenestration.

Introduction

Solar heat gain through windows and skylights is a major contributor to cooling loads and peak electric demand. Significant opportunities to update and improve the standards existed which would help achieve the Legislature's goals as expressed in AB 970. The fenestration criteria in the California nonresidential standards were last updated in 1992, and at the time only very basic glazing technologies were considered, since low-e coatings and other advanced glazing technologies were relatively new and still fairly costly (Eley, 1991).

For the AB 970 standards, life-cycle cost analysis was performed to determine the most cost effective fenestration constructions among the newer glazing technologies. The result is criteria that are more stringent and appropriate for modern buildings, especially with regard to reflective glass and low-e coatings. The technologies needed to comply with the recommended requirements are not new. They are quite common in nonresidential buildings and available from numerous suppliers.

This life-cycle cost analysis for fenestration is very conservative. For instance, the value assigned to future energy savings is on the low side of the various scenarios developed by the CEC and the California Public Utilities Commission (CPUC). The process for selecting the criteria is also conservative, because each criterion is determined to be cost effective with any of the alternative costs that were developed. Maybe the biggest conservatism in the analysis is the decision to not consider the cost savings related to downsizing mechanical equipment. High performance windows can cost a little more, but they reduce peak loads and the prudent mechanical engineer will select smaller cooling equipment in response. Not only can smaller primary heating and cooling systems be used, but air distribution and hydronic distribution systems can also be made smaller in many cases. Previous studies have shown that when the first cost reduction of downsizing HVAC systems is accounted for, these savings can sometimes exceed the cost premium associated with better glass (Eley Associates 1990).

Goals

For both windows and skylights, the goal of this project was to update the U-factor and solar heat gain coefficient (SHGC) criteria for nonresidential and high-rise residential occupancies to account for advances in glazing technologies such as thermal break frames, advanced spacers, and low-e and reflective coatings. The following bullets describe the details.

- Make the window and skylight SHGC criteria more stringent with larger areas, e.g. higher window-wall ratio (WWR) for windows and higher skylight-roof ratio (SRR) for roofs. Also, calculate separate criteria for north and non-north orientations.
- Develop the criteria using a methodology similar to that used to develop *ASHRAE/IESNA Standard 90.1-1999*, but adapt the methodology for California climates and conditions. Replace the heating degree energy model used for the *ASHRAE/IESNA Standard 90.1-1999* with a model that is specific to California climates and update the cost estimate for fenestration products for California conditions.
- Since fenestration and insulation typically last for the life of the building, base the life-cycle cost analysis on a 30-year time horizon, rather than the 15-year time horizon used for lighting and HVAC measures.
- A 15-year life cycle cost analysis had been used to develop the existing nonresidential fenestration criteria.
- Develop one set of U-factor criteria for windows, but base these on operable windows. Fixed windows tend to have a lower U-factor, when all other factors are equal, so they would comply with the criteria for operable windows.
- Present the skylight U-factor and SHGC criteria separately for glass and plastic skylights. For glass skylights, present separate criteria for those mounted on a curb and those that are not[2]. Plastic skylights include acrylic, fiberglass, and other petro-chemical based products. Drop the distinction between translucent and transparent in the current standards and replace it with the glass/plastic classifications.
- Map the U-factor criteria to generic products represented in the *1997 ASHRAE Handbook: Fundamentals* U-factor table (also included as Table A-17 in the *ASHRAE/IESNA Standard 90.1-1999* and *2001*).

Non-Monetary Benefits of High Performance Fenestration

The California statute requires that energy efficiency measures in the code be shown to be cost effective on a life-cycle cost basis. Life-cycle cost accounts for the monetary value of energy savings; however, many of the benefits of high performance glazing are not accounted for in an life-cycle cost analysis, including:

[2] NFRC ratings for skylights include heat loss through the curb. In order to use NFRC ratings, the criteria must be expressed in a way that includes the curb.

- Condensation is reduced or eliminated with dual glazing and low-e coatings. This is especially important in cold weather, where the surface temperature of single glazing can be below the dew point temperature and water can condense on the inside surface creating maintenance problems.
- Double glass provides greater acoustic attenuation and can be a great benefit in hotel guest rooms, classrooms, and other spaces where quiet is important.
- Fenestration is a major contributor to the mean radiant temperature of spaces and can have a significant impact on human comfort (and employee productivity).
- HVAC systems and equipment can be smaller. This benefit could have been, but is not included in the life-cycle cost analysis performed as part of this study.

NFRC 100 and Site-Built Glazed Wall Systems

Another impact of the standards is to require National Fenestration Rating Council (NFRC) testing and label certificates for site-built fenestration in buildings that are larger than 100,000 square feet and that have fenestration areas larger than 10,000 square feet. It is estimated that this could affect 12% of buildings and 50% of the floor area of new buildings constructed each year (RLW Analytics, Inc. 1999). The use of NFRC testing and rating procedures for site-built glazing systems is recent and most codes, including California (before 2001) and *ASHRAE/IESNA Standard 90.1-1999*, exempt site-built fenestration from the NFRC testing and labeling procedures. Before California, the only known jurisdiction that had implemented NFRC for site-built glazing systems was the State of Washington (State of Washington 2000). The California procedures are based on the experience gained in the State of Washington and the City of Seattle, in particular.

For manufactured fenestration products that arrive at the construction site as a unit, the manufacturer assumes the burden of doing the testing and labeling. However, with site-built glazing systems, there are multiple entities responsible for the glazing system. Architects and/or engineers design the basic glazing system by specifying the components, the geometry of the components, and sometimes, their method of assembly. An extrusion manufacturer provides the mullions and frames that support the glazing and is responsible for thermal breaks, etc. A glazing manufacturer provides the glazing units, cut to size and fabricated as insulated glass units. The glazing manufacturer is responsible for tempering or heat strengthening, the tint of the glass, any special coatings, and the spacers and sealants. A glazing contractor (usually a subcontractor to the general contractor) puts the system together at the construction site and is responsible for many quality control aspects. Glazed wall systems are custom designed for many buildings making it difficult or impossible to predetermine the performance of the system as a whole.

In order for a glazed wall system to be tested, simulated, and labeled, one of the parties identified above must take responsibility for testing and labeling. The responsible party must obtain an NFRC license and establish relationships with an NFRC-accredited simulation laboratory, an NFRC-accredited testing laboratory, and an NFRC-accredited independent agent (IA) (NFRC 2000). Once these relationships are established and the proper licenses are obtained, the following steps are carried out:

1. Identify the number of product lines that are contained in the building project.
2. Arrange for an NFRC-accredited simulation laboratory to evaluate each product line.

3. Make an arrangement with an NFRC-accredited testing laboratory to test each product line.
4. Arrange for the glazing manufacturer and the extrusion manufacturer to mockup samples for testing and to send them to the testing laboratory.
5. The NFRC-accredited IA then issues a label certificate that is kept on file in the general contractor's on-site construction office. The label certificate provides the same function as the temporary label that is required with manufactured fenestration products.

The City of Seattle reported that the glazing contractor typically takes responsibility for NFRC labeling and certification. It is common for the design team to include language in the construction specification that makes the general contractor responsible; the general contractor will typically assign this responsibility to the glazing contractor. The city reports that once the glazing contractor has established a relationship with an IA, a simulation laboratory, and a testing laboratory, things seem to go fairly smoothly (Hogan 2000).

The City of Seattle also reports that if the process works well, it does not delay either the design or construction process (Hogan 2000). At the time the compliance documentation is prepared, testing or labeling is needed. However, the local building department plans examiners verify that the levels of fenestration performance shown in the contract documents (plans and specifications) and used in the compliance calculations are "reasonable" and achievable. This requires some judgment and knowledge on the part of the plan examiner that will require training. If assumptions are made that are beyond the "reasonable" range, then the examiner may require that the design team consult with an NFRC-accredited simulation laboratory to determine what technologies might be required to achieve the specified level of performance.

After the construction contract is awarded, the glazing contractor then takes responsibility for getting the simulations and tests completed, and for obtaining the label certificate. The IA issues a separate label certificate for each "product line." Each label certificate has the same information as the NFRC temporary label, but includes other information specific to the project such as the name of the glazing manufacturer, the extrusion contractor, the places in the building where the product line is used, and other details. The label certificate remains on file in the construction office for the building inspector to view. Afterwards, the label certificate should be filed in the building office with the as-built drawings as well as other operations and maintenance data to give building managers the information needed for repairs or replacements.

The cost for testing and labeling site-built glazing systems varies with the size of the project. Many of the costs are fixed, so the cost per square foot is lower in larger projects. The cost ranges from a low of about $0.16/square foot of glazing for a large story office tower to a high of about $0.94/square foot for a small low rise building with only 5,000 square feet of glazing (Benny 2000). These cost differences are the rationale for currently requiring NFRC testing and labeling only in larger buildings.

Methodology

The basic approach for developing the criteria for fenestration within California's process in the 2001 standards is to identify all the reasonable fenestration products or systems that are applicable for windows and skylights, and establish the conditions that would warrant setting different criteria levels, and for each condition, find the fenestration product that is most cost effective. The conditions for determining cost effectiveness are climate zone, building type (nonresidential or residential), window/skylight orientation, and fenestration area. The following steps describe the general approach in more detail.

1. Identify the candidate fenestration products that may be used in vertical and horizontal applications. A library of constructions was developed to include metal, thermal break, and wood/vinyl frames; clear, tinted, and high performance tinted glass; a variety of low-e and reflective coatings; and, both standard and insulating spacers for insulating glass units.
    a. Calculate the performance characteristics of each fenestration product in a consistent manner. The WINDOW 4.1 program was used for this purpose (LBNL 1994).
    b. Collect cost data on each of the various fenestration products in the library. A cost model was developed that assigns a cost premium to various glazing technologies and provides a method to calculate the cost for each fenestration product. See discussion below on the cost models used in the analysis.
2. Develop a simple energy model (see more discussion below) that gives the energy performance of the candidate fenestration products and accounts for differences in:
    a. U-factor, SHGC, and visible light transmission (VLT). The later is accounted for through the addition of a daylighting term in the energy savings models.
    b. Nonresidential and high-rise residential space categories.
    c. Fenestration area and orientation. For skylights, only one orientation (horizontal) is considered.
3. Develop a subset of the records in the library of fenestration products that represent technologies intended primarily for reducing U-factor. These are clear products with low-e and other coatings intended to reduce thermal transmittance, as opposed to reducing SHGC.
4. Calculate the life-cycle cost of each of the U-factor subset of fenestration products for a WWR of 0.25 for vertical fenestration and a SRR of 0.02. The fenestration product with the lowest life-cycle cost is used to set the U-factor criteria for all fenestration area ranges. This process is repeated for each climate zone and for both high-rise residential and nonresidential building types.
5. Establish conditions that would warrant setting different SHGC criteria levels (i.e. climate zone, building type, fenestration, orientation, fenestration area).
6. For each SHGC condition, calculate the life-cycle cost of each fenestration product. The fenestration product with the lowest life-cycle cost is used to set the SHGC criteria. The SHGC conditions include two orientations for vertical fenestration (north and all), and four window-wall area ratio ranges (0-10%, 11-20%, 21-30%, and 31-40%). For skylights, two fenestration area ranges are considered (0-2% and >2-5%). The criteria are calculated for the upper end of each fenestration area range.
7. Review the criteria that resulted from the above steps and apply professional judgment. This step results in criteria that are more consistent between climates and fenestration ratios, yet always cost effective. See discussion above on the method of selecting fenestration products.

Life-Cycle Cost Model

The following equation shows how life-cycle cost was calculated.

$$LCC_i = Cost_i + (kWh_i + kWh_{Lights}) \cdot NPV_E + Therms_i \cdot NPV_G$$

where

LCC_i The life-cycle cost of the i^{th} fenestration product considered in the analysis.

$Cost_i$ The initial cost of the i^{th} fenestration product.

KWh_i The annual heating and cooling electric energy associated with the i^{th} fenestration product. This is calculated on the basis of a square foot of exterior wall for vertical fenestration, or a square foot of roof for skylights. See the discussion of the energy model for how this is calculated.

KWh_{Lights} The annual lighting energy associated with the i^{th} fenestration product.

$Therms_i$ The annual gas use associated with the i^{th} fenestration product. This is calculated on the basis of a square foot of exterior surface (including opaque). See the discussion of the energy model for how this is calculated.

NPV_E The present value of a kWh of electricity over the 30-year study period.

NPV_G The present value of a therm of natural gas over the 30-year study period.

Note that there is no credit for downsizing HVAC equipment. This makes the procedure conservative in cases where it is possible to downsize the equipment.

Value of Future Energy Savings

A study period or building life of 30 years is used for evaluating fenestration products, which is contrasted with the 15-year life assumed for lighting and HVAC. The rationale for using 30 years is that the building shell typically lasts much longer than building systems. A 30-year time horizon has always been used for analysis of low-rise residential buildings. Calculations are based on a net present value for electricity of $1.68/kWh-y and a net present value for gas of $11.43/therm-y (Eley Associates 2000b).

Library of Fenestration Products

A wide variety of fenestration products are available for nonresidential and high-rise residential buildings. The variation of available products are the choice of glazing material(s), the coatings applied to one or more surfaces of glazing, the construction of the frame, and the type of spacer used to separate insulating glass units.

In this study, only three types of tinted glass are considered (clear, green, and high performance tint). Other standard tinted products cost roughly the same as green, but do not perform as well since they have a lower light transmission. For simplicity, these products are all assumed to have a thickness of 6 mm (1/4 in.). While this is the most common thickness for architectural (nonresidential) glazing products, other thicknesses are available from most manufacturers. A 12 mm (1/2 in.) air gap is assumed for all dual glazed assemblies.

Many different types of frame constructions are available. In this study, three are considered. The first is a standard metal frame, which is typically constructed of aluminum. The second option provides a thermal break in the metal frame, which is achieved by separating the metal extrusion in two or more parts and connecting them with a non-metallic bond, typically some type of rigid urethane. The third option is to construct the frame with non-metallic materials such as fiberglass, wood, or vinyl. While the wood/vinyl option is considered in the life-cycle cost analysis, these technologies are not used to establish the U-value requirements since they are not applicable for all nonresidential building applications.

Insulating glass units consist of multiple panes of glazing separated by spacers. Two types of spacers are considered in this analysis. The standard spacer used for most insulated glass units consists of a hollow aluminum extrusion that is perforated on the side facing the air gap. The hollow spacer is typically filled with a desiccant to absorb any moisture that might be trapped in the air gap. Insulated spacers use either a non-metallic material or are constructed of thin stainless steel. Their advantage is that less heat is conducted around the edges of the insulating glass unit. Insulating spacers reduce both U-factor and SHGC.

Special coatings can be applied to one or more of the surfaces of single, double, or triple insulating glass units. Coatings can be applied in one of two ways. Pyrolytic coatings are applied while the glass is being manufactured and while it is still in a molten or semi-molten state. Pyrolytic coatings are hard and durable enough to be used in exposed applications. Most can be used in single glazing applications. The second way to apply a coating is through a sputter process where molecules of various types of metal are deposited onto the surface of the glass. Sputtered coatings are often layered to provide special properties, such as being able to filter light from certain wavelengths (spectrally selective coatings). Sputter coatings are soft and are generally applied to the inner (second or third) surface of insulated glass units where they are protected from abrasion.

A variety of low-e coatings are considered in the analysis. Only one reflective coating is considered which is fairly low in reflectance and has medium performance. The reflective coating is only considered in setting the criteria for nonresidential buildings, not high-rise residential buildings. It is not considered in setting the criteria for high-rise residential buildings. Highly reflective coatings, especially those applied to the first surface, are deliberately excluded, since these are not applicable in all cases.

Cost Model

The life-cycle cost approach requires that each fenestration construction be assigned a cost. The basecase construction (single, clear glass in a metal frame) is assumed to have a cost of zero. Other products have a cost premium relative to the basecase, which depends on the technologies added to the basecase. The cost premiums used in the analysis are listed in Table 1 for each of the technologies. These premiums are summed to get the total cost premium and then 30% is added to account for contractors' overhead and profit.

The ASHRAE cost premiums were developed from surveys conducted in the early 1990s. However, the data were reviewed by the ASHRAE project committee and updated several times, with the most recent occurring in 1998. As part of this project, six manufacturers and coaters are contacted to make a spot check on the ASHRAE cost data. Those that respond verify the accuracy of the ASHRAE cost data.

In addition to the ASHRAE cost model, data are also collected specifically for California as part of the CADMAC project (Xenergy, Inc. 1996). These data are available for fenestration products with glass, but not for acrylic or fiberglass skylights. The CADMAC data includes price quotes for low-volume and high-volume purchases. The CADMAC and

ASHRAE data were reviewed by a number of persons in the fenestration industry and the general view was that the cost estimates were high, making the analysis conservative. Table 1 has the ASHRAE price as well as the high-volume and low-volume prices from the CADMAC data set. As a sensitivity study, life-cycle cost is calculated using all three prices.

U-Factor Subset of Fenestration Products

When searching for the low-life-cycle cost fenestration product to use as the basis of the U-factor criteria, only a subset of the glazing constructions are used in the analysis. This subset includes only glazing constructions having features, products, and technologies that are intended to reduce U-factor as opposed to reducing SHGC. The U-factor subset includes all frame types and spacers since the primary impact of these technologies is to reduce the U-factor. Clear glazing products are considered in the U-factor set. Also, only the pyrolytic (Pye) and sputter low-e coatings (Spe) are considered in the analysis: However, the sunbelt low-e product (Sbe), super low-e (Sue) product, and the medium performance reflective coating (Mpr) are excluded from the U-factor set, since they are primarily intended to reduce SHGC.

The U-Factor Criterion and NFRC Certification

Each of the fenestration products considered in the analysis has several U-factors associated with it. Three U-factors are calculated with the WINDOW 4.1 program (LBNL 1994): UVertW41, USkyCurbW41, and USkyNoCurbW41. These values are used in calculating the criteria, since they reflect subtle differences between various technologies and are calculated in a consistent manner. However, the values actually published as criteria are the corresponding values from Table A-17 of *ASHRAE/IESNA Standard 90.1-1999* and the *2001 ASHRAE Handbook: Fundamentals*. These are more consistent with NFRC rating procedures, which will be used to show compliance with the criteria.

Energy Model

A simplified energy model is used to calculate the energy use of each fenestration product. The model is based on DOE-2 simulations and is discussed in greater detail below. The energy models include a term for heating, one for cooling, and one for a daylighting benefit. The daylighting term is needed to provide a credit for fenestration products that have a high VLT. VLT is critical since it provides daylighting to spaces, views to the exterior, and other benefits. Standard drapes/blinds are assumed in the models and, therefore, in the life-cycle cost analysis.

Table 1. Glass Technologies, Codes and Cost Premiums

Item	Code	Cost ($/ft²) ASHRAE	CADMAC High Vol.	CADMAC Low Vol.	Description
Glass Products	Clr	Basecase			Standard 6 mm thick **CL**ea**R** pane.
	Clr	3.02	3.01	3.50	Premium for an additional pane of 6 mm clear glass. This premium includes a standard spacer (see below).
	Grn	0.39	0.37	0.43	Standard **GR**ee**N** 6 mm thick tinted glass available from all primary glass manufacturers. The premium is the difference between clear glass and the green tint. Bronze and gray tinted glass are not considered since they have a lower VLT, but equal or near equal SHGC.
	Hpt	1.10	1.35	1.57	**H**igh **P**erformance **T**inted 6 mm thick glass such as Azurlite or Evergreen.
Frame Types	Mtl	Basecase			Standard **MeTaL** frame without a thermal break.
	Brk	1.50	0.64	0.75	Metal frame with a thermal **Br**ea**K.**
	Vnl	4.00	1.36	1.59	**V**i**N**y**L** or wood frame.
Spacers	Std	Basecase			**ST**andar**D** spacer.
	Ins	0.80	N.A.	N.A.	**INS**ulating spacer. The cost premium is the difference between the standard spacer and the insulting spacer.
Coatings	Nct	Basecase			No coating.
	Mpr	1.68	2.01 Brz 2.38 Clr	2.34 Brz 2.76 Clr	A generic **M**edium **P**erformance **R**eflective coating. This is a durable coating that can be used on single glazing, but is less reflective than LOF Eclipse or PPG Solarcool.
	Pye	1.00	1.46	1.71	**PY**rolytic low-**E** coating similar to LOF Energy Advantage. This is a hard low-e coating that has an emissivity on the order of 0.20.
	Spe	1.88	2.81	3.27	Standard **SP**utter low-**E** coating. This coating is offered by many manufacturers and has an emissivity on the order of 0.10.
	Sbe	1.88	2.81	3.27	**S**un**B**elt low-**E** coating. This has similar emissivity as the Spe product, but a lower SHGC. An example is Guardian's NU-40 coatings.
	Sue	1.88	2.81	3.27	**SU**per low-**E** coating. This is an advanced coating that has an emissivity below 0.04. It also has a lower SHGC.
Suspended Film	HtMr22	6.35	9.05 + Dbl	10.51 + Dbl	These are Heat Mirror suspended films with varying transmission. The 22 in the code to the right is the light transmission of the film and includes other values: 33, 44, 55, 66, 77, and 88. The cost premium is the same for all transmissions and includes spacers and other sealants.

Notes:
The CADMAC cost database has values for residential and commercial products. The values presented in this table are for commercial products, with the exception of the pyrolytic low-e coating. For this product, only a residential price is presented in the CADMAC data.

Heating and cooling energy. Regression equations are developed using DOE-2 simulation data from each climate zone. The coefficients for the equations in this analysis are developed specifically for California's 16 climate zones. Producing regression coefficients for each climate zone allows the energy equations to account for all climate variables such as wet-bulb temperature, solar radiation, and wind speed. The following shows the structure of the equations. The coefficients are $h_{1,j}$ and $h_{2,j}$ for heating, and $c_{1,j}$ and $c_{2,j}$ for cooling. The "j" subscript is a reference to a climate zone. The "i" subscript is a reference to a particular fenestration product. The coefficients are calculated separately for high-rise residential and nonresidential occupancies.

$$Therms_i = h_{1,J} \text{ x } (FR \text{ x } U_i) + h_{2,J} \text{ x } (FR \text{ x } SHGC_i / U_i) \qquad \text{(windows)}$$

$$Therms_i = h_{1,J} \text{ x } (FR \text{ x } U_i) + h_{2,J} \text{ x } (FR \text{ x } SHGC_i) \qquad \text{(skylights)}$$

$$kWhCool_i = c_{1,J} \text{ x } (FR \text{ x } U_i) + c_{2,J} \text{ x } (FR \text{ x } SHGC_i) + kWh_{Lights}$$

where

$Therms_i$	Gas use per square foot of exterior wall or roof.
$h_{1,J}$, $h_{2,J}$	Heating coefficients where the "J" subscript refers to one of the 16 climates.
FR	Fenestration ratio. For walls, this is window-wall ratio (WWR) and for roofs, it is skylight to roof ratio (SRR).
$SHGC_i$	Solar heat gain coefficient for the Ith fenestration construction.
U_i	U-factor for the Ith fenestration construction.
$kWhCool_i$	Electricity use in kWh/year/square foot of exterior wall or roof.
$c_{1,J}$, $c_{2,J}$	Cooling coefficients where the "J" subscript refers to one of the 16 climates.
kWh_{Lights}	Electricity use associated with the lighting, also expressed per square foot of wall or roof (see below for more information on this term).

Daylighting. The energy equations include a credit for fenestration products that have a high VLT, relative to other fenestration products. Without this credit, the methodology would not distinguish between fenestration products with different VLTs. Even though daylighting controls may not be installed or used, there is a benefit to having windows with a high light transmission, all else being equal. This benefit is accounted for in the daylighting term. The credit is summarized in the following equation (Eley 1992).

$$kWh_{Lights} = LPD \cdot Hours \cdot (1 - K_d)$$

where

kWh_{Lights}	The electric energy use associated with a square foot of wall or roof. This is based on assumptions on floor-to-floor height.
LPD	Lighting power density in W/square foot.
Hours	Full time equivalent lighting hours.
K_d	Daylighting savings fraction (see below).

The daylight savings fraction is calculated using the following equation.

$$K_d = [\phi_1 + \phi_2 (C / T_{vis_i})][1 - e^{(\phi_3 + \phi_4 \bullet C) FR \bullet VLT_i \bullet WF}]$$

where

K_d	Daylight savings fraction (unitless).
VLT	Visible light transmission of the fenestration (unitless).

FR Fenestration ratio (unitless). For skylights, this is the ratio of the skylight area to the area of the roof. For windows, this is the window-wall ratio.

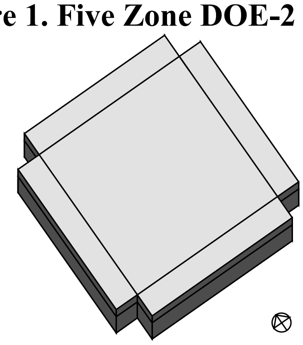
WF Well factor (unitless). Assumed to be 0.6 in life-cycle cost analysis for plastic skylights and 0.8 for glass skylights. This is assumed to be 1.0 for windows.

C Design illumination (footcandles).

ϕ_n Coefficients developed through regression analysis. The coefficients vary between windows and skylights.

DOE-2 model. DOE-2.1E is used to create a database of heating and cooling energy for a wide variety of fenestration designs. A total of 1,120 building energy simulation runs are performed using a simple one-story, five-zone model. The interior zone is 100 feet x 100 feet, and each perimeter zone is 15 feet x 100 feet. The arrangement for thermal zoning is intentionally designed so that perimeter zones are connected only to the interior zone and not to other perimeter zones. This tends to isolate solar effects for each building facade. Skylights are modeled only in the interior zone. Windows are modeled only on each perimeter zone.

Figure 1. Five Zone DOE-2 Model



Source: Eley Associates 2000b

The model is simulated with both nonresidential and high-rise residential schedules of operation, taken from the 1998 nonresidential ACM approval manual. A lighting power density (LPD) of 1.25 W/square foot and an equipment power density (EPD) of 0.75 W/square foot are used in both building types. The opaque construction elements are set to be in minimum compliance with the Title 24 prescriptive envelope criteria.

Five different glazing constructions are modeled to represent a wide range of possible fenestration U-factor and SHGC combinations. The WWR is varied from 0 to 45% in four steps (0%, 15%, 30%, and 45%). The skylight area is varied from 0 to 10% in three steps (0%, 5%, 10%). All exterior zones are set with double bronze vertical glazing at a 15% WWR during the skylight performance runs. No skylights are placed in the model during window performance runs. These fenestration constructions are described in Table 2.

Table 2. Glass Types Modeled

Glazing Code	Description	U-value	SHGC
1000	Single Clear	0.91	0.86
1403	Single Bronze, High Reflective	0.89	0.22
2204	Double Bronze, 12mm Air	0.45	0.49
2642	Double Clear, Low-E, Argon	0.25	0.65
3692	Triple Tinted Heat Mirror 33	0.21	0.15

A single zone packaged HVAC system with an air side economizer is assumed to serve each thermal zone.

Results

The procedure described above is applied to each construction in the database and the life-cycle cost is calculated for each. This process is repeated for each combination of climate zone, building type, WWR, and orientation (Eley Associates 2000). For each combination, the list of constructions are ranked by life-cycle cost. For glass products, the life-cycle cost rankings are performed separately using the ASHRAE cost model, and the CADMAC high volume and low volume cost estimates. Life-cycle cost is calculated based on a net present value for electricity of $1.68/kWh-y and a net present value for gas of $11.43/therm-y. These values are based on CEC projections of electricity and gas prices, a 3% real discount rate, and a 30-year life cycle analysis period.

Professional judgment is used in selecting criteria from the ranked lists, e.g., the low life-cycle cost choice is not always selected. However, the selected criteria is always cost effective. The method of selection is based on a few principles described below.

- Vinyl window frames are not permitted as the basis of the standards, since such frames are not acceptable for all building types covered by the nonresidential standards (especially over three stories).
- Reflective coatings are not permitted as the basis of the SHGC criteria for the high-rise residential cases, but the coatings are considered acceptable for nonresidential.
- Constructions are selected which are always cost effective using the ASHRAE cost model. In almost all instances, the recommended criteria is also cost effective with the CADMAC high and low cost estimates.

The adopted fenestration criteria for windows (vertical fenestration) are shown in Tables 3 and 4 below. These contain the criteria for nonresidential and high-rise residential, respectively. The U-factor criteria apply for all WWR ranges. However, the SHGC criteria vary with WWR, in four ranges up to a maximum of 40%. Buildings that have a WWR greater than 40% must use a performance method and make trade-offs. The criteria are presented as relative solar heat gain (RSHG). When there are no overhangs, the RSHG is equal to the SHGC, so for unshaded windows, the criteria can be read as SHGC criteria.

Table 3. RSHG Criteria for Vertical Fenestration – Nonresidential

Climate Zones	**South Coast**		**North Coast**		**Central Valley**		**Desert**		**Mountains**	
Max. U-factor	0.81		0.81		0.49		0.49		0.49	
Max. SHGC	Non-North	North	Non-North	North	Non-North	North	Non-North	North	Non-North	North
0-10% WWR	0.61	0.61	0.61	0.61	0.47	0.61	0.46	0.61	0.49	0.72
11-20% WWR	0.55	0.61	0.61	0.61	0.36	0.51	0.36	0.51	0.43	0.49
21-30% WWR	0.41	0.61	0.39	0.61	0.36	0.47	0.36	0.47	0.43	0.47
31-40% WWR	0.41	0.61	0.34	0.61	0.31	0.47	0.31	0.40	0.43	0.47

Note: In climate zone 1, the criteria for north oriented fenestration shall be used for all orientations.

Table 4. RSHG Criteria for Vertical Fenestration – High-Rise Residential

Climate Zones	South Coast		North Coast		Central Valley		Desert		Mountains	
Max. U-factor	0.49		0.49		0.49		0.49		0.49	
Max. SHGC	Non-North	North	Non-North	North	Non-North	North	Non-North	North	Non-North	North
0-10% WWR	0.41	0.61	0.47	0.61	0.36	0.49	0.36	0.47	0.46	0.68
11-20% WWR	0.40	0.61	0.40	0.61	0.36	0.49	0.31	0.43	0.46	0.68
21-30% WWR	0.31	0.61	0.36	0.61	0.31	0.40	0.26	0.43	0.36	0.47
31-40% WWR	0.26	0.55	0.31	0.61	0.26	0.40	0.26	0.31	0.30	0.47

Note: In climate zone 1, the criteria for north oriented fenestration shall be used for all orientations.

The fenestration criteria for skylights (horizontal fenestration) are shown in Tables 5 and 6 below. These contain the criteria for nonresidential and high-rise residential, respectively. The U-factor criteria apply for all SRR ranges, but depend on the class of skylight: glass with curb, glass without curb, and plastic. A curb is assumed for all plastic skylights. The SHGC criteria vary with SRR, in two ranges up to a maximum of 5%. Buildings that have a SRR greater than 5% must use a performance method and make tradeoffs.

Table 5. Proposed Criteria for Skylights – Nonresidential

		South Coast	North Coast	Central Valley	Desert	Mountains
U-factor	Glass w/Curb	1.18	1.18	0.99	0.99	0.99
	Glass w/o Curb	0.68	0.68	0.57	0.57	0.57
	Plastic w/Curb	1.30	1.30	1.10	1.10	0.87
SHGC, Glass	0-2% SRR	0.79	0.79	0.46	0.46	0.68
	2.1-5% SRR	0.40	0.40	0.36	0.36	0.46
SHGC, Plastic	0-2% SRR	0.79	0.77	0.77	0.71	0.77
	2.1-5% SRR	0.65	0.62	0.62	0.58	0.58

Table 6. Proposed Criteria for Skylights – High-Rise Residential

		South Coast	North Coast	Central Valley	Desert	Mountains
U-factor	Glass w/Curb	1.18	1.18	0.99	0.99	0.99
	Glass w/o Curb	0.68	0.68	0.57	0.57	0.57
	Plastic w/Curb	1.30	1.30	1.10	0.87	0.87
SHGC, Glass	0-2% SRR	0.58	0.61	0.46	0.46	0.46
	2.1-5% SRR	0.32	0.40	0.32	0.31	0.36
SHGC, Plastic	0-2% SRR	0.65	0.65	0.65	0.65	0.71
	2.1-5% SRR	0.39	0.65	0.34	0.27	0.55

Summary

The procedure used to develop the nonresidential fenestration criteria for the 2001 California standards was similar to the procedure used for development of *ASHRAE/IESNA Standard 90.1-2001*. The primary difference is that the energy model was updated to be consistent with California modeling assumptions and made specific to California climate conditions. Where ASHRAE relied on heating and cooling degree days to explain climate differences, the California models are specific to each climate zone and take direct account of climate factors such as solar, diurnal temperature swings, etc. Also, the generic library of constructions used in the analysis is essentially the same as used for ASHRAE, except that the cost data was updated for California conditions and verified in the public review process.

Perhaps the biggest difference between the ASHRAE and the California analysis is the value placed on future energy savings. ASHRAE considers each kWh/y of electricity savings to have a present value of only $0.64[3], while for the California analysis, the value is $1.68. This results in standards that are considerably more stringent. For instance, where ASHRAE allows single glass in California coastal climates, the 2001 California standards requires double low-e glass.

The 2001 nonresidential standards are estimated to save about 80 GWh per year statewide and reduce peak demand by 63 MW each year. Although an analysis was not done separately for the fenestration requirement, many of the savings are associated with this change. Other changes included increasing the HVAC equipment efficiency requirements, modifying the lighting control requirements, and requiring demand control ventilation in high occupancy spaces. The statewide savings estimates are based on the *Nonresidential New Construction Baseline Study* (RLW Analytics, Inc. 1999) in which each building in the database is modeled in minimum compliance with the 1998 standards and again in minimum compliance with the 2001 standards. The difference in the savings for each site are appropriately weighted by climate and by building type to yield statewide savings.

Conclusion

The procedure use to develop the fenestration requirements for the 2001 California standards proved to be solid. It is really the second generation of an approach already tested for ASHRAE, but enhanced for California conditions. The fenestration required by a standard needs to account for building type (nonresidential vs. residential), climate, orientation (north facing and other), and fenestration area (ranges of window wall ratio or skylight roof ratio). The method worked for these variations and produced reasonable results.

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[3] In the ASHRAE analysis, a national average electricity price of $0.08 per kWh was assumed and a scalar ration of 8. The scalar accounts for discount rate, study period and many other factors. The present value is the product of the price and the scalar or $0.64.

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