OPTIMIZATION OF GLAZING DESIGN FOR RESIDENTIAL USE

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ABSTRACT

The thermal performance of several glazing designs is quantified, and the designs are optimized to achieve low U-values and high shading coefficients (SC). Thermal performance estimates are produced using VISION, a computer program developed specifically to model glazing systems. Glazing design characteristics considered include glass type (conventional float, low-iron, and low-reflective low iron), number of glazings (one to four), optical coatings, and non-air fill gas. The thermal performance of each design is optimized with respect to interpane spacing. The economic performance of the optimized glazing designs is estimated, based on incremental material and manufacturing costs and heating energy savings relative to a conventional double-glazed window.

INTRODUCTION

Windows play an important role in the energy performance of a building envelope. They contribute significantly to conductive heat losses and gains and are responsible for virtually all direct solar energy gains. In recognition of their importance, recent research efforts have been directed toward the development of energy-efficient "superwindow" designs. As a result, numerous superwindow designs have appeared on the market. These windows utilize a variety of techniques to enhance thermal performance, including multiple glazings, low conductivity fill gases, optical coatings and surface treatments, and interpane films.

Recent advances in glazing materials and optical coatings, as well as the development of a computer program specifically designed to model superwindow performance, led to the initiation of the multiphase research project. The ultimate objective of this project was the development and commercialization of an economical and reliable residential window with superior cold weather thermal performance. This paper presents the results of the first phase of the project. This first phase had two objectives:

1. The quantification of the thermal performance of a broad range of window designs.

2. The quantification of the economic performance of those window designs which achieved acceptable thermal performance.

APPROACH

The project was comprised of three steps. Candidate window designs were first selected. Since commercialization of a window was the ultimate objective of the project, the designs selected generally reflected materials and manufacturing processes which were currently available.

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Following the development of a set of candidate window designs, the thermal performance of each window design was estimated using VISION, a detailed computer program developed specifically to simulate the performance of innovative window designs (Ferguson and Wright 1983). In addition to conventional single glazed and multiglazed windows, the program is capable of modelling features such as substitute gases, diathermanous glazings, optical coatings, and partial or full vacuums. As noted previously, the objective of the project was the development of a window with superior cold weather performance. Such a window would have a low U-value, to minimize conduction losses, and a high SC, to maximize solar heat gains. For the purposes of this project, a U-value of 0.18 Btu/h·ft^2·F (1·W/m^2·K) was considered to be a feasible target.

Based on the thermal performance results, the condidate window designs which achieved acceptable thermal performance were selected for economic analysis. Economic performance was quantified using a simple payback period. For this application, payback period was defined as the length of time in years required for the value of the space heating energy savings attributable to a particular window, compared to a reference window, to just equal the additional capital costs of that window. The reference window used for this study was a conventional double glazed insulating glass unit.

Incremental window costs (i.e., costs in excess of a double glazed unit) were established based on information gathered from glass manufacturers, window assemblers, optical coating manufacturers and window consultants. Energy savings were estimated using a method developed recently by Harrison and Barakat (1983). The technique enables the calculation of the net annual window heat loss given window orientation, location and thermal performance.

CANDIDATE DESIGN SELECTION

The availability of a broad range of glazing materials, optical coatings, interpane films, etc., as well as the large variety of possible design configurations, combined to create an unlimited number of potential window designs. To develop a manageable set of glazing designs, the following limitations and assumptions were made.

1. The maximum number of glazings and interpane films considered was four. Windows with panes in excess of four were not analyzed due to cost, weight, and size considerations.

2. Low-iron glass was selected as the base glazing material, due to its high solar transmittance compared to conventional glass (92% vs. 85% for normal incidence angle). Although not currently used in large quantities, commercial production capabilities of low-iron glass do exist. Outer glazings (i.e., exterior and interior panes) were assumed to be 0.12 in (3 mm) thick. The thickness of the inner panes of triple and quad assemblies was 0.09 in (2.16 mm), due to lower strength requirements and weight considerations. Limited analyses of conventional float glass and a low-iron glass with low-reflective treatment were also undertaken. Refer to Table 1 for a summary of glazing properties for conventional and low-iron glass. The use of a special surface treatment on the low-iron low-reflective glass prevented direct analytical calculation of optical properties. As a result, measured data were used. For the purposes of comparison, the normal solar transmittance of this glass is 98%.

2. Interpane spacings of 0.39, 0.49, 0.59, and 0.79 in (10, 12.5, 15, and 20 mm) were modeled for all multipane windows. Spacings of 0.20 and 0.30 in (5 and 7.5 mm) were also considered for a limited number of designs to verify performance trends. Only equal spacing was used; no geometrically asymetric windows were considered.

3. Optical coatings were modeled for each multiglazed window. The coating was applied to only one surface of an air or gas space. The surface selected was always a warm (i.e., interior) side, following the recommendation of Rubin et al. (1983). For multispace windows (i.e., triple and quad) optical coatings were applied starting with the interior glazing, again following the recommendations of Rubin et al. Refer to Table 1 for a summary of properties of coated glazings.

4. Three fill gases were considered: air, Argon, and a 70/30 mixture of Argon and SF6. In addition, the effects of a complete vacuum were also analyzed.

THERMAL ANALYSIS

Environmental Conditions

Both the U-value and the SC are functions of the environmental conditions. The U-values presented in this report were calculated using an outdoor temperature of 32 F (0°C), an indoor temperature of 70 F (21°C), and a wind speed of 7.5 mph (12.5 kmph). The conditions used to calculate the shading coefficient were selected to match as closely as possible those used by ASHRAE (ASHRAE 1981).

Results and Discussions

A summary of the results of the initial set of VISION runs is presented in Figures 1 to 4 and Table 2. Based on these results, several observations can be made.

Non-Air Fill Gas. Use of a non-air fill gas can decrease the U-value. Argon is the better of the two non-air alternatives, yielding U-value reductions ranging from 4% (double-glazed, 0.79 in (20 mm) spacing, no optical coatings) to 23% (quad-glazed, 0.39 in (10 mm) spacing, three optical coatings). Use of the Argon/SF6 mixture can actually increase the U-value for certain designs. The benefits of a non-air fill gas increase with the number of optical coatings used, because as the number of coatings increase, the radiative heat transfer component decreases. Therefore, the relative contribution of the conductive/convective component, which decreases with the use of a gas such as Argon, is greater. A comparison of SC results, not presented here, indicates that fill gas type has virtually no effect on this factor.

Vacuum. Completely evacuating the interpane spaces yields a dramatic decrease in the window U-value. This decrease ranges from 19% (double-glazed, no optical coating) to 72% (quad-glazed, three optical coatings) compared to similar air-filled windows. The performance improvements are greatest for windows with optical coatings, for the same reasons outlined previously in the discussion of fill gas.

Interpane Spacing. Refering to Figures 1 to 3, it is clear that the U-value decreases with increasing spacing up to a limit. Beyond this limit, the U-value remains virtually unaffected by increases in spacing. The pane spacing at which the U-value levels out is a function of the number of glazings and ranges from approximately 0.4 in (10 mm) for double-glazed windows to 0.6 in. (15 mm) for quad units.

These results are consistent with conductive/convective transfer characteristics. For small spacing, all nonradiative heat transfer occurs by conduction and laminar convection alone. Beyond a certain spacing, however, turbulent convective currents are established, and heat transfer remains virtually unchanged as the spacing is increased. The transition between the two heat transfer regimes is dependent not only on spacing, but on the temperature differential as well. The transition occurs at smaller spacing for double-glazed windows compared to triple or quad windows, because the temperature differential across the space is greatest for the double-glazed window for a given indoor/outdoor temperature differential. The results of additional simulations not presented here indicate that a minimum interpane spacing of approximately 0.5, 0.6, and 0.7 in (13, 15, and 18 mm) for double, triple, and quad windows, respectively, would ensure that a window assembly lies beyond the transitional region for a realistic maximum temperature differential (as opposed to the 38 F (21°C) used for the simulations).

Optical Coatings. The use of optical coatings can significantly decrease the U-value. A comparison of the relative reductions for air- and Argon-filled windows with 0.5 in (13 mm) spacing indicates that optical coatings can decrease the U-value by up to 57%. However, as indicated in Figure 4, the use of optical coatings also leads to a reduction in SC. For air- and Argon-filled windows with 0.5 in (13 mm) interpane spacing, the reduction can approach 45%.

Glazing Material. As noted previously, the base glazing used for thermal analysis was 0.12 in (3 mm) and 0.09 in (2.16 mm) low-iron glass for outer and inner panes respectively. Limited simulations were also performed for windows using 0.12 in (3 mm) low-iron glass for all panes, conventional 0.12 in (3 mm) float glass, and low-iron, low-reflective glass. Refering to Table 2, the results indicate that the use of conventional float glass decreases the SC by approximately 12% compared to the low-iron unit. Use of the low-reflective low-iron glass improves the SC compared to untreated low-iron glass and leaves the U-value unchanged. Replacement of all panes with low-reflective low-iron glass yields a SC of 21% for the triple-glazed unit considered. If only the inner pane is replaced, the SC increases by 6%.

ECONOMIC ANALYSIS

Window Design Selection

A total of 7 window designs were selected from the designs analyzed in the previous section for further economic assessment. The designs selected were:

1. Triple-glazed, Argon-filled, one optical coating;
2. Triple-glazed, air-filled, two optical coatings;
3. Triple-glazed, Argon-filled, two optical coatings;
4. Quad-glazed, air-filled, one optical coating;
5. Quad-glazed, Argon-filled, one optical coating;
6. Quad-glazed, air-filled, two optical coatings;
7. Quad-glazed, air-filled, three optical coatings.

All triple windows were assumed to have interpane spacings of 0.6 in (15 mm), and all quad windows were assumed to have interpane spacings of 0.7 in (18 mm).

These 7 designs were selected for further economic analysis from the initial set of designs for several reasons. All single- and double-glazed designs were eliminated from further consideration because of their inability to achieve the target U-value of 0.18 $Btu/h \cdot ft^2 \cdot F$ (1 $W/m^2 \cdot K$). For similar reasons, triple- and quad-glazed air- and Argon-filled windows with no optical coatings and triple-glazed air-filled windows with 1 optical coating were also eliminated.

The Argon/SF6 gas mixture was not considered because of its inferior performance compared to pure Argon. Windows incorporating a hard vacuum were not selected because the scope of the overall project did not include addressing the difficult technical implications inherent in the fabrication of a fully evacuated window design.

Quad Argon-filled windows with 2 and 3 optical coatings were also not considered further. These windows exceed the target U-value by as much as 50%. It was felt that the marginal energy saving resulting from halving the target U-value would not justify the incremental cost associated with the additional optical coatings and/or non-air fill gas.

Consistent with the initial design selection, low-iron glass was used for the majority of the economic assessment. However, limited analysis of float glass and low-reflective low-iron glass was also undertaken.

Assumptions

Various assumptions were necessary to calculate the capital and energy cost components. Window costs were estimated based on the following unit prices (in Canadian dollars).

1. Float glass	$0.55/ft^2	($ 5.92/m^2)
2. Low-iron glass	$1.10/ft^2	($11.84/m^2)
3. Low-iron low-reflective glass	$1.65/ft^2	($17.76/m^2)
4. Argon fill gas	$0.48/ft^2	($ 5.14/m^2)
5. Optical coating	$0.48/ft^2	($ 5.14/m^2)

The energy costs were estimated based on the following assumptions:

1. The U-value and SC of the reference double-glazed window was 0.51 $Btu/h \cdot ft^2 \cdot F$ (2.9 $W/m^2 \cdot K$) and 0.85 respectively.

2. Window area was equally distributed in the four cardinal directions.

3. The heating season ran from October 1 to April 30.

4. The windows were located in Ottawa, Canada. The average monthly solar radiation was based on values tabulated by Barakat (1980). The average outdoor temperature over the heating season was 36 F (2°C), per Harrison and Barakat (1983), and the indoor temperature was 70 F (21°C).

5. The utilization efficiency of the solar gain was assumed to be 100%. In other words, no overheating occured, and the net heat loss was calculated simply as the difference between conductive heat loss and solar heat gain. This assumption avoided the need to select a specific house design for consideration, as the results could be normalized on a per square foot basis.

6. The space heating energy cost was $0.0233/kWh, based on natural gas costs (1983) and a conversion efficiency of 65%.

Limitations

Several limitations are inherent in the economic analysis methodology and assumptions. The analysis is suitable for building applications where the dominant window energy components are conductive heat loss and solar heat gains during the heating season. Therefore, the results are not applicable to air-conditioned residences or commercial buildings. Furthermore, the effects of unwanted solar gain or contribution to daylighting, two components that can dominate the net window energy performance of some buildings, were also not considered.

The analysis provides an estimate of simply payback only. Considerations such as future fuel escalation rates, or the time value of money, were not accounted for. This was not considered to be a serious limitation, since the effects of each of these two factors tend to balance each other.

Results and Discussion

The economic performance results are presented in Table 3. Payback periods are presented for each orientation, as well as the average payback for all orientations.

Referring to the average payback periods, it is evident that the economic performance varies over a broad range. The payback period of those windows whose U-values are less than 0.2 $Btu/h \cdot ft^2 \cdot F$ (i.e., all but the uncoated triple- and quad-glazed windows) ranges from 4.6 to 32 years. In general, the triple glazed windows appear to be more cost-effective than the quad windows. The best performers, in terms of lowest payback period, are the triple (float) glazed, Argon-filled, single-coated window followed by the triple (float) glazed, Argon-filled, double coated, and triple (low-iron) glazed, Argon filled, single-coated windows. The window with the longest payback period is the quad-glazed, air-filled window with three optical coatings, reflecting the diminishing returns on the additional cost of energy conserving features as the U-value is decreased below 0.2 $Btu/hr \cdot ft^2 \cdot {}^oF$.

Economic performance is very sensitive to window orientation. For example, the payback period for the best overall performer (triple (float) glass, Argon-filled with one optical coating) varies from 3.2 years for a northern exposure to 7.2 years for southern. As expected, this sensitivity is most pronounced for windows with low SC values, since solar gain is the only directionally dependent heat gain/loss component considered. Stated another way, since solar heat is the dominant energy component for south-facing windows, a high SC is of prime importance for southern orientations. Similarily, since conductive heat loss is the dominant energy component for north-facing windows, windows to be used for this orientation should have low U-values. These observations simply restate well known facts. However, it is interesting to note the magnitude of the variation in payback periods. The range of values could actually justify the use of different windows for different orientations.

The results also indicate that the use of Argon must be considered on an individual basis. For example, use of Argon in two of the triple-glazed designs results in a decreased overall payback period, whereas use of Argon increased the payback period of one of the quad windows.

It would appear that conventional float glass is more economical than low-iron glass. The payback periods for three different triple-glazed designs decreased upon substitution of float glass for low-iron glass. Similarly, the results suggest that the increase in SC resulting from the use of low-iron, low-reflective glass in place of the low-iron glass does not warrant the additional cost. For both triple and quad windows, the payback period increases as the number of low-iron, low-reflective panes increase.

The reader is once again reminded that the preceding analysis is relevant primarily for residential applications. Considerations of applications in commercial buildings would necessitate a comprehensive analysis of daylighting and cooling load components, in addition to heating loads.

CONCLUSION

A comprehensive analysis of the thermal and economic performance of a broad range of innovative window design has been undertaken. Based on the results of this analysis, the following conclusions can be made.

Thermal Performance

1. At least three glazings are required to achieve the target U-value of 0.2 $Btu/h \cdot ft^2 \cdot F$ (1.0 $W/m^2 \cdot K$).

2. Use of a non-air fill gas can significantly reduce the U-value. The reductions are greatest for windows with a maximum number of optical coatings.

3. The optimum interpane spacing for double-, triple- and quad-glazed windows is approximately 0.5, 0.6, and 0.7 in (13, 15 and 18 mm) respectively.

4. Low emmisivity optical coatings decrease the U-value but also decrease the SC.

5. Use of conventional float glass decreases the SC by 10% to 15% compared to the low-iron glass. Use of antireflective low-iron glass increases the SC by a similar magnitude compared to the nontreated low-iron glass.

Economic Performance

1. Triple-glazed windows appear to be more cost-effective than quad-glazed windows. The most economical windows with respect to average payback period are triple (float) glazed, Argon-filled, single- and double-coated, and triple (low-iron) glazed, Argon-filled, single-coated windows.

2. Economic performance can be very sensitive to orientation, particularly for windows with low SC. The magnitude of this sensitivity could justify the consideration of using different windows for different orientations.

3. Float glass appears to be more cost effective than the low-iron and low-reflective low-iron alternatives.

4. Use of Argon instead of air as a fill gas appears to be cost-effective for triple-glazed but not for quad-glazed windows.

5. Since the economic analysis rests heavily on the cost assumptions, any change in these costs would require a reassessment of the rankings.

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TABLE I

Glazing Properties

						Coated Glazing		
	Index of Refraction	Extinction Coefficient	Surface Emissivity		Thickness	Solar Reflectivity		Solar Transmissivity
Glazing Type		cm^{-1}	Uncoated Surface	Coated Surface	mm	Uncoated Surface	Coated Surface	
Conventional Float	1.52	0.257	0.84	0.09	2.16	0.21	0.25	0.61
					3.0	0.20	0.25	0.60
Low Iron	1.474	0.0458	0.84	0.09	2.16	0.23	0.25	0.64
					3.0	0.22	0.25	0.64

TABLE 2

Effect of Glazing Material on Thermal Performance

Number of Glazings	Type*	Interpane Spacing		Fill Gas Type	Number of Optical Coatings	Thermal Performance		
						U-Value		SC
		in	mm			$\frac{Btu}{h \cdot ft^2 \cdot F}$	$\frac{W}{m^2 \cdot K}$	
3	LI	0.6	15	Air	2	0.17	0.97	0.61
3	FL	0.6	15	Air	2	0.17	0.97	0.52
3	LI	0.6	15	Air	0	0.33	1.90	0.90
3	LI(2) AR(1)	0.6	15	Air	0	0.33	1.90	0.95
3	AR	0.6	15	Air	0	0.33	1.90	1.09

* LI = Low Iron
FL = Conventional float
AR = Antireflective low iron

TABLE 3

Economic Performance

Window Description				Thermal Performance			Economic Performance						
Number of Glazings	Number of Optical Coatings	Glass Type*	Fill Gas Type	U-Value		SC	Incr. Cost		Payback Period				
				$\frac{Btu}{h \cdot ft^2 \cdot F}$	$\frac{W}{m^2 \cdot K}$		$\$/ft^2$	$\$/m^2$	North	East	South	West	Average
3	1	LI	Arg	0.19	1.09	0.72	3.20	34.40	5.9	6.8	8.5	6.7	6.9
3	1	FL	Arg	0.19	1.09	0.63	1.55	16.70	3.2	4.2	7.2	4.1	4.6
3	2	LI	Air	0.17	0.97	0.61	3.20	34.40	6.2	8.1	14.2	7.9	9.1
3	2	FL	Air	0.17	0.97	0.52	1.55	16.70	3.3	5.0	18.1	4.8	7.8
3	2	LI	Arg	0.13	0.76	0.61	3.70	39.80	6.3	7.8	12.1	7.7	8.5
3	2	FL	Arg	0.13	0.76	0.53	2.05	22.05	3.8	5.4	12.9	5.2	6.8
3	0	LI	Air	0.33	1.90	0.90	2.20	23.70	5.9	5.7	5.5	5.8	5.7
3	0	AR	Air	0.33	1.90	1.09	3.85	41.40	7.9	6.5	5.3	6.6	6.6
4	1	LI	Air	0.18	1.01	0.73	3.80	40.90	6.6	7.4	9.0	7.3	9.2
4	1	LI	Arg	0.15	0.88	0.73	4.30	46.30	6.8	7.6	8.4	7.5	9.7
4	2	LI	Air	0.13	0.76	0.56	4.30	46.30	7.7	10.4	20.1	10.1	15.7
4	3	LI	Air	0.11	0.62	0.45	4.80	51.60	8.8	13.7	57.5	13.1	32.0
4	0	LI	Air	0.24	1.38	0.84	3.30	35.50	6.4	6.6	6.9	6.6	7.2
4	0	AR	Air	0.24	1.38	1.07	5.50	59.20	8.4	7.3	6.2	7.3	8.0

* LI = Low Iron
FL = Conventional float
AR = Antireflective low iron

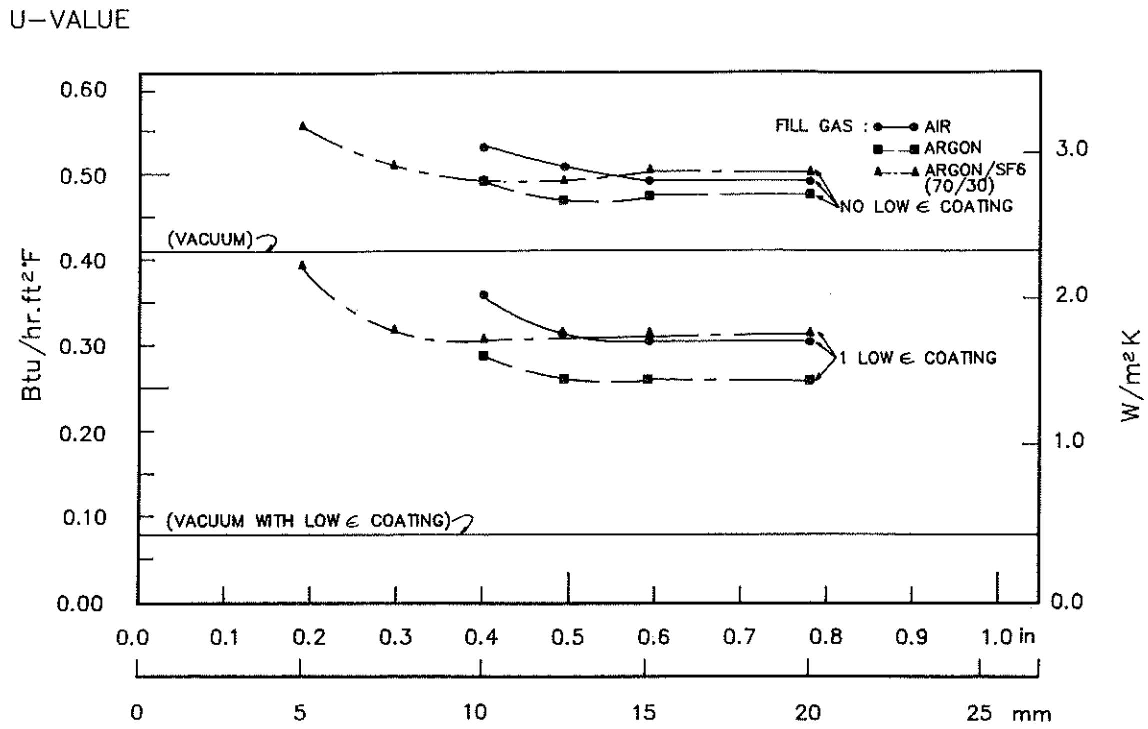

Figure 1. Thermal performance of double-glazed windows

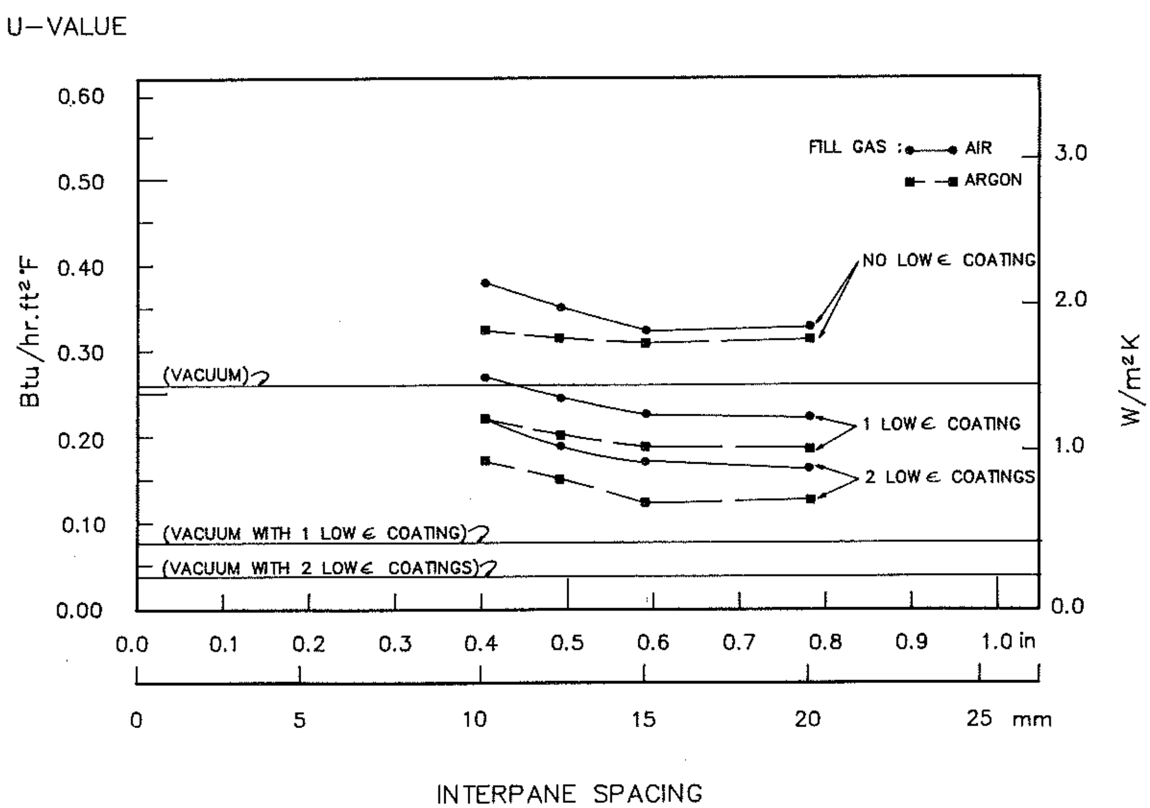

Figure 2. Thermal performance of triple-glazed windows

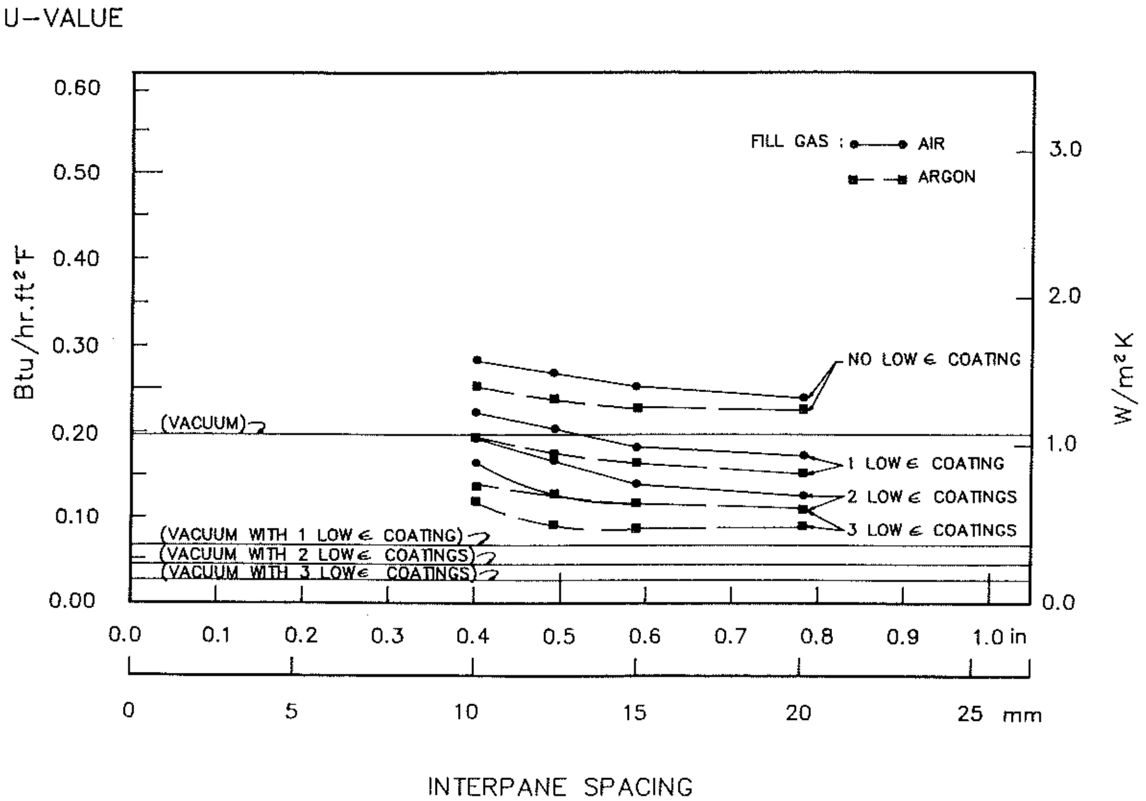

Figure 3. Thermal performance of quad-glazed windows

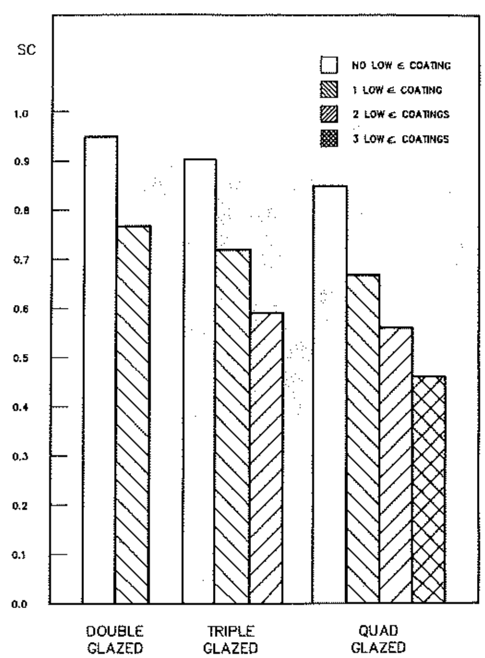

Figure 4. Effect of optical coatings on SC