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UTILIZATION OF HIGH THERMAL PERFORMANCE WINDOWS AND GLAZING FOR PASSIVE SOLAR HEATING OF HOUSES

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ABSTRACT

This paper examines the potential for passive solar heating afforded by high thermal performance window and glazing technologies. More than 25% of residential space conditioning energy consumption in conventional dwellings is due to windows, accounting for billions of dollars of annual energy use in North America's cold climate zones. Since the 1980s, government sponsored research and development has led to the development of sophisticated window technologies employing low-emissivity (low-E) coatings, inert gas fills, low conductivity edge spacers, and insulated frame assemblies with thermal breaks. Guidelines for the optimal use of these technologies for passive solar heating in conventional dwellings have not kept pace. This paper is based on a limited study of the energy conserving and non-energy related implications of currently available residential window technology.

Using computer simulations of annual energy performance, this paper applies a life cycle economic analysis to a range of solar apertures for the various types of glazing systems currently available. It considers the sensitivity of thermal efficiency and solar apertures according to various energy price forecasting scenarios over the useful life of the windows. The paper also considers related issues, including: thermal comfort, condensation control, cooling, and daylighting.

Finally, this paper introduces interim guidelines for the selection and utilization of currently available window technologies. It concludes with a discussion of the critical research and technology transfer initiatives needed to promote a fuller utilization of high thermal performance windows and glazing.

INTRODUCTION

The energy efficiency of residential buildings located in cold climates is significantly impacted by the size, characteristics and arrangement of windows and glazing (fenestration). Until the recent past, designers had only three options; single, double or triple-pane clear glazing. Double glazing remains the predominant choice for cold climate windows, however, during the past decade, research and development of high thermal performance windows offers a considerably broader spectrum of alternatives. This paper identifies key aspects of fenestration design needed to attain a fuller utilization of available and emerging high thermal performance windows and glazing.

2. DEFINITION OF HIGH THERMAL PERFORMANCE WINDOWS AND GLAZINGS

High thermal performance windows and glazing are not formally defined, however, they commonly possess the following characteristics [1]:

- 2 or more sealed panes of glass;
- 1 or more low-emissivity coatings/suspended films;
- inert gas fills between the sealed panes (e.g., argon, krypton);
- low thermal conductivity edge spacers;
- frame assemblies with integral thermal breaks; and
- airtight and waterproof seals around operating units.

Table 1 presents a summary of the thermal and optical properties of conventional and high thermal performance glazing for residential applications. It should be appreciated that for designers, builders and consumers, the task of selecting appropriate windows and glazing is no longer simple. The growing array of available glass, coatings, gas fills, edge spacers and frame assemblies offers a degree of choice which requires increasingly sophisticated knowledge.

Table 1 - Typical U-Values (Centre of Glass) and Solar Heat Gain Coefficients for Glazings

Glazing Type	U-value*	RSI	SHGC*
Single Glazing			
Clear Glass	5.91	0.17	0.86
Double Glazing			
12.7 mm air filled	2.73	0.37	0.75
12.7 mm air filled, e=0.20 on one surface	1.99	0.50	0.65
12.7 mm air filled, e=0.10 on one surface	1.82	0.55	0.54
12.7 mm argon filled, e=0.10 on one surface	1.53	0.65	0.54
Triple Glazing			
13 mm air filled	1.76	0.57	0.67
13 mm air filled, e=0.20 on one surface	1.42	0.70	0.60
13 mm air filled, e=0.10 on two surfaces	1.02	0.98	0.45
13 mm argon filled, e=0.10 on two surfaces	0.80	1.25	0.45

*Compiled from Tables 5 and 11, Chapter 29, *ASHRAE Handbook of Fundamentals*, 1997.

Table 1 indicates that high thermal performance glazings are typically about twice as energy efficient as clear double glazing. High performance windows using glazing with a U-value of about 1.0 or less, are commonly referred to as "*super high performance*" windows.

An important aspect of window performance is the relationship between the centre of glass U-values and those for the edge of glass and the window frame. When a low thermal conductivity edge spacer and insulated frame with thermal breaks are combined with a high performance glazing, the effective thermal resistance of the entire window assembly is marginally lower than the centre of glass value. As thermal bridging in the assembly increases, the difference between the effective and centre of glass thermal resistance values rapidly diverges. This suggests that windows are an integrated system of components whose individual contributions to overall performance require careful harmonization by manufacturers, and proper selection by designers, builders and consumers. From an energy conservation perspective, the significance of recent innovations in window and glazing technology are best appreciated by considering the potential for passive solar energy.

3. PASSIVE SOLAR POTENTIAL IN HOUSES

The CANMET report entitled *Passive Solar Potential in Canada: 1990 - 2010* [2], indicates the following passive solar potential for houses to the year 2010, as depicted in Table 2.

Table 2 - Canadian Residential Passive Solar Potential, 1990 - 2010

	Ultimate Passive Solar Potential (PJ/Year)	Technically Feasible Potential (PJ/Year)	Reasonably Achievable Market Potential (PJ/Year)
Existing Residential Retrofit Potential	296	136	36
New Residential (non high rise)	151	53	25

Adapted from Table 1, p. xiii, *Passive Solar Potential in Canada: 1990 - 2010*.

Potential improvements in the reasonably achievable utilization of high thermal performance windows are enormous. In fact, any marginal closing of the 128 PJ/year gap between *reasonably achievable* and *technically feasible* solar potentials will prove significant. At present, this potential is not being fully realized in conventional houses, in sharp contrast to what has been demonstrated in advanced passive solar homes. This implies that more appropriate means of technology transfer are needed to impact the vast majority of new and existing dwellings, based on the following rationale:

- Housing designers, builders and consumers seldom retain design specialists, as do other sectors of the building industry;.
- Guidelines which demonstrate optimal utilization of high thermal performance windows are more "user friendly" than computer tools; and
- Non-energy benefits of high thermal performance windows (condensation control, thermal comfort, and daylighting), once comparatively monetized with other investments in housing technology, will more fully convey the advantages of these technological advances.

The next section of this paper examines the cost effectiveness of high thermal performance windows based on energy savings.

4. COST EFFECTIVENESS OF HIGH PERFORMANCE GLAZINGS

In order to determine the cost effectiveness of high performance windows, a life cycle cost analysis was performed according to a widely accepted methodology [3]. This process consisted of the following steps:

1. A conventional new house design was developed which resembled typical new housing starts in the Toronto area (see Figure 1);
2. ENERPASS™ software was used to simulate the annual energy performance of this model dwelling using Toronto weather data and various solar apertures (ratios of south-facing glazing area to floor area). ENERPASS™ software , developed by Enermodal Engineering is capable of performing hourly calculations of building temperatures, energy consumption, peak demand loads, daylighting control, inter-zone heat and air transfer, transient effects of solar radiation, and passive solar design (including thermal mass and sol-air effect). ENERPASS™ simulations have been validated by TASK 13 of the International Energy Agency [4].
3. A life cycle analysis was performed using current energy and window prices, over a 25 year study period, to determine the present worth of various combinations of solar aperture and glazing type.

For all cases, space heating was assumed to be provided by a 90% efficient natural gas furnace. The highest energy conversion efficiency was combined with the lowest cost fuel ($5.94/GJ) [5], to conservatively estimate the cost effectiveness of energy efficiency improvements among window alternatives. When more expensive fuels are used, such as electricity ($25.27/GJ), oil ($10.17/GJ) or propane ($14.20/GJ), the energy savings due to decreased transmission losses and higher net solar gains correspondingly increase. Clearly, if high performance windows are cost effective when heating with natural gas, they are even more cost effective with more expensive heating fuels.

Minimum window areas were assigned to each of the rooms in the dwelling according to the requirements of the 1995 National Building Code [6]. For the south facing rooms, this resulted in a total window area of 4.8 m^2, translating into a solar aperture of 3%. Subsequently, only the south facing window areas were increased in 2% increments up to a 15% solar aperture, or 24 m^2 of window area.

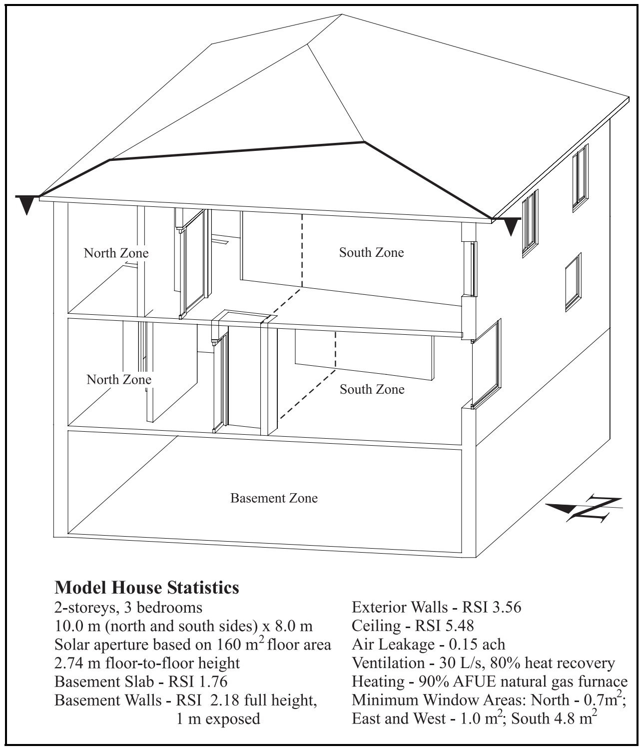

Figure 1 - Schematic of House Simulation Model

Currently available windows were modelled in the simulations. All frames were assumed to be thermally broken, and all sealed glazing units were to have low thermal conductivity edge spacers, except for the double clear units. The physical characteristics and capital costs of the windows used in analyses are summarized in Table 3. Capital costs for windows were obtained from the most recent study conducted on behalf of the National Research Council Canada during its development of the model *National Energy Code for Houses* [7].

Table 3 - Characteristics and Costs of Windows Used in Analyses

Glazing Type	U-Value	SHGC	Cost ($/m^2)
Double, clear	2.73	0.75	232
Double, low-E	1.82	0.54	248
Double, low-E, argon	1.53	0.54	265
Triple, low-E, argon	0.80	0.45	333

Because of the sensitivity of life cycle analyses to fuel cost escalation rates [8], two future fuel price scenarios were examined. The first scenario assumed the rate of fuel price escalation over the study period would remain less than the discount rate. In the second scenario, fuel price escalation outpaces the discount rate, indicating the effect of moving toward world energy prices or the imposition of a carbon tax.

The results of the analyses are depicted in Figures 2 and 3 below.

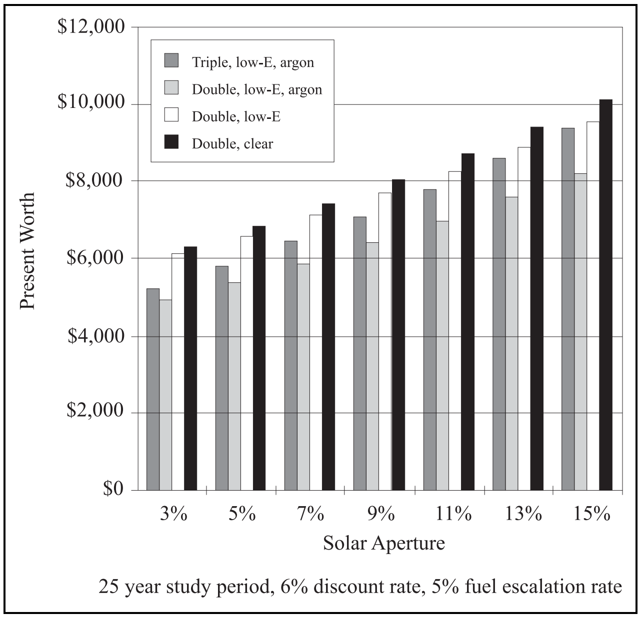

Figure 2 - Life Cycle Cost Comparison (Low Fuel Cost Escalation Rate)

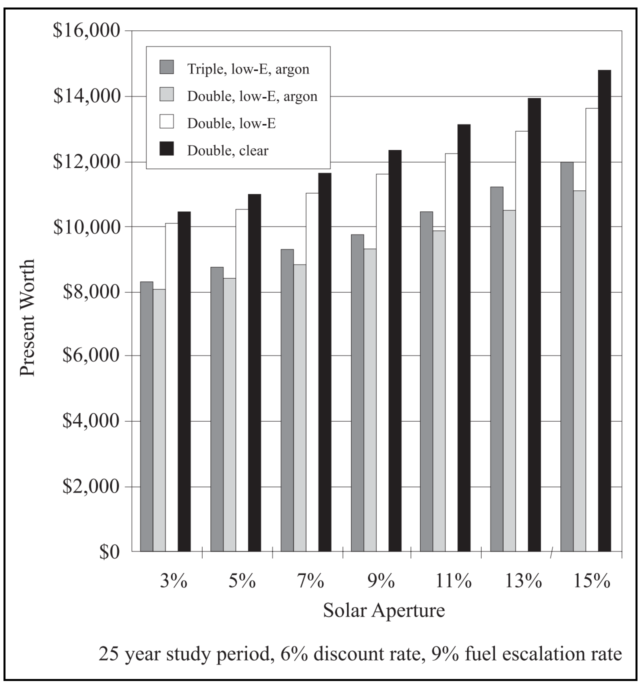

Figure 3 - Life Cycle Cost Comparison (High Fuel Cost Escalation Rate)

In both cases, the most cost effective window utilizes double glazing with a low-emissivity coating and argon gas fill. The second best choice is the super high performance triple glazed window. Sensitivity analyses indicated that these two window types are virtually equivalent in terms of cost effectiveness for natural gas and oil, but the super high performance window is the best choice when electricity or propane are used for space heating. Another interesting relationship which was examined was annual heating load versus solar aperture by glazing type. In the past, passive solar guidelines recommended a maximum 8% solar aperture in most parts of Canada [9]. Analyses from this study now indicate that this varies according to glazing characteristics. Figure 4 depicts these relationships, indicating that the older rules-of-thumb only apply to double clear, and double, low-E coated glazing. Double, low-E and argon glazing was found to have an optimal solar aperture of about 12%. Triple, low-E and argon glazing does not have an optimum solar aperture. Analyses indicate that the greater the solar aperture, the lower the annual heating load. This is a significant advancement over the energy penalties associated with earlier, less thermally efficient glazing.

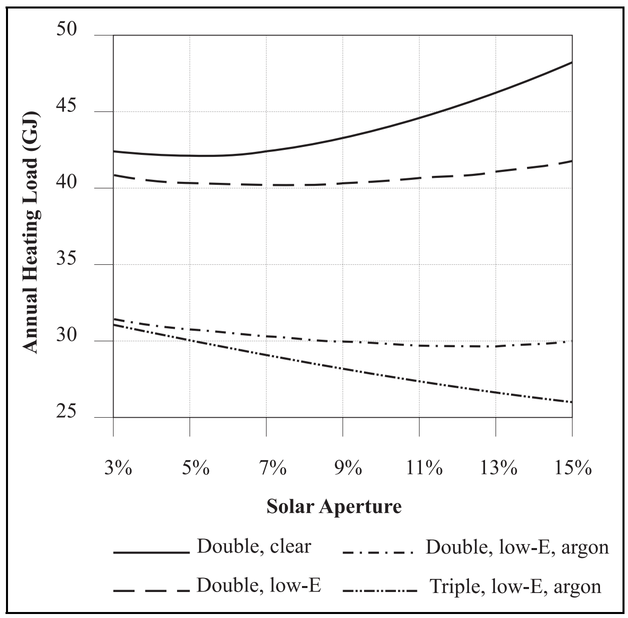

Figure 4 - Annual Heating Load as a Function of Solar Aperture and Glazing Type

Another interesting relationship was the comparison between annual solar fraction and solar aperture by glazing type. Due to the higher solar heat gain coefficient (SHGC) of low thermal efficiency windows, the amount of passive solar gain is greater than the amount captured by higher efficiency glazings, due to their lower SHGC values. However, the conductive and radiative losses through higher efficiency glazing are much lower, hence the net solar gains expressed as a fraction of the annual heating load are higher.

Figure 5 indicates that high performance windows attain higher solar fractions than more traditional windows, particularly at higher solar apertures. This is due to the improved thermal efficiency of the dwelling (see Figure 4), more than offsetting lower SHGC values.

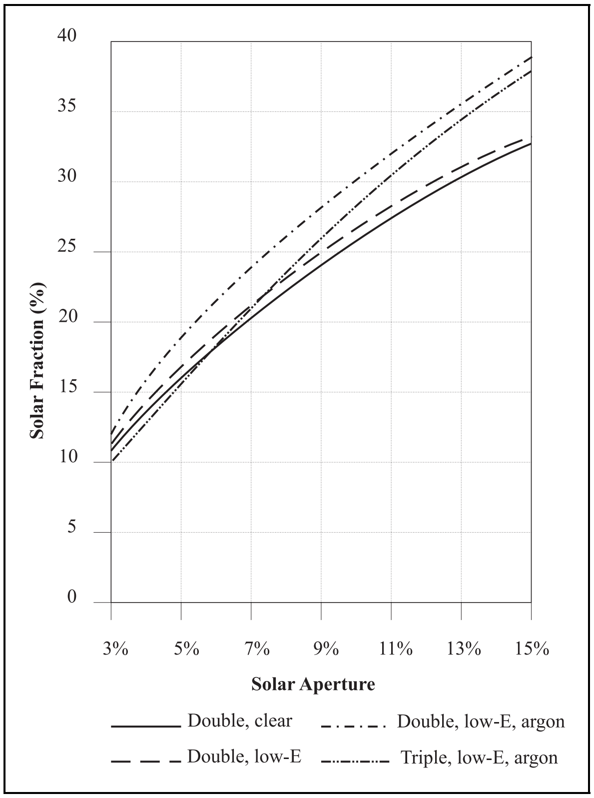

Figure 5 - Annual Solar Heating Fraction as a Function of Solar Aperture and Glazing Type

These limited analyses demonstrate the energy advantages of high and super high performance windows. It is important to note that these advantages vary with climate and the cost of energy. There are additional considerations to energy efficiency when designing fenestration.

5. ADDITIONAL CONSIDERATIONS

Fenestration serves many purposes in dwellings, and can significantly impact the performance of the building envelope. Some important factors to consider include: thermal comfort; condensation control; cooling; and daylighting.

Thermal Comfort

A well recognized phenomenon associated with discomfort is asymmetric thermal radiation, caused by exposure to radiative surfaces at different temperatures [10]. The interior surface temperatures of glazing increases as the U-value decreases, due to the diminishing effect of the inside air film on the overall thermal resistance of the window assembly. In areas of a dwelling with large expanses of glazing, unacceptable levels of discomfort may be predicted at night during the coldest months of winter. High performance windows can virtually eliminate this phenomenon.

Another aspect of thermal comfort is overheating during the day, especially during the shoulder months. Figure 6 depicts the maximum simulated south-zone air temperatures as a function of solar aperture by glazing type. Note the effect of the 2 ^{o}C setback of the thermostat modelled in simulations.

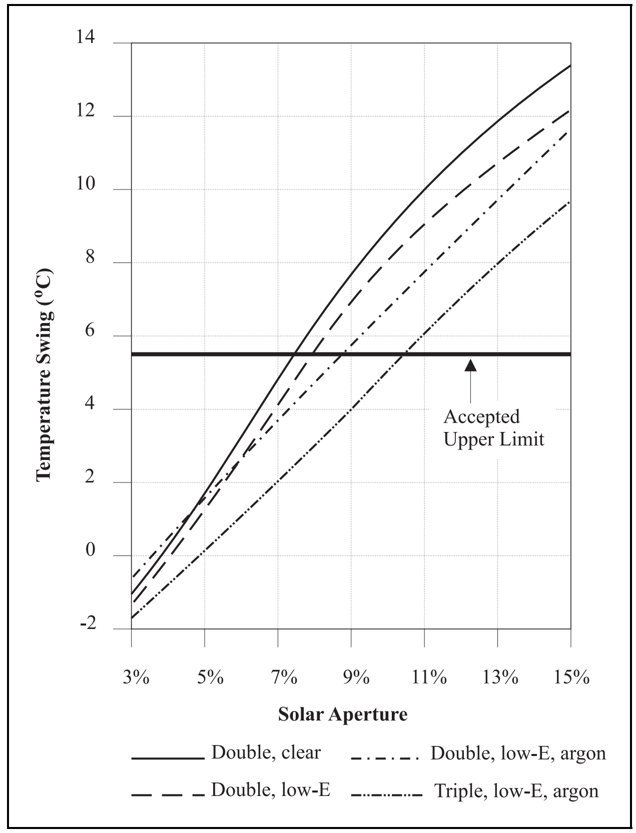

Figure 6 - Temperature Swing Aboout 22 ^{o}C as a Function of Solar Aperture and Glazing Type

A major advantage of high performance windows is the reduction in overheating normally experienced with conventional windows. The accepted upper limit of temperature swing indicated in Figure 6 conforms with that used in earlier studies of passive solar utilization [11].

Based on the computer simulations, it may be concluded that overheating can be well controlled when high performance windows and conventional solar apertures are used. When the super high performance windows (triple, low-E, argon) were simulated, the maximum temperatures predicted using hour-by-hour calculations were only sustained for 2 to 3 hours in the late afternoon periods. Additional simulations were performed to determine the effects of thermal storage and mechanical air circulation between zones of dwelling. With the moderate introduction of thermal mass and air circulation, temperature swings in the south zone were reduced to less than 3 ^{o}C. The influence of high performance windows on overheating caused by east and west facing fenestration was not examined.

Condensation Control

Another advantage of high thermal performance windows is superior condensation control. Figure 7 depicts the maximum indoor relative humidity which is sustainable without condensation for typical glazing units. The data were generated using edge of glass U-values and standard indoor and outdoor environmental conditions. More sophisticated and accurate condensation prediction methods for the whole window assembly are available [12].

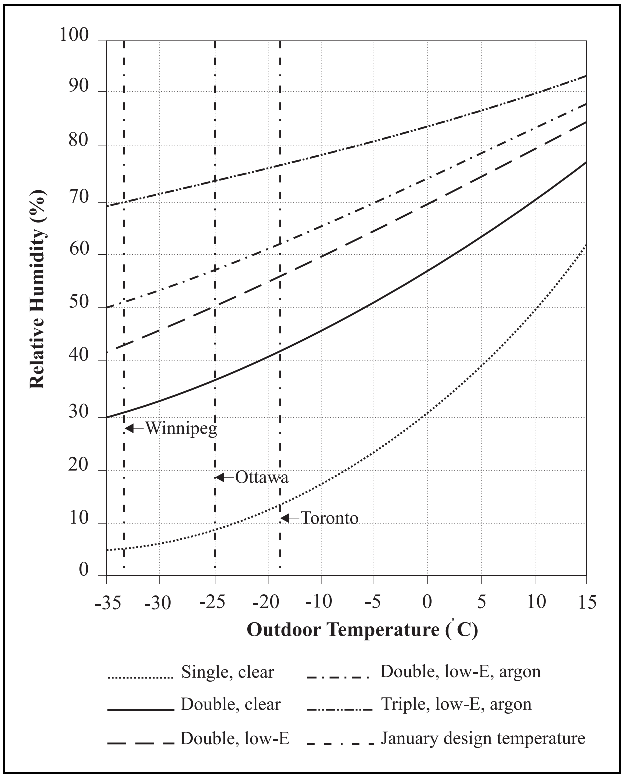

Figure 7 - Maximum Relative Humidity Levels Without Condensation in Relation to Outdoor Temperature for Typical Glazings

For Toronto, clear double glazing is adequate for maintaining desirable levels of indoor relative humidity during the coldest winter periods, however, condensation may be experienced when high humidity conditions are created through normal household activities such as bathing, cooking and washing. In colder areas, such as Ottawa and Winnipeg, a more thermally efficient glazing is required to avoid window condensation. It is important to recognize the positive influence of condensation control on occupant health, and the durability of window components and finishes.

Cooling

A limited analysis of the influence of high performance windows on cooling load was carried out. The thermal and optical properties of high performance windows were found to reduce peak cooling loads and cooling energy demand. Triple, low-E with argon glazing was found to produce the most significant reduction.

Daylighting

Prior to the introduction of high performance windows, the provision of a generous view and ample daylighting in cold climate housing translated into an energy intensive luxury. Large expanses of glass admitted higher levels of airborne noise, caused seasonal discomfort, and desiccated indoor air during cold periods. Clear glazings do not adequately control the ultraviolet fading of fabrics and finishes in the dwelling. Low-E glazings can be engineered to selectively reflect portions of the sun's light spectrum. This enables the flexible design of fenestration which enhances view and light, while avoiding many of the disadvantages normally associated with larger windows.

Despite the inherently superior qualities of high performance windows, the majority of Canadian residential windows being purchased are of the conventional type. The Canadian Window and Door Manufacturers' Association reports that about 32% of residential windows use low-E coated glazings, but estimates that only a small fraction of these incorporate argon gas fills and low conductivity edge spacers [13]. This implies that the full benefits of high performance window technology are not being effectively communicated to manufacturers, designers, builders and consumers. Clearly, research and development alone are not sufficient to promote energy conservation, and capitalize on Canada's technically feasible passive solar potential.

6. WINDOW SELECTION GUIDELINES

Recommended applications of available window glazings are summarized in Table 4 and are intended to represent an approach to technology transfer which is more appropriate to the needs of designers, builders and consumers.

Given the limited nature of the analyses presented in this paper, the guidelines which are presented below should be viewed as being of an interim nature, and applicable within the more moderate range of cold climate. Many of the benefits associated with high performance windows will require monetization to fully convey their advantages. More sophisticated methodologies for passive solar fenestration design have been advanced, but their application to conventional dwellings has been limited [14,15].

Table 4 - Recommended Application of Available Window Glazing Alternatives

	WINDOW GLAZING			
APPLICATION	Double clear	Double low-E	Double low-E argon	Triple low-E argon
Seasonal, Temporary or Unheated Building	❍	❍		
Sunroom, Conservatory, Greenhouse			❍	⊙
Most Cost Effective Energy Efficiency				
- natural gas, oil			⊙	❍
- electricity, propane			❍	⊙
Optimal Solar Aperture	6%	8%	12%	15% +
Thermal Comfort				
- overheating			❍	⊙
- asymmetric radiation			❍	⊙
Cooling Load Reduction			❍	⊙
Humidity Control			❍	⊙
Sound Control				⊙
UV Fading Control			❍	⊙

LEGEND: ❍ Acceptable ⊙ Superior

Note: Application of the ratings in this table is limited to areas with a Southern Ontario (Toronto) climate.

Energy efficiency is not the sole criterion for window selection. The style, durability and security of windows are equally important considerations. However, technological innovations in the thermal and optical properties of glazing do not conflict with these considerations, and often enhance desirable characteristics. Further, high thermal performance windows are demonstrably more environmentally benign (reduced greenhouse gas emissions), economically viable (lower life cycle costs), and superior in non-energy aspects of performance.

7. CONCLUSIONS

This limited study of high thermal performance windows offers the following conclusions:

1. High thermal performance windows and glazing offer superior performance in terms of energy efficiency, cost effectiveness, thermal comfort, condensation control and daylighting potential.
2. Research into the monetization of the non-energy benefits of high performance windows is needed to more fully convey their inherent advantages.
3. A more comprehensive study of *conventional* houses across representative regions of Canada is needed to assess appropriate fenestration design strategies which are sensitive to climate and regional energy prices, and take fuller advantage of Canada's technically feasible passive solar potential. This work should include an examination of east and west facing fenestration, and appropriate shading devices.
4. Technology transfer remains a critical aspect of realizing the full benefits of technological innovation. Appropriate guidelines on the energy conserving opportunities, selection and design of residential fenestration are needed to assist designers, builders and consumers make informed decisions.

As window and glazing technology evolves, a greater degree of fenestration design freedom will be made available, and hopefully realized in practice. High thermal performance window technology can be expected to become more affordable and cost effective over time. Appropriate fenestration selection and design practices can enhance the physical and psychological well being of occupants, increase housing affordability, and contribute to the reduction of greenhouse gas emissions. View, daylight, thermal comfort, energy efficiency and occupant health need no longer be conflicting objectives of fenestration design within housing architecture.

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REFERENCES

[1] "Energy-Saving Windows", 1993, CANMET, Natural Resources Canada, Ottawa.

[2] A.J. Parekh and R.E. Platts, Scanada Consultants Ltd., 1990, "Passive Solar Potential in Canada: 1990 - 2010". DSS Contract No. 69SZ.23216-8-9043. The CANMET Energy Technology Centre, (CETC) Energy Technology Branch, Energy Sector, Department of Natural Resources Canada, Ottawa, Ontario.

[3] ASTM E 1185-93, "Standard Guide for Selecting Economic Methods for Evaluating Investments in Buildings and Building Systems", ASTM Standards on Economics, Third Edition, 1994, pp. 3-7.

[4] ENERPASS Version 4.0, August 1996, Enermodal Engineering, Kitchener, Ontario.

[5] M. Lio and T. Kesik, "Implications of Adopting the National Energy Code for Housing in Ontario, July 1995, Contract Report for Ontario Hydro", Ontario Ministry of Housing, Ontario Ministry of Environment and Energy, Canada Mortgage and Housing Corporation and the Ontario Natural Gas Association, CMHC, Ottawa, p. 3-13.

[6] "National Building Code of Canada", 1995, Canadian Commission on Building and Fire Codes, National Research Council Canada, Ottawa, Article 9.7.1.2.

[7] "Cost and Performance of Canadian Windows", May 1993, Enermodal Engineering Ltd., Report prepared for National Research Council Canada, Ottawa.

[8] ASTM E 917-93, "Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems", ASTM Standards on Economics, Third Edition, 1994, p. 32.

[9] "Passive Solar House Designs for Canada", 1989, Canada Mortgage and Housing Corporation, Ottawa.

[10] "ASHRAE Handbook: Fundamentals", 1997, American Society of Heating, Refrigeration and Air-Conditioning Engineers, Atlanta, Georgia, p. 8.13.

[11] S.A. Barakat and D.M. Sander, 1982, "Utilization of Solar Gain through Windows for Heating Houses", Building Research Note No. 184, Division of Building Research, National Research Council of Canada, Ottawa, Ontario.

[12] McGowan, A., "Predicting Window Condensation Potential," ASHRAE Journal, July 1995.

[13] Ducker Research Company Inc., 1997, "Study of the Canadian Market for Windows and Doors", Canadian Window and Door Manufacturers' Association, Toronto, Ontario.

[14] D.M. Sander and S.A. Barakat, 1984, "Mass and Glass. How Much? How Little?", ASHRAE Journal, Vol. 26, No. 11, pp. 26-31.

[15] Kesik, T. and M. Lio, 1995, "Housing Energy Design with HOT2000 Applications", Habitechnica, Toronto, Ontario.