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TOWARDS DEVELOPING SKYLIGHT DESIGN TOOLS FOR THERMAL AND ENERGY PERFORMANCE OF ATRIUMS IN COLD CLIMATES

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ABSTRACT

This paper presents an analysis of the impact of selected design alternatives on the thermal and energy performance of atriums based on the methodology outlined in the accompanying paper. Computer simulation programs were used to predict the impact of the selected design alternatives on the design performance outputs of atriums. Design alternatives focused on fenestration glazing types, fenestration surface area, skylight shape, atrium type, and interaction of the atrium with its adjacent spaces. Design performance outputs, evaluated with respect to a basecase design, included seasonal solar heat gain, cooling and heating peak loads and annual cooling, heating and total (heating plus cooling) energy. Design tools were developed to quantify the impact of the design alternatives on the performance outputs. The design tools were cast into two-dimensional linear relationships with the glazing U-value and SHGC as independent parameters. The results for the enclosed atriums showed that the annual cooling energy ratio increased at a rate of 1.196 per unit of SHGC ratio and decreased at a rate of 0.382 per unit of U-value ratio. However, the annual heating energy ratio increased at a rate of 1.954 per unit of U-value ratio and decreased at a rate of 1.081 per unit of SHGC ratio. Similar trends were also found for the three-sided and linear atriums. Pyramidal/pitched skylights increased the solar heat gain ratio by up to 25% in the heating season compared to flat skylights. The effect of the skylight shape on the annual cooling and heating energy may be positive or negative, depending on the glazing U-value and SHGC ratios and the atrium type. Atriums open to their adjacent spaces reduced the annual cooling energy ratio by up to 76% compared to closed atrium spaces. However, open atrium spaces increased the annual heating energy ratio by up to 19%.

INTRODUCTION

The atrium is proliferating, with an increasing frequency, in new, renovated, and converted office and commercial buildings, especially in cold climate regions. Atriums revive the indoor space by admitting natural light, simulating the outdoors, and increasing people interaction. Atriums were also reported to increase the marketing values of many buildings, beside their psychological and physiological effects on increasing the morale of people and exposure to daylight. However, these amenities may be counteracted by excessive solar heat gains in summer, high total energy consumption and expensive operation.

Physical characteristics of atriums affect the indoor environment conditions, thermal loads and daylighting performance. Daylighting has the potential to reduce electrical lighting and cooling energy consumption [1,2]. However, in most atrium buildings, electrical lighting operation is not controlled based on daylight availability. Furthermore, the sizes and forms of atrium spaces lend themselves to complex skylight shapes and surface areas that result in excessive solar heat gains in summer and high heat losses in winter. The impact of skylight and atrium physical parameters on the atrium thermal and energy performance has not been well understood. Therefore, there is a need to develop design tools to take full advantage of skylight potential daylighting, improve thermal performance, and optimize the total energy consumption of atriums for lighting, heating and cooling.

Extensive studies were devoted to developing design strategies for atriums. Kainlauri and Vilmain [3] conducted a survey on atrium research to develop design criteria that focused on atrium orientation, building envelope, HVAC system and indoor thermal environment. Mills [4] reviewed completed atrium research projects in Europe and the United Kingdom, and compiled design strategies that focused on the incorporation of passive solar principles into the atrium design. Yoshino et al. [5] reviewed current atrium research projects in Japan, and identified common trends in the design of the indoor thermal environment and the construction of atrium buildings. Bryn [6] presented a historical development of atriums and discussed design aspects from the perspective of atrium function, indoor thermal environment and energy use.

Computer simulation programs were used extensively to investigate the impact of design strategies on daylighting and thermal performance and energy use of atriums. Duke [7] compared the energy cost of a building with an open courtyard and a building with a glazed courtyard using the DOE2 program. The author concluded that adding a glazed roof to an open courtyard resulted in energy cost savings of about 10%. Landsberg et al. [8] investigated the impact of a wide range of design strategies on the energy performance of atrium buildings. The design strategies focused on the characteristics of the fenestration and HVAC system and control strategies. Four types of atrium buildings in different cities in the USA were monitored and modeled using the DOE2 computer program. Field measurements were used to supplement the

input data for the computer program to overcome its limitations in modeling atriums. The authors found that three out of the four buildings, when configured to include effective design strategies, resulted in lower energy consumption than that of similar buildings without the atrium. Gillette and Treado [9] and Gillette [10] investigated the impact of atrium roof glazing on the lighting and thermal performance of a linear atrium in hot and humid, and cold and dry climates. The computer program TARP was used for this purpose. The authors analyzed the performance of the atrium alone, the atrium with its daylighting zone of influence and the atrium with the rest of the building as whole. They concluded that in both climates, the use of a glazed roof over an opaque roof increased both the heating and cooling energy in the atrium, and the benefits were found only in the reduced lighting energy. However, positive energy savings may be achieved when the atrium was treated as an integral part of the building. Wall [11] used the computer program DEROB-LTH to investigate the influence of the design options on the climate and energy requirements of three types of atrium buildings in Swedish regions. The atrium types included enclosed, three-sided and linear atriums with dimensions of 9 m deep, 18 m long and 9 m high. 20% of the atrium internal wall surface areas were double-glazed. The atrium space was not conditioned, and was modeled as one-thermal zone with a uniform temperature. The design options focused on the glazing types of the exterior fenestration, thermal inertia, atrium orientation, infiltration air change rate, ventilation system and sun shades. The design performance outputs were the atrium indoor temperature and the energy use of the adjacent buildings. The results were presented in absolute values, which allowed to compare the performance of the different atrium types. The author found that the three-sided atrium was the best at collecting and retaining solar heat gains and, therefore, the heating energy requirements of the adjacent buildings may be reduced.

OBJECTIVES

The purpose of this study is to use computer simulation programs to predict the effect of selected skylight and atrium physical parameters on thermal and energy performance of atriums. The specific objectives were:

1. To analyze the impact of selected design alternatives on the thermal and energy performance of the selected atrium types; and
2. To develop design tools to quantify the impact of the selected design alternatives on the thermal and energy performance of the selected atrium types.

Design tools were developed for the region of Ottawa, Canada, a typical cold climate region. However, the design tools may be applied to any other region with similar climate.

METHODOLOGY

The methodology outlined in the accompanying paper was employed here to predict the impact of the selected design alternatives on thermal and energy performance of selected atrium types. The computer program ESP-r was used for thermal and energy simulation. However, lighting heat gains of the atrium space were calculated using the ADELIN software, and then fed into ESP-r as time step heat gains. This method was found to be faster than the simultaneous coupling of ESP-r and RADIANCE software.

The simulated atriums were four-storey buildings with total ground-to-roof height of 16 m. The atriums had perimeter walkways of 2 m width along the internal, opaque walls at each floor level. Figure 1 shows the geometry and dimensions of the enclosed, three-sided and linear atriums as simulated when the atrium roof and walls are 100% glazed. The figure shows only the transparent portion of the fenestration surface (75% of the total fenestration surface). The remaining portion of the fenestration surface, which accounts for the frame structure, was dumped in the roof or wall surface. When the atrium roof and walls are 50% glazed, the fenestration, as simulated, takes the following dimensions: The skylight aperture is 9.8 m x 9.8 m for the enclosed and three-sided atriums, and 6 m x 48 m for the linear atrium. The glazed wall surface is 6 m x 16 m for the three-sided and linear atriums. The pitch angle is kept constant for the pyramidal and pitched skylight, and is equal to 45°.

The performance outputs were presented in terms of dimensionless ratios relative to the basecase design. The performance outputs included seasonal solar heat gain, cooling and heating peak loads and annual cooling, heating and total energy. Table 1 shows the performance characteristics of the basecase design for each atrium type. In the following, the design performance outputs were analyzed and design tools were developed as a function of the design parameters.

SOLAR HEAT GAINS

Figure 2 shows the ratio of the solar heat gain absorbed by the atrium interior surfaces during the cooling and heating seasons to that of the basecase. The solar heat gain ratio in the cooling and heating season increased with the solar transmittance ratio (ratio of the transmittance of a given design to that of the basecase). As compared with the basecase design (with double clear glazing), the triple clear low-e and double gray glazing reduced the seasonal solar heat gain ratio by about 52%, triple clear glazing by about 27%, and double clear low-e glazing by about 22%. As compared with the flat skylight, the pyramidal/pitched skylight did not significantly affect the solar heat gain ratio in the cooling season (less than 6% difference). However, the pyramidal/pitched skylight increased the solar heat gain ratio by up to 25% for the enclosed and linear atriums, and by up to 10% for the three-sided atrium in the heating season. This was due

to the fact that the pyramidal/pitched skylight collected and transmitted more solar radiation at low sun altitudes (in winter) than did the flat skylight.

By fitting the data of figure 2 using second degree polynomial regression (with regression constant $R^2 > 0.98$), the following design equations were obtained for atriums with 100% glazed roof and walls (see figure A-1 for correlation plots):

Enclosed atrium:

Flat skylight,

$$\begin{aligned} \text{SSHGR} &= \text{STR} \cdot (0.173 \cdot \text{STR} + 0.823), & \text{for heating season} \\ \text{SSHGR} &= \text{STR} \cdot (0.127 \cdot \text{STR} + 0.872), & \text{for cooling season} \end{aligned} \quad (1)$$

Pyramidal skylight,

$$\begin{aligned} \text{SSHGR} &= \text{STR} \cdot (0.118 \cdot \text{STR} + 1.071), & \text{for heating season;} \\ \text{SSHGR} &= \text{STR} \cdot (0.108 \cdot \text{STR} + 0.927), & \text{for cooling season} \end{aligned} \quad (2)$$

Three-sided atrium:

Flat skylight,

$$\begin{aligned} \text{SSHGR} &= \text{STR} \cdot (0.135 \cdot \text{STR} + 0.863), & \text{for heating season} \\ \text{SSHGR} &= \text{STR} \cdot (0.136 \cdot \text{STR} + 0.862), & \text{for cooling season} \end{aligned} \quad (3)$$

Pyramidal skylight,

$$\begin{aligned} \text{SSHGR} &= \text{STR} \cdot (0.109 \cdot \text{STR} + 0.967), & \text{for heating season;} \\ \text{SSHGR} &= \text{STR} \cdot (0.123 \cdot \text{STR} + 0.89), & \text{for cooling season} \end{aligned} \quad (4)$$

Linear atrium:

Flat skylight,

$$\begin{aligned} \text{SSHGR} &= \text{STR} \cdot (0.144 \cdot \text{STR} + 0.854), & \text{for heating season} \\ \text{SSHGR} &= \text{STR} \cdot (0.105 \cdot \text{STR} + 0.895), & \text{for cooling season} \end{aligned} \quad (5)$$

Pitched skylight,

$$\begin{aligned} \text{SSHGR} &= \text{STR} \cdot (0.097 \cdot \text{STR} + 1.109), & \text{for heating season;} \\ \text{SSHGR} &= \text{STR} \cdot (0.105 \cdot \text{STR} + 0.924), & \text{for cooling season} \end{aligned} \quad (6)$$

Where:

SSHGR: the ratio of the seasonal solar heat gain of a given design to that of the basecase (decimals); and

STR : the ratio of the solar transmittance of a given glazing to that of the basecase (decimals).

Figure 3 shows the effect of the fenestration surface area ratio on the seasonal solar heat gain ratio. The SSHGR was proportional to the fenestration surface area ratio. In the heating season, reducing the fenestration surface area by 50% resulted in a reduction of the SSHGR by up to 50% for flat skylights and by up to 40% for pyramidal/pitched skylights, particularly for the enclosed and linear atriums. In the cooling season, however, reducing the fenestration surface area by 50% reduced the SSHGR by up to 50% for both flat and pyramidal/pitched skylights.

By fitting the data of figure 3 using linear regression (with regression constant $R^2 > 0.98$), the following design equations were obtained:

Enclosed atrium:

Flat skylight,

$$\text{SSHGR} = \text{FSAR}, \quad \text{for heating and cooling season} \quad (7)$$

Pyramidal skylight,

$$\begin{aligned} \text{SSHGR} &= 1.208 \cdot \text{FSAR}, & \text{for heating season;} \\ \text{SSHGR} &= 1.050 \cdot \text{FSAR}, & \text{for cooling season} \end{aligned} \quad (8)$$

Three-sided atrium:

Flat skylight,

$$\text{SSHGR} = 1.004 \cdot \text{FSAR}, \quad \text{for heating and cooling season} \quad (9)$$

Pyramidal skylight,

$$\begin{aligned} \text{SSHGR} &= 1.088 \cdot \text{FSAR}, & \text{for heating season;} \\ \text{SSHGR} &= 1.027 \cdot \text{FSAR}, & \text{for cooling season} \end{aligned} \quad (10)$$

Linear atrium:

Flat skylights,

$$\text{SSHGR} = 1.019 \cdot \text{FSAR}, \quad \text{for heating and cooling season} \quad (11)$$

Pitched skylight,

$$\begin{aligned} \text{SSHGR} &= 1.236 \cdot \text{FSAR}, & \text{for heating season;} \\ \text{SSHGR} &= 1.054 \cdot \text{FSAR}, & \text{for cooling season} \end{aligned} \quad (12)$$

Where FSAR is the ratio of the fenestration (skylight and glazed walls) surface area to that of the roof and walls (decimals).

COOLING AND HEATING PEAK LOADS

Impact of Fenestration Glazing Types

Figure 4 shows the effect of the fenestration glazing types on the cooling and heating peak load ratios of the three atriums with flat skylight and 100% glazed roof and walls. The atrium space was closed to the adjacent spaces. The cooling peak load ratio decreased mainly with the SHGC of the glazing. As compared with the basecase design, the double gray or triple clear low-e glazing reduced the cooling peak load ratio by between 30% to 39%, double clear low-e glazing by about 17% to 20%, and triple clear glazing by about 10% to 13%. This was because low SHGC values resulted in low solar heat gains and, therefore, low cooling loads. However, the U-value of the glazing did not significantly affect the cooling peak load ratio.

The heating peak load ratio decreased with the U-value of the glazing, which had a dominant effect over the SHGC. As compared with the basecase design, the double gray glazing increased the heating peak load ratio by up to 6%, and the double clear glazing by up to 3%. Nevertheless, the triple clear glazing decreased the heating peak load ratio by up to 29%, double clear low-e glazing by up to 36%, and triple clear low-e glazing by up to 58%. This was due to lower glazing U-values, which resulted in lower heat losses from the building and, therefore, lower heating peak loads. The effect of the solar heat gains on the heating peak load ratio in winter days was not significant.

By fitting the data of figure 4 using linear regression (with regression constant $R^2 > 0.98$), the following design equations were obtained for atriums with flat skylights and 100% glazed roof and walls (see figure A-2 for correlation plots):

Enclosed atrium:

$$\text{CPLR} = \text{SHGCR} + 0.007 \quad (13)$$

$$\text{HPLR} = 0.934 \cdot \text{UR} + 0.087 \quad (14)$$

Three-sided atrium:

$$\text{CPLR} = 0.909 \cdot \text{SHGCR} + 0.099 \quad (15)$$

$$\text{HPLR} = 0.824 \cdot \text{UR} + 0.178 \quad (16)$$

Linear atrium:

$$\text{CPLR} = 0.881 \cdot \text{SHGCR} + 0.138 \quad (17)$$

$$\text{HPLR} = 0.81 \cdot \text{UR} + 0.191 \quad (18)$$

Where:

CPLR : cooling peak load ratio (decimals);

HPLR : heating peak load ratio (decimals);

SHGCR: ratio of the SHGC of a given glazing to that of the basecase (decimals); and

UR : ratio of the U-value of a given glazing to that of the basecase (decimals).

Impact of Fenestration Surface Area

Figure 5 shows the cooling and heating peak load ratios of the three atriums with flat skylight and 50% glazed roof and walls. The atrium space was closed to the adjacent spaces. The cooling and heating peak load ratios decreased with the fenestration surface area ratio. As compared with an atrium with 100% glazed roof and walls (figure 4), the cooling peak load ratio of an atrium with 50% glazed roof and walls was reduced by about 50% for the three atrium types. This was due to the fact that the reduction of the fenestration surface area by 50% translated into a reduction of about 50% in solar heat gains, which were the major cooling loads in summer (see figure 3). However, the reduction rate in the heating peak load ratio decreased with the U-value of the glazing. Double clear/gray glazing reduced the heating peak load ratio by between 33% to 41%, triple clear glazing by between 25% to 35%, double clear low-e glazing by between 20% to 33%, and triple clear low-e glazing by between 10% to 23%. This was due to the fact that the heat loss through the fenestration constituted a major part of the building heating loads, especially for glazing with high U-values. However, the sensitivity of the heating peak load ratio to reducing the fenestration surface area for glazing with low U-values was reduced, due to low heat losses through the fenestration.

By fitting the data of figure 5 using linear regression (with regression constant $R^2 > 0.98$), the following design equations were obtained for atriums with flat skylights and 50% glazed roof and walls (see figure A-3 for correlation plots):

Enclosed atrium:

$$\text{CPLR} = 0.46 \cdot \text{SHGCR} + 0.02 \quad (19)$$

$$\text{HPLR} = 0.457 \cdot \text{UR} + 0.152 \quad (20)$$

Three-sided atrium:

$$\text{CPLR} = 0.434 \cdot \text{SHGCR} + 0.055 \quad (21)$$

$$\text{HPLR} = 0.37 \cdot \text{UR} + 0.301 \quad (22)$$

Linear atrium:

$$\text{CPLR} = 0.468 \cdot \text{SHGCR} + 0.065 \quad (23)$$

$$\text{HPLR} = 0.387 \cdot \text{UR} + 0.249 \quad (24)$$

Impact of Skylight Shape

Figure 6 shows the cooling and heating peak load ratios of three atriums with pyramidal/pitched skylight and 100% glazed roof and walls. The atrium space was closed to the adjacent spaces. The effect of skylight shape on the cooling peak load ratio may be positive or negative, depending on the glazing SHGC and the atrium type. As compared with the flat skylight (figure 4), the pyramidal skylight for the enclosed atrium reduced the CPLR by between 3% to 12%. For the three-sided atrium, the pyramidal skylight reduced the CPLR by between 12% to 22%. For the linear atrium, however, the pitched skylight reduced the CPLR by 2% for glazing with high SHGC values (e.g., double/triple clear glazing), and increased the CPLR by 3% for glazing with low SHGC values (e.g., double gray and triple clear low-e glazing).

The effect of skylight shape on the heating peak load ratio (HPLR) may be positive or negative, depending on the glazing U-value. As compared with the flat skylight (figure 4), the pyramidal/pitched skylight reduced the HPLR by about 6% to 18% for high U-value glazing (e.g., double clear/gray), and increased the HPLR by up to 7% for low U-value glazing (e.g., triple clear low-e). This was due to the fact that the top floor of the atrium with the flat skylight lost heat to the outdoor while the top floor of the atrium with the pyramidal/pitched skylight lost heat to the skylight zone above it. The heating load for the atrium with the pyramidal/pitched skylight was therefore lower than that for the atrium with the flat skylight, particularly for high U-value glazing. However, for low U-value glazing, the top floor of the atrium with flat skylight lost less heat to the outdoor than did the top floor of the atrium with pyramidal/pitched skylight to the skylight zone.

By fitting the data of figure 6 using linear regression (with regression constant $R^2 > 0.98$), the following design equations were obtained for closed atrium spaces with pyramidal/pitched skylights and 100% glazed roof and walls (see figure A-4 for correlation plots):

Enclosed atrium:

$$\text{CPLR} = 0.765 \cdot \text{SHGCR} + 0.122 \quad (25)$$

$$\text{HPLR} = 0.601 \cdot \text{UR} + 0.249 \quad (26)$$

Three-sided atrium:

$$\text{CPLR} = 0.538 \cdot \text{SHGCR} + 0.245 \quad (27)$$

$$\text{HPLR} = 0.676 \cdot \text{UR} + 0.271 \quad (28)$$

Linear atrium:

$$\text{CPLR} = 0.79 \cdot \text{SHGCR} + 0.211 \quad (29)$$

$$\text{HPLR} = 0.629 \cdot \text{UR} + 0.292 \quad (30)$$

Impact of Adjacent Spaces

Figure 7 shows the cooling and heating peak load ratios of the three atriums with pyramidal/pitched skylight and 100% glazed roof and walls. The atrium space was open to the adjacent spaces. As compared with a closed atrium space (figure 6), an open atrium space reduced the cooling peak load ratio by between 26% to 41% for the enclosed atrium, by between 13% to 18% for the three-sided atrium and by about 7% for the linear atrium. However, an open atrium space did not significantly affect the heating peak load ratio. This was due to the fact that the air flow from the adjacent spaces (which were conditioned at 21°C) to the atrium space contributed to lower the atrium temperature, especially that of the ground floor and, therefore, resulted in lower cooling loads.

By fitting the data of figure 7 and from other simulation results [12] using linear regression (with regression constant $R^2 > 0.98$), the following design equations were obtained for open atrium spaces with flat skylights (see figures A-2, A-3 and A-4 for correlation plots):

Enclosed atrium:

For flat skylight with 100% glazed roof,

$$\text{CPLR} = 1.04 \cdot \text{SHGCR} - 0.256 \quad (31)$$

$$\text{HPLR} = 0.928 \cdot \text{UR} + 0.097 \quad (32)$$

For pyramidal skylight with 100% glazed roof,

$$\text{CPLR} = 0.79 \cdot \text{SHGCR} - 0.136 \quad (33)$$

$$\text{HPLR} = 0.593 \cdot \text{UR} + 0.263 \quad (34)$$

For flat skylight with 50% glazed roof,

$$\text{CPLR} = 0.397 \cdot \text{SHGCR} - 0.151 \quad (35)$$

$$\text{HPLR} = 0.455 \cdot \text{UR} + 0.158 \quad (36)$$

Three-sided atrium:

For flat skylight with 100% glazed roof and wall,

$$\text{CPLR} = 0.929 \cdot \text{SHGCR} - 0.019 \quad (37)$$

$$\text{HPLR} = 0.822 \cdot \text{UR} + 0.178 \quad (38)$$

For pyramidal skylight with 100% glazed roof and wall,

$$\text{CPLR} = 0.552 \cdot \text{SHGCR} + 0.131 \quad (39)$$

$$\text{HPLR} = 0.674 \cdot \text{UR} + 0.27 \quad (40)$$

For flat skylight with 50% glazed roof and wall,

$$\text{CPLR} = 0.454 \cdot \text{SHGCR} - 0.069 \quad (41)$$

$$\text{HPLR} = 0.37 \cdot \text{UR} + 0.3 \quad (42)$$

Linear atrium:

For flat skylight with 100% glazed roof and walls,

$$\text{CPLR} = 0.887 \cdot \text{SHGCR} + 0.071 \quad (43)$$

$$\text{HPLR} = 0.809 \cdot \text{UR} + 0.183 \quad (44)$$

For pitched skylight with 100% glazed roof and walls,

$$\text{CPLR} = 0.799 \cdot \text{SHGCR} + 0.143 \quad (45)$$

$$\text{HPLR} = 0.611 \cdot \text{UR} + 0.293 \quad (46)$$

For flat skylight with 50% glazed roof and walls,

$$\text{CPLR} = 0.478 \cdot \text{SHGCR} - 0.006 \quad (47)$$

$$\text{HPLR} = 0.384 \cdot \text{UR} + 0.245 \quad (48)$$

ANNUAL COOLING, HEATING AND TOTAL ENERGY

Impact of Fenestration Glazing Types

Figure 8 shows the effect of the fenestration glazing types on the annual cooling, heating and total (cooling plus heating) energy ratios for the three atriums with flat skylights and 100% glazed roof and walls. The atrium space was closed to the adjacent spaces (i.e., with closed doors/corridors).

The double gray glazing yielded the lowest annual cooling energy ratio. As compared with the basecase design, the double gray glazing reduced the annual cooling energy ratio by between 51% to 58%, triple clear low-e glazing by between 27% to 31%, double clear low-e glazing by between 17% to 21%, triple clear glazing by between 11% to 18% and double clear glazing by between 5% to 11%. Low-e coating reduced the annual cooling energy ratio by between 11% to 19%. The annual cooling energy ratio decreased with decreasing the SHGC and with increasing the U-value of the glazing. Obviously, the SHGC had a dominant effect over the U-value

because the solar heat gains in summer were high. For instance, decreasing the SHGC by 38% (compare double clear with double gray glazing, which had approximately equal U-values) reduced the annual cooling energy ratio by about 53% for the enclosed atrium, by about 51% for the three-sided atrium, and by about 48% for the linear atrium. This was because high solar heat gains increased the cooling loads. On the other hand, increasing the U-value by 189% (compare triple clear low-e with double gray glazing, which had approximately equal SHGC) reduced the annual cooling energy ratio by about 39% for the enclosed atrium, by about 35% for the three-sided atrium, and by about 33% for the linear atrium. This was because high U-value glazing resulted in high heat losses from the building and, therefore, low cooling loads when the indoor temperature was higher than that of the outdoor, which was mostly the case in the region of Ottawa, Canada.

However, the double gray glazing yielded the highest annual heating energy ratio. As compared with the basecase design, the double gray glazing increased the annual heating energy ratio by between 28% to 50%, and double clear glazing by between 4% to 11%. Nevertheless, the triple clear glazing reduced the annual heating energy ratio by between 28% to 47%, double clear low-e glazing by between 45% to 54%, and triple clear low-e glazing by between 71% to 77%. Low-e coating reduced the annual heating energy ratio by between 46% to 59%. The annual heating energy ratio decreased with decreasing the U-value of the glazing and with increasing the SHGC. Obviously, the U-value of the glazing had a dominant effect over the SHGC because the solar heat gains in winter were somewhat low (about 30 to 50% lower than that in summer). For instance, decreasing the U-value by 65% (compare double gray with triple clear low-e glazing, which had approximately equal SHGC) reduced the annual heating energy ratio by about 85% for the enclosed atrium, by about 82% for the three-sided atrium, by about 77% for the linear atrium. This was because high U-values resulted in high heat losses from the building and, therefore, high heating loads. On the other hand, increasing the SHGC by 60% (compare double gray with double clear glazings, which had approximately equal U-values) reduced the annual heating energy ratio by about 26% for the enclosed atrium, by about 25% for the three-sided atrium, by about 19% for the linear atrium. This was because high solar heat gains reduced the heating loads. In some cases with high SHGC glazing (e.g., double clear glazing), the atrium required cooling over some periods in the heating season, particularly in sunny days.

The double clear glazing yielded the highest annual total energy ratio and the triple clear low-e glazing the lowest annual total energy ratio. As compared with the basecase design, the double clear glazing reduced the annual total energy ratio by up to 7%, triple clear glazing by between 19% to 24%, double gray glazing by between 23% to 35%, double clear low-e glazing by about 27%, and triple clear low-e glazing by about 41%. Low-e coating reduced the annual total energy ratio by between 19% to 27%. The annual total energy ratio decreased with the U-value and SHGC. For instance, decreasing the U-value by 65% (compare double gray with triple clear low-e glazing) reduced the annual total energy ratio by about 9% for the enclosed atrium, by about

15% for the three-sided atrium, and by about 25% for the linear atrium. Decreasing the SHGC by 38% (compare double clear and gray glazing) reduced the annual total energy ratio by about 30% for the enclosed atrium, by about 28% for the three-sided atrium, and by about 21% for the linear atrium.

The results also revealed that the electrical lighting heat gains, upon using a continuous-dimming control, increased the annual heating energy ratio by about 11%, and reduced the annual cooling energy ratio by up to 11% and the annual total energy ratio by up to 7%.

By fitting the data of figure 8 using linear regression (with regression constant $R^2 > 0.98$), the following design equations were obtained for atriums with flat skylights and 100% glazed roof and walls (see figure A-5 for correlation plots):

Enclosed atrium:

$$ACER = 1.196 \cdot SHGCR - 0.382 \cdot UR + 0.07 \quad (49)$$

$$AHER = -1.081 \cdot SHGCR + 1.954 \cdot UR + 0.174 \quad (50)$$

$$ATER = 0.738 \cdot SHGCR + 0.082 \cdot UR + 0.096 \quad (51)$$

Three-sided atrium:

$$ACER = 1.255 \cdot SHGCR - 0.364 \cdot UR + 0.062 \quad (52)$$

$$AHER = -0.903 \cdot SHGCR + 1.695 \cdot UR + 0.212 \quad (53)$$

$$ATER = 0.717 \cdot SHGCR + 0.162 \cdot UR + 0.09 \quad (54)$$

Linear atrium:

$$ACER = 1.194 \cdot SHGCR - 0.347 \cdot UR + 0.105 \quad (55)$$

$$AHER = -0.665 \cdot SHGCR + 1.485 \cdot UR + 0.184 \quad (56)$$

$$ATER = 0.578 \cdot SHGCR + 0.28 \cdot UR + 0.117 \quad (57)$$

where:

ACER : annual cooling energy ratio (decimals);
AHER : annual heating energy ratio (decimals); and
ATER : annual total energy ratio (decimals).

Impact of Fenestration Surface Area

Figure 9 shows the annual cooling, heating and total energy ratios for three atriums with flat skylights and 50% glazed roof and walls. The atrium space was closed to the adjacent spaces.

Reducing the fenestration surface area resulted in a significant reduction in the annual cooling and heating energy ratios. As compared with an atrium with 100% glazed roof and walls (figure 4), a 50% reduction in the fenestration surface area reduced the annual cooling energy ratio by between 51% to 58%. This was due to the fact that reducing the fenestration surface area by 50% translated into a reduction of up to 50% in solar heat gains, which were the major cooling loads in summer (figure 3). However, the reduction rate of the annual heating energy ratio was a function of the glazing U-value. The annual heating energy ratio was reduced by between 40% to 50% for double clear/gray glazing, by between 34% to 38% for triple clear glazing, by between 33% to 35% for double clear low-e glazing, and by between 13% to 20% for triple clear low-e glazing. This was because thermal heat losses through the fenestration for high and moderate U-value glazing constituted a major part of the building heating loads. However, the thermal heat losses for low U-value glazing constituted a relatively small part of the building heating loads. Therefore, the sensitivity of the heating loads to reducing the fenestration surface area was reduced.

The annual total energy ratio was accordingly reduced by between 47% to 54% for all glazing types. This was because the annual cooling energy of the building constituted a major part of the annual total energy (the annual cooling energy was about 80% of the annual total energy for the enclosed atrium, 74% for the three-sided atrium and 65% for the linear atrium).

By fitting the data of figure 9 using linear regression (with regression constant $R^2 > 0.98$), the following design equations were obtained for atriums with flat skylights and 50% glazed roof and walls (see figure A-6 for correlation plots):

Enclosed atrium:

$$ACER = 0.616 \cdot SHGCR - 0.158 \cdot UR - 0.024 \quad (58)$$

$$AHER = -0.597 \cdot SHGCR + 0.826 \cdot UR + 0.278 \quad (59)$$

$$ATER = 0.362 \cdot SHGCR + 0.045 \cdot UR + 0.042 \quad (60)$$

Three-sided atrium:

$$ACER = 0.609 \cdot SHGCR - 0.159 \cdot UR - 0.016 \quad (61)$$

$$AHER = -0.642 \cdot SHGCR + 0.959 \cdot UR + 0.262 \quad (62)$$

$$ATER = 0.334 \cdot SHGCR + 0.09 \cdot UR + 0.043 \quad (63)$$

Linear atrium:

$$ACER = 0.628 \cdot SHGCR - 0.146 \cdot UR - 0.012 \quad (64)$$

$$AHER = -0.441 \cdot SHGCR + 0.763 \cdot UR + 0.26 \quad (65)$$

$$ATER = 0.262 \cdot SHGCR + 0.169 \cdot UR + 0.078 \quad (66)$$

Impact of Skylight Shape

Figure 10 shows the annual cooling, heating and total energy ratios for the three atriums with pyramidal/pitched skylights and 100% glazed roof and walls. The atrium space was closed to the adjacent spaces. The shape of the skylight may reduce or increase the annual cooling energy ratio, depending on the atrium type and the SHGC of the fenestration. As compared with the flat skylight (figure 8), the pyramidal skylight for the three-sided atrium reduced the annual cooling energy ratio by up to 19%, particularly for glazing with high SHGC (e.g., double clear w/o coating). However, the pitched skylight for the linear atrium increased the annual cooling energy ratio by up to 12%, especially for glazing with low SHGC (e.g., double gray, or triple clear low-e). The pyramidal skylight for the enclosed atrium reduced the annual cooling energy ratio by up to 6% for glazing with high SHGC (e.g., double clear w/o coating), and increased the annual cooling energy ratio by up to 10% for glazing with low SHGC (e.g., double gray, or triple clear low-e). The reduction rate of the annual cooling energy ratio due to skylight shape decreased with the SHGC. This was due to the fact that, in summer, the pyramidal skylight lowered the indoor space temperature as hot air stagnated in the space under the skylight above the top floor, resulting in lower cooling loads. In spring/fall (where the indoor temperature was significantly higher than the outdoor temperature), the pyramidal/pitched skylight transmitted more solar heat gains than did the flat skylight. These solar heat gains offset the heat losses through the larger surface area of the pyramidal/pitched skylight, resulting in lower cooling loads, especially for glazing with high SHGC. However, the solar heat gains for the pyramidal/ pitched skylight with low SHGC were lower than the heat losses through the larger surface area of the pyramidal/pitched skylight, resulting in higher cooling loads, especially for high U-value glazing.

However, the effect of the skylight shape on the annual heating energy ratio was dependent on the SHGC and U-value of the fenestration. As compared with the flat skylight (figure 8), the pyramidal/pitched skylight with double gray glazing reduced the annual heating energy ratio by about 30% for the enclosed atrium, by about 13% for the linear atrium and by about 7% for the three-sided atrium. However, the pyramidal/pitched skylight with triple clear low-e glazing increased the annual heating energy ratio by about 13% for the enclosed atrium, by about 7% for the linear atrium and by about 24% for the three-sided atrium. This was due to the fact that, first, the pyramidal/pitched skylight transmitted more solar heat gains in winter than did the flat skylight (figure 2), especially for glazing with high SHGC (e.g., double clear glazing). Second, the thermal zone under the pyramidal/pitched skylight, which was at higher temperature than the outdoor temperature, acted like a buffer zone to the atrium top floor. The top floor of the atrium with the

flat skylight lost heat to the outdoor while the top floor of atrium with the pyramidal/pitched skylight lost heat to the skylight zone above it. The heating load for the atrium with the pyramidal/pitched skylight was thus lower than that for the atrium with the flat skylight, particularly for high U-value glazing (e.g., double clear/gray glazing). However, for low U-value glazing (e.g., triple clear low-e), the top floor of the atrium with the flat skylight lost less heat to the outdoor than did the top floor of the atrium with the pyramidal/pitched skylight to the skylight zone.

The pyramidal/pitched skylight may also reduce or increase the annual total energy ratio, depending mainly on the U-value of the glazing. For the enclosed and linear atriums, the pyramidal/pitched skylight decreased the annual total energy ratio by between 3% to 11%, particularly for double gray glazing, and increased the annual total energy ratio by up to 10%, particularly for triple clear low-e glazing. However, for the three-sided atrium, the pyramidal skylight decreased the annual total energy ratio by up to 14%, particularly for double clear glazing.

By fitting the data of figure 10 using linear regression (with regression constant $R^2 > 0.98$), the following design equations were obtained for atriums with pyramidal/pitched skylights and 100% glazed roof and walls (see figure A-7 for correlation plots):

Enclosed atrium:

$$ACER = 0.966 \cdot SHGCR - 0.406 \cdot UR + 0.272 \quad (67)$$

$$AHER = -0.525 \cdot SHGCR + 1.194 \cdot UR + 0.159 \quad (68)$$

$$ATER = 0.667 \cdot SHGCR - 0.089 \cdot UR + 0.251 \quad (69)$$

Three-sided atrium:

$$ACER = 0.84 \cdot SHGCR - 0.335 \cdot UR + 0.255 \quad (70)$$

$$AHER = -0.692 \cdot SHGCR + 1.454 \cdot UR + 0.245 \quad (71)$$

$$ATER = 0.479 \cdot SHGCR + 0.127 \cdot UR + 0.226 \quad (72)$$

Linear atrium:

$$ACER = 1.102 \cdot SHGCR - 0.383 \cdot UR + 0.254 \quad (73)$$

$$AHER = -0.505 \cdot SHGCR + 1.174 \cdot UR + 0.235 \quad (74)$$

$$ATER = 0.573 \cdot SHGCR + 0.159 \cdot UR + 0.224 \quad (75)$$

Impact of Adjacent Spaces

Figure 11 shows the annual cooling, heating and total energy ratios of the three atriums with pyramidal/pitched skylight and 100% glazed roof and walls. The atrium space was open to the adjacent spaces, i.e., with open doors/corridors. As compared with a closed atrium space (figure 10), an open atrium space reduced the annual cooling energy ratio by between 62% to 70% for the enclosed atrium, by between 34% to 40% for the three-sided atrium and by between 22% to 27% for the linear atrium. The annual heating energy ratio of an open atrium space was also reduced by up to 6% for the linear atrium. However, the annual heating energy ratio for the enclosed and three-sided atriums increased by up to 19%, particularly for triple low-e glazing. The annual total energy ratio was accordingly reduced from 41% to 60% for the enclosed atrium, from 18% to 33% for the three-sided atrium and from 14% to 22% for the linear atrium. This was due to the fact that the air flow from the adjacent spaces (which were conditioned at 21°C) to the atrium space contributed to lower the atrium temperature, especially that of the ground floor and, therefore, resulted in lower cooling loads. However, the atrium convection and infiltration heat losses due to the air flow from the atrium to the adjacent spaces and to the outside increased the heating energy requirement of the atrium space, particularly that of the top floor.

By fitting the data of figure 11 and that from other simulation results [12] using linear regression (with regression constant $R^2 > 0.98$), the following design equations were obtained for open atrium spaces (see figures A-5, A-6 and A-7 for correlation plots):

Enclosed atrium:

For flat skylight with 100% glazed roof,

$$ACER = 0.631 \cdot SHGCR - 0.119 \cdot UR - 0.175 \quad (76)$$

$$AHER = -1.210 \cdot SHGCR + 1.823 \cdot UR + 0.376 \quad (77)$$

$$ATER = 0.267 \cdot SHGCR + 0.289 \cdot UR - 0.077 \quad (78)$$

For pyramidal skylight with 100% glazed roof,

$$ACER = 0.363 \cdot SHGCR - 0.160 \cdot UR + 0.073 \quad (79)$$

$$AHER = -0.813 \cdot SHGCR + 1.205 \cdot UR + 0.407 \quad (80)$$

$$ATER = 0.144 \cdot SHGCR + 0.133 \cdot UR + 0.116 \quad (81)$$

For flat skylight with 50% glazed roof,

$$ACER = 0.125 \cdot SHGCR - 0.015 \cdot UR - 0.058 \quad (82)$$

$$AHER = -0.574 \cdot SHGCR + 0.843 \cdot UR + 0.292 \quad (83)$$

$$ATER = -0.019 \cdot SHGCR + 0.169 \cdot UR + 0.011 \quad (84)$$

Three-sided atrium:

For flat skylight with 100% glazed roof and wall,

$$ACER = 1.027 \cdot SHGCR - 0.224 \cdot UR - 0.136 \quad (85)$$

$$AHER = -1.016 \cdot SHGCR + 1.676 \cdot UR + 0.332 \quad (86)$$

$$ATER = 0.517 \cdot SHGCR + 0.269 \cdot UR - 0.03 \quad (87)$$

For pyramidal skylight with 100% glazed roof and wall,

$$ACER = 0.63 \cdot SHGCR - 0.21 \cdot UR + 0.08 \quad (88)$$

$$AHER = -0.81 \cdot SHGCR + 1.461 \cdot UR + 0.36 \quad (89)$$

$$ATER = 0.28 \cdot SHGCR + 0.235 \cdot UR + 0.126 \quad (90)$$

For flat skylight with 50% glazed roof and wall,

$$ACER = 0.371 \cdot SHGCR - 0.055 \cdot UR - 0.118 \quad (91)$$

$$AHER = -0.709 \cdot SHGCR + 0.935 \cdot UR + 0.351 \quad (92)$$

$$ATER = 0.133 \cdot SHGCR + 0.174 \cdot UR - 0.02 \quad (93)$$

Linear atrium:

For flat skylight with 100% glazed roof and walls,

$$ACER = 1.038 \cdot SHGCR - 0.241 \cdot UR - 0.048 \quad (94)$$

$$AHER = -0.686 \cdot SHGCR + 1.426 \cdot UR + 0.228 \quad (95)$$

$$ATER = 0.463 \cdot SHGCR + 0.336 \cdot UR + 0.03 \quad (96)$$

For pitched skylight with 100% glazed roof and walls,

$$ACER = 0.943 \cdot SHGCR - 0.278 \cdot UR + 0.096 \quad (97)$$

$$AHER = -0.588 \cdot SHGCR + 1.132 \cdot UR + 0.304 \quad (98)$$

$$ATER = 0.435 \cdot SHGCR + 0.219 \cdot UR + 0.144 \quad (99)$$

For flat skylight with 50% glazed roof and walls,

$$ACER = 0.472 \cdot SHGCR - 0.075 \cdot UR - 0.104 \quad (100)$$

$$AHER = -0.46 \cdot SHGCR + 0.741 \cdot UR + 0.289 \quad (101)$$

$$ATER = 0.156 \cdot SHGCR + 0.209 \cdot UR + 0.025 \quad (102)$$

CONCLUSION

Design tools were developed through computer simulation to quantify the impact of selected design alternatives on the thermal and energy performance of atriums in cold climates. The ESP-r and ADELIN software were used for thermal and lighting simulation, respectively. The design alternatives focused on the fenestration glazing types and surface area, skylight shape, atrium type and interaction of the atrium space with its adjacent spaces. The design performance outputs, evaluated as a ratio of the output of a given design to that of the basecase design, are heat gain ratio, cooling and heating peak load ratios and annual cooling, heating and total energy ratios. The following findings should be highlighted:

- The pyramidal/pitched skylight increased the solar heat gain ratio by up to 25% in the heating season for the enclosed and linear atriums, and by up to 10% for the three-sided atrium, as compared with the flat skylight. However, the skylight shape did not significantly affect the solar heat gain ratio in the cooling season.
- The cooling peak load ratio decreased mainly with the SHGC ratio while the heating peak load ratio decreased mainly with the U-value ratio. As compared with the basecase, the double gray glazing reduced the cooling peak load ratio by between 30% to 39%. The triple clear low-e glazing reduced the heating peak load ratio by between 52% to 58%.
- The annual cooling energy ratio decreased with decreasing the Solar Heat Gain Coefficient ratio SHGCR and with increasing the U-value ratio (UR). As compared with the basecase, the double gray glazing (SHGCR=0.63 and UR=1.03) reduced the annual cooling energy ratio by between 51% to 58%. The triple clear low-e glazing (SHGCR=0.63 and UR=0.36) reduced the ACER by between 27% to 31%. However, the annual heating energy ratio decreased with decreasing the UR and with increasing the SHGCR. The double gray glazing increased the annual heating energy ratio by between 28% to 50%. The triple clear low-e glazing reduced the annual heating energy ratio by between 71% to 77%. The annual total energy ratio decreased with the UR and SHGCR. The double gray glazing reduced the annual total energy ratio by between 23% to 35%, and the triple clear low-e glazing by about 40%.
- Reducing the fenestration surface area by 50% resulted in more than 48% reduction in the cooling peak load ratio and annual cooling and total energy ratios. However, the reduction in the heating peak load ratio varied from 41% for the double gray glazing to 10% for the triple clear low-e glazing. The reduction in the annual heating energy ratio varied from 42% for the double clear glazing to 13% for the triple clear low-e glazing.
- The pyramidal skylight reduced the cooling peak load ratio by up to 22% only for the enclosed and three-sided atriums. However, the pyramidal/pitched skylight reduced the heating peak

load ratio by up to 18% for the double clear glazing, and increased the heating peak load ratio by about 7% for the triple clear low-e glazing for the three atrium types.

- The effect of the skylight shape on the annual cooling energy ratio depended mainly on the SHGCR and the atrium type. As compared with the flat skylight, the pyramidal skylight for the enclosed atrium reduced the annual cooling energy ratio by up to 6% for the double clear glazing, and increased the annual cooling energy ratio by up to 10% for the double gray glazing. However, the pyramidal skylight for the three-sided atrium reduced the annual cooling energy ratio by up to 19% for all glazing types. The pitched skylight for the linear atrium increased the annual cooling energy ratio by up to 12% for all glazing types. The effect of the skylight shape on the annual heating energy ratio depended on the UR and SHGCR. The pyramidal/pitched skylight reduced the annual heating energy ratio by between 7% to 30% for the double gray glazing, and increased the annual heating energy ratio by between 7% to 24% for the triple clear low-e glazing. The effect of the skylight shape on the annual total energy ratio depended mainly on the UR for the enclosed and linear atriums, and on the SHGCR for the three-sided atrium. The pyramidal/pitched skylight reduced the annual total energy ratio of the enclosed/linear atrium by up to 11% for the double gray glazing, and increased the annual total energy ratio by up to 10% for the triple clear low-e glazing. However, the pyramidal skylight reduced the annual total energy ratio of the three-sided atrium by between 3% to 14%.
- The effect of the adjacent spaces on the annual energy performance depended on the atrium type. As compared with a closed space, an open space reduced the annual cooling energy ratio by up to 70% for the enclosed atrium, by up to 41% for the three-sided atrium, and by up to 27% for the linear atrium. However, the annual heating energy ratio increased by up to 19% for the enclosed or three-sided atrium, and decreased by up to 6% for the linear atrium. The annual total energy ratio was accordingly reduced by up to 60% for the enclosed atrium, by up to 33% for the three-sided atrium, and by up to 22% for the linear atrium. An open space reduced only the cooling peak load ratio by up to 41% for the enclosed atrium, by up to 18% for the three-sided atrium and by up to 8% for the linear atrium.

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APPENDIX- CORRELATION PLOTS

Figures A-1 to A-7 show the plots of the quantities calculated using the previously developed correlations versus the predicted quantities using the computer simulation. The quantities under consideration included the seasonal solar heat gain ratio, the cooling and heating peak load ratios, and the annual cooling, heating and total energy ratios. The correlation types for these quantities were as follows:

Seasonal solar heat gain ratio (SSHGR):

$$\text{SSHGR} = \text{STR} \cdot (\text{A} \cdot \text{STR} + \text{B}) \quad (103)$$

Cooling peak load ratio (CPLR):

$$\text{SSHGR} = \text{A} \cdot \text{SHGCR} + \text{B} \quad (104)$$

Heating peak load ratio (HPLR):

$$\text{SSHGR} = \text{A} \cdot \text{UR} + \text{B} \quad (105)$$

Annual cooling energy ratio (ACER):

$$\text{SSHGR} = \text{A} \cdot \text{SHGCR} + \text{B} \cdot \text{UR} + \text{C} \quad (106)$$

Annual heating energy ratio (AHER):

$$\text{SSHGR} = \text{A} \cdot \text{SHGCR} + \text{B} \cdot \text{UR} + \text{C} \quad (107)$$

Annual total energy ratio (ATER):

$$\text{SSHGR} = \text{A} \cdot \text{SHGCR} + \text{B} \cdot \text{UR} + \text{C} \quad (108)$$

Where:

A, B, C : the correlation constants, determined for each quantity.

STR : the ratio of the solar transmittance of a given glazing to that of the basecase (decimals), varying within the range 0.49 to 1.

SHGCR: the ratio of the solar heat gain coefficient of a given glazing to that of the basecase (decimals), varying within the range 0.63 to 1.

UR : the ratio of the U-value of a given glazing to that of the basecase (decimals), varying within the range 0.36 to 1.

Table 1 Performance characteristics of the basecase design reported per ground-floor surface area.

	Enclosed	Three-sided	Linear
Ground floor surface area (m ²)	400	360	960
Total fenestration surface area (m ²)	256	512	1280
Solar Heat Gains - cooling season (kWh/m ²)	224	366	335
Solar Heat Gains - heating season (kWh/m ²)	112	262	174
Cooling Peak Load (W/m ²)	204	340	317
Heating Peak Load (W/m ²)	63	134	134
Annual Cooling Energy (kWh/m ²)	243	384	331
Annual Heating Energy (kWh/m ²)	65	136	175
Annual Total Energy (kWh/m ²)	308	521	506

Enclosed atrium

Three-sided atrium

Linear atrium

Figure 1 Atrium shapes as simulated with pyramidal/pitched skylights and 100% glazed roof and walls.

Figure 2 Effect of fenestration glazing types on seasonal solar heat gain ratio of atriums with 100% glazed roof and walls.

Figure 3 Effect of fenestration surface area ratio on seasonal solar heat gain ratios.

Figure 4 Effect of fenestration glazing types on cooling and heating peak load ratios of closed atrium spaces with flat skylights and 100% glazed roof and walls.

Figure 5 Effect of fenestration surface area on cooling and heating peak load ratios of closed atrium spaces with flat skylights and 50% glazed roof and walls.

Figure 6 Effect of skylight shape on cooling and heating peak load ratios of closed atrium spaces with 100% glazed roof and walls.

Figure 7 Effect of adjacent spaces on cooling and heating peak load ratios of atriums with pyramidal/pitched and 100% glazed roof and walls.

Figure 8 Effect of fenestration glazing types on annual cooling, heating and total energy ratios of closed atrium spaces with flat skylights and 100% glazed roof and walls.

Figure 9 Effect of fenestration surface area on annual cooling, heating and total energy ratios of closed atrium spaces with flat skylights and 50% glazed roof and walls.

Figure 10 Effect of skylight shape on annual cooling, heating and total energy ratios of closed atrium spaces with 100% glazed roof and walls.

Figure 11 Effect of adjacent spaces on annual cooling, heating and total energy ratios of atriums with pyramidal/pitched and 100% glazed roof and walls.

Figure A-1 Correlation plots of the seasonal solar heat gain ratio of atriums with 100% glazed roof and walls.

Figure A-2 Correlation plots of the cooling and heating peak load ratios of atriums with flat skylights and 100% glazed roof and walls.

Figure A-3 Correlation plots of the cooling and heating peak load ratios of atriums with flat skylights and 50% glazed roof and walls.

Figure A-4 Correlation plots of the cooling and heating peak load ratios of atriums with pyramidal/pitched skylights and 100% glazed roof and walls.

Figure A-5 Correlation plots of the annual cooling, heating and total energy ratios of atriums with flat skylights and 100% glazed roof and walls.

Figure A-6 Correlation plots of the annual cooling, heating and total energy ratios of atriums with flat skylights and 50% glazed roof and walls.

Figure A-7 Correlation plots of the annual cooling, heating and total energy ratios of atriums with pyramidal/pitched skylights and 100% glazed roof and walls