HIGH OR LOW-E?
LOW-E COATED GLASS FOR APARTMENT BUILDINGS

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The dominant form of apartment building design in major urban areas in Canada is the double-loaded corridor type in which most apartments tend to face in opposite directions and have exposure only on one face of the building (Photo 3), although the plan shape could vary. Less common are three wing, four wing (cross) and L-shaped (Photo 4) plans. In these buildings, some apartments might have exposure to more than one side of the building and only rarely on opposite sides.

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Older apartment buildings, up to late 1970s vintage, have similar window characteristics as houses. Windows in bedrooms are usually small. Living and dining rooms, typically adjoined, usually have windows extending across the width of the space and often, glazed doors. Space heating is usually provided by hydronic or electric baseboard radiators extending across the width of outside walls, beneath windows and doors. Hydronic radiator hot water supply and return pipe networks are usually not zoned, that is, the heated water of the same temperature is delivered to all apartments equally. Space cooling is rarely provided.

More recent apartment buildings, late 1970s to present, are generally outfitted with fan-coil units for space heating and cooling. Central heating boilers, chillers, cooling towers and related circulation equipment are typically located on the roof with a two-pipe circulation system connecting the equipment to the fan-coils in each apartment below. Heated water is provided in the winter for space heating and cooled water is provided during the rest of the year for space cooling. Distribution networks are usually not zoned so that all apartments are either in space heating or cooling mode. From about the mid-1990s onward, more expensive, condominium ownership apartment buildings were sometimes fitted with heat pump units that can supply space heating and or cooling at any time of the year. Heat pumps are connected to a distribution network that is maintained at a constant temperature with roof-top boilers and fluid coolers.

The focus of this study is on older buildings with hydronic baseboard radiators and more recent buildings with two-pipe fan-coil units. In these buildings, residents often have limited control over the operation of space heating equipment and, if provided, space cooling equipment. In apartments with low heat demand, space heating may not be needed and under conditions of strong solar radiation gain, space cooling may be desired but cannot be provided because space heating is needed for other apartments with less solar radiation gain. (Figure 4).[i] Weather effects can lead to discomfort in all apartments; for example, it is common in the spring to experience several days to a week or more of almost summer-like weather but space heating operation must be maintained in anticipation of the inevitable return to cooler weather. Discomfort to residents is common, especially in apartments with low space heating demand.

Building operators are put in a difficult position. In the residential condominium sector, client building owners and property managers have often commented that in the fall, they must pay close attention to the daily weather, long term forecasts and reports of uncomfortably cool conditions from residents in apartments with little sun exposure in order to judge when it is best to start up the heating system. Despite best efforts, some discomfort to residents in apartments with more sun exposure is likely. A similar balancing act is required in the spring. In the private rental and social housing sector, the decision when to start up and shut down the heating system is often easier, not because the buildings are better designed but because the dates are determined by Provincial legislation, such as the *Residential Tenancies Act* (RTA) in Ontario or local Municipal By-law. [ii] Regardless of the outdoor weather, the system is turned on at a fixed date each fall until a fixed date in early summer.

Residents suffering overheating often attempt to obtain relief opening windows and doors for ventilation. However, because most apartments have exposure only to one face of the building, the opportunity for flow-through ventilation driven by wind pressure differences on opposite sides of the building is greatly limited. Fans may be placed within or close to windows to force outdoor to indoor air flow or vice versa. Through-window air conditioners may also be used, if permitted by building owners. Other coping strategies include trying to reduce solar heat gain with blinds, draperies and aluminum foil to reflect solar radiation (Photo 5).

The use of aluminum foil to reflect solar energy brings us back to the issue of low-e coated window glass which are microscopically thin and virtually transparent reflective coatings. Can low-e coated glass help alleviate resident discomfort? If solar gain is an issue, it seems intuitive that LSG low-e would be beneficial in controlling solar heat gain. However, would not some beneficial wintertime heat gain be lost, as was found in the CCHT study? Can it be assumed that what is best for residential houses is also appropriate for residential apartment buildings, given the physical differences? This research study was initiated to study these issues by studying the impact on thermal comfort of residents.

Our High rise Housing Stock is Large and Ageing

In the larger urban regions of Toronto, Montreal, Vancouver, Ottawa-Gatineau, Calgary and Edmonton (Census Metropolitan Areas over 1 million population) up to 50% of people live in apartments, and in the downtown core, up to 70% (Montreal Census Subdivision). Almost 45% of Canadians now live in these large urban areas and the vast majority of population growth in Canada occurs there.[iii] Official plans for these areas call for increasing "intensity" which generally involves higher density housing, including apartment buildings.

Large numbers of apartment buildings were constructed in the 1960s and 1970s. A second significant wave of high-rise construction followed in the mid to late 1980s, extending into the 1990s in western Canada, and many cities are now experiencing a third wave of apartment construction. These waves relate to growth of the Canadian population following World War II and subsequent 'echoes' and to planning choices made to locate much of that growth in high-rise residential apartment buildings.[iv, v]

Existing apartment buildings are ageing and require renewal. The first wave of apartment buildings has been undergoing infrastructure renewal for some time, including replacement of exterior windows and doors. In the author's experience, replacement windows and doors rarely included uncoated glass in the 1990s although initially HSG low-e and later, LSG low-e coated glasses were available and becoming common in windows and doors for houses. The second wave of apartment buildings built in the late 1980s and early 1990s similarly rarely included low-e coated glass. Often, low-e coated glass (and other energy-saving features such as warm-edge spacers and argon gas fill) were not used. Windows and doors in these two waves of buildings will require renewal at about the same time to address normal ageing and development of condensation (fog) within insulating glass unit cavities. An opportunity exists to include low-e coated glass during renewal to improve resident thermal comfort in these older buildings.

Inclusion of low-e coated glass and other energy saving features such as warm-edge spacers and argon gas fill also provides an opportunity of other cost savings. In these older buildings, the central space heating and (if provided) cooling systems are ageing. The typical average life span of a residential, gas-fired hot water boiler for space heating water is about 25 to 30 years. The average life span of a chiller is about 20 to 25 years.[vi] Cooling towers are usually replaced at the same time if not compatible with replacement chillers. In the first and second wave of high-rise apartment buildings, such equipment is at (in some cases beyond) the end of its useful life and needs replacement. Replacing insulating glass units that do not include low-e coated glass with new units that do, may provide an opportunity to reduce heating and cooling loads. Coordinating insulating glass unit replacement with replacement of space heating and cooling equipment may provide an opportunity to down-size new equipment and save some capital cost, and reduce energy consumption and save some future operating cost.

A study of low-e coated glass for apartment buildings is therefore of value to building owners and residents, and timely. This study addresses performance improvements in the context of resident thermal comfort. Space heating and cooling demand was not directly measured but a qualitative inference can be made from other measurements made, as discussed in the following section of this report. Energy performance modelling to quantify effects on building operation was beyond the scope of this study.

Three southeast facing apartments were fitted with equipment to monitor indoor air temperature and relative humidity and solar radiation received through windows. The windows were original glazed with uncoated glass which was left as-is in one apartment. High solar gain (HSG) low-e glazing was installed in the second apartment and low solar gain (LSG) low-e glazing was installed in the third. For one year, data was collected. Periodic visits were also made to interview the residents on their perceptions of comfort and to examine how the apartments were operated to adjust indoor conditions to achieve comfort. Analysis of the data obtained revealed that ‘shoulder season’ discomfort is related to solar heat gain and LSG low-e glass can alleviate discomfort. However, space heating demand was higher in the LSG and HSG apartments which suggests there is some benefit to solar gain. In summer months, all residents experienced discomfort from time to time so that it appears the use of HSG or LSG low-e coated glass is of limited value.

Extrapolation of the study data indicates that HSG low-e glass should be used for north elevations, LSG low-e for west elevations, and either HSG or LSG low-e for east elevations, depending on the extent of glazing and/or reports of resident discomfort. However, compensatory actions should be considered to offset the loss of “free” space heating from solar gain in winter and to address summer discomfort.

INTRODUCTION

In apartment buildings residents often report discomfort arising from solar heat gain through windows and glazed doors. Apartment buildings typically lack features to control solar gain such as exterior shades or shutters. Balconies may provide some protection against solar gain depending on balcony depth and sill height of windows but usually, this would be only at living and dining rooms. Space heating systems tend to be simple designs, hydronic or electric baseboard in older buildings, two-pipe hydronic fan-coil systems in newer buildings, arrayed in a single zone and so without flexibility to respond to high solar gain on one elevation and shaded conditions on others. Controls to adjust space heating output within apartments may be provided but they may not be sufficient to reduce output to balance solar gain. Residents experiencing solar gain related overheating may seek relief by opening exterior windows and doors, wasting both solar heat gain as well as space heating energy. Since window and door glazing is part of the problem, can it be part of the solution?

RESEARCH PROGRAM

Study Building

A research study was carried out in an occupied building in Ottawa, Ontario (Figure 1) owned by Centretown Citizens Ottawa Corporation (CCOC), a private, non-profit, social housing provider. Funding for the study was provided by Canada Mortgage and Housing Corporation (CMHC) through its External Research Program and by Natural Resources Canada (NRCan). Proposal submission, equipment acquisition, installation of instrumentation and about half of the field monitoring were carried out while the lead author was employed at GRG Building Consultants in Newmarket, Ontario. The balance field monitoring and all of the data analysis and reporting (including this paper and the conference presentation) were

Figure 1: Study building in downtown Ottawa, Ontario, view of southeast (left) and northeast elevations.

carried out during both authors' current employment at Morrison Hershfield in Ottawa, Ontario. A report is available from CMHC giving detailed observations, analysis, conclusions and recommendations (Torok, 2012). This paper provides a summary of that report.

Three southeast-facing, one-bedroom apartments in the CCOC building (floor plans, Figure 2) were fitted with equipment to monitor indoor air temperature, indoor relative humidity, solar radiation received at the exterior of the building and solar radiation received through window glazing. Existing window and door glass was clear, without coatings. One apartment was left as found as a 'control' condition, one was refitted with high solar gain (HSG) low-e glass in windows and doors and one was refitted with low solar gain (LSG) low-e glass. Monthly visits were made to download data, review apartment operation and to question the residents of the test units on their perceptions of thermal comfort. The test program period extended from late August September 2010 through September 2011. At the end of the monitoring period, data and observations in the three apartments were compared what were the effects of HSG and LSG low-e glass on resident thermal comfort.

Figure 2: Floor plans of study apartments, oriented as in the building, facing east of south by 31˚.

The study was carried out in an occupied building because a controlled research facility with simulated occupancy does not exist for apartment building research. There are such facilities for low-rise 'house' construction, such as the 'twin house' facility at the Canadian Centre for Housing Technology (CCHT) at the National Research Council of Canada campus in Ottawa, Ontario. In the absence of a similar facility for apartment buildings, an existing, occupied building was used instead, selected with care to have many characteristics common to apartment buildings in Canada. The typical floor plate is a double-loaded centre corridor type with apartments facing opposite directions with single exposure and thus, no opportunity for flow-through ventilation by outdoor air. There was limited mechanical ventilation in the form of a roof-top make-up air unit operating continuously, supplying air to the centre corridors from where it could flow into apartments through gaps around the corridor entrance door slab to replace air expelled through kitchen and bathroom exhaust fans and ductwork. The space heating system was hydronic baseboard radiators on exterior walls in the bedrooms and living rooms controlled with separate thermostats. There was no space cooling system in the building although the resident of the HSG apartment had a through-window air conditioner (Figure 3). That resident reported using the air conditioner sparingly, when clients were present (the resident operated a home-based business). For cooling, residents normally relied on opening windows and doors and used fans of various types.

The three study apartments were almost identical in layout, size and solar exposure. Each apartment was normally occupied by one person, with occasional guests. Detailed comings and goings of residents were not recorded. Apartments in the building in general, and the study apartments in particular, were not individually metered to record resident energy usage. During monthly visits, operation of windows, usage of fans, baseboard radiator thermostat settings, etc. were recorded and residents were questioned on operation and perceived comfort or discomfort.

In apartment buildings with single-zoned space heating systems is complicated by solar gain. In condominium buildings, the dates on which the space heating system is energized in the fall and de-energizing in the spring are not fixed. The building operator is often put in a difficult position, balancing the need for space heating in apartments with little or no solar heat gain against the need for relief from space heating in apartments with strong solar gain. In rental buildings, in the Province of Ontario, the *Residential Tenancies Act* (RTA, 2006) and municipal by-laws (City of Ottawa, 2006) regulate the dates for energizing and de-energizing the space heating system, regardless of the outdoor weather. The study building space heating system was energized about September 15th and de-energized about May 15th.

Existing and Replacement Glazing

Figure 3: Test building, HSG apartment living room. Typical arrangement of sliding patio door and fixed-over-slider window, with balcony beyond.

Windows and doors were identical in each apartment (Figures 3 and 4). In each living room there was a sliding patio door and a window. The doors included two parallel pairs of horizontal sliding, single-glazed sashes. The windows were a composite type with a fixed, double-pane, sealed insulating glass unit supported by an intermediate rail above two parallel pairs of horizontal sliding, single-glazed sliding sashes. Frame material of these windows was thermally-broken aluminum. In each bedroom there was one combination window, consisting of an awning window stacked on top of a fixed-glazed (picture) window. Both windows were glazed with double-pane, sealed insulating glass units. Characteristics of the original glazing retained in the Control apartment and replacement glazing installed in the HSG and LSG low-e apartments are given in Table 1.

Table 1:
Performance Data for Existing (Control) and Replacement Glazing

Apartment	**Glazing Products**	**U-factor** W/m^{2}K (BTU/hr/ft^2/°F)	**Solar Heat Gain Coefficient**
Control	Living/dining and bedroom windows, double glazed, sealed insulating glass units	2.73 (0.49)	0.76
	Living/dining sliding door and window, double-run, single-glazed sashes	2.80 (0.49)	0.76
HSG Low-e	Living/dining and bedroom windows, double-glazed, sealed insulating glass units	1.91 (0.33)	0.72
	Living/dining sliding door and window, double-run, single-glazed sashes	2.04 (0.33)	0.72
LSG Low-e	Living/dining and bedroom windows, double-glazed, sealed insulating glass units	1.69 (0.30)	0.40
	Living/dining sliding door and window, double-run, single-glazed sashes	1.99 (0.33)	0.59

Since the apartments included single glazed sashes and sealed, insulating glass units, pyrolitic type low-e coated glasses were selected to be installed. This was achieved in the HSG apartment but not in the LSG apartment. At the time of the study, only two LSG low-e coatings were available. Attempts were made to obtain both but neither was available for the glass thicknesses required. As a compromise, sputter-coated, LSG low-e coated glass was used in sealed, insulating glass units and a combination of pyrolitic HSG low-e overlaid with a reflective film was used for single-glazed sashes. Modelling with the Window 5 software program by Lawrence Berkeley National Laboratory (LBNL) indicated the performance combination was about the same as available pyrolitic LSG low-e coated glass.

Figure 4: Test building, HSG apartment bedroom. Typical arrangement of awning-over-fixed window.

Equipment and Monitoring

Test equipment was obtained from Structure Monitoring Technologies Research Ltd. (SMT) in Winnipeg, Manitoba and consisted of the following:

- In each apartment, two WiDAQ-011-420-E 'mobile' data loggers with built-in temperature and relative humidity sensors were installed, one in the combined living/dining room and the other in the bedroom (Figure 5).
- In each apartment, one SP-110 pyranometer manufactured by Apogee Instruments Inc., was mounted behind the lower fixed glazed window in the bedroom, in the vertical position facing outward to receive radiation passing through the fixed window (Figure 6).
- At the building exterior, two Apogee SP-110 pyronometers were installed to measure incident solar radiation. One was installed on the roof parapet above the control apartment, in the horizontal position and the other was installed at the edge of the wall opening for the bedroom window of the HSG apartment, in the vertical position facing outward (Figure 7).
- At the exterior of the building, outside the bedroom window of the LSG apartment, one SMT HTM2500-01-006 outdoor temperature and relative humidity sensor was installed. This sensor was attached to the WiDAQ-022-810-E 'industrial' data logger inside the apartment for recording data.

Figure 5: Datalogger measuring indoor air temperature and relative humidity.

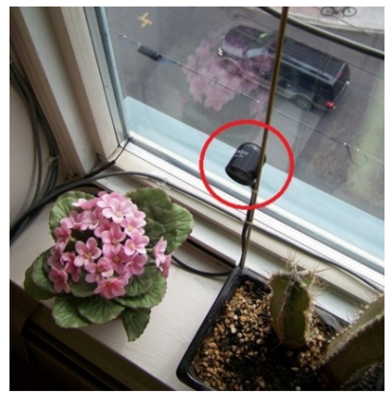

Figure 6: Pyranometer installed behind the fixed glazed portion of the HSG apartment bedroom window

Figure 7: Pyranometer installed outside the HSG apartment bedroom window.

The Apogee pyranometers are relatively inexpensive devices that provide similar, although not identical results to more sophisticated pyranometers such as used by national meteorlogical services. In order to assess the quality of data obtained with the Apogee device mounted in the horizontal position would be compared against solar radiation records from Environment Canada measured at the nearby MacDonald Cartier International Airport during the same period. However, although data was collected by Environment Canada during the test period it was not processed and available for distribution such that a comparative assessment was not possible. Other attempts were made using data in the RETScreen software from NRCan which is based on field measurements, although not coincident with the period of this study which revealed a good match. Based on this, it was assumed that measurements made in the vertical position would be an accurate representation of solar radiation received at the face of the study building and transmitted into each apartment.

The various WiDAQ units were fitted with transmitters for remote data download data to a netbook computer fitted with a USB WiKey receiver, with SMT's proprietary Building Intelligence Gateway (BIG) software for equipment configuration and data management. The dataloggers were configured to record as much data as possible as possible over 30 day periods at which time a visit to the building was required to download data (Figure 8). Data was recorded every 30 minutes. As noted previously, the visits provided opportunities to examine the equipment for correct function, to question residents for their subjective impressions of comfort, and to observe apartment operation. Several equipment faults and occasional battery failure occurred during the monitoring period which resulted in short periods of missed data, from different pieces of equipment. System-wide data loss did not occur. Repairs were made as needed.

Figure 8: Wireless data download in progress from WiDAQ dataloggers to netbook.

ASSESSMENT

Indoor Air Temperature and Relative Humidity

The effect of Control, HSG and LSG low-e glazing on indoor conditions was examined by comparing measured indoor air temperature and relative humidity with resident reports of thermal comfort. Temperature and relative humidity measurements were plotted on psychrometric charts on which were plotted also 'comfort zones' from the American Society of Heating, Refrigerating and Air-conditioning Engineers Standard 55 (ASHRAE 55) and Health Canada guidelines for indoor air relative humidity exposure limits.

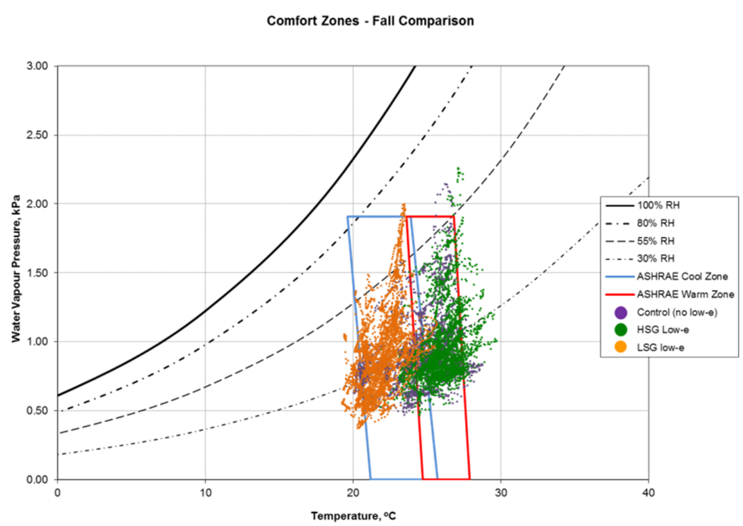

Figure 9: Indoor air temperature and relative humidity for all apartments, fall period, on a psychrometric chart with ASHRAE Standard 55 climate zones and Health Canada indoor humidity levels.

In the fall (Figure 9), the resident of the LSG apartment reported comfortable indoor conditions. During monthly visits, radiator thermostats were found set to minimum until late fall and windows and doors were closed. Appropriately, on the psychrometric chart, temperature and relative humidity data points are generally in the ASHRAE 55 cool weather comfort zone. The resident of the Control apartment reported indoor conditions were often too warm early in the fall but more comfortable later as the outdoor weather cooled. When it was too warm, that resident set baseboard radiator thermostats to minimum and opened windows and/or the balcony sliding door to reduce indoor air temperature. On the psychrometric chart, temperature and relative humidity data points range from the ASHRAE 55 warm weather comfort zone to the cool weather comfort zone. The resident of the HSG apartment reported indoor conditions were too warm in the early fall and then too cool in the late fall. When it was too warm that resident opened windows and/or the balcony door but paradoxically, set radiator thermostats to maximum to supply heat. Not surprisingly, air temperature and relative humidity data points extend from the ASHRAE 55 are mostly in the warm weather zone.

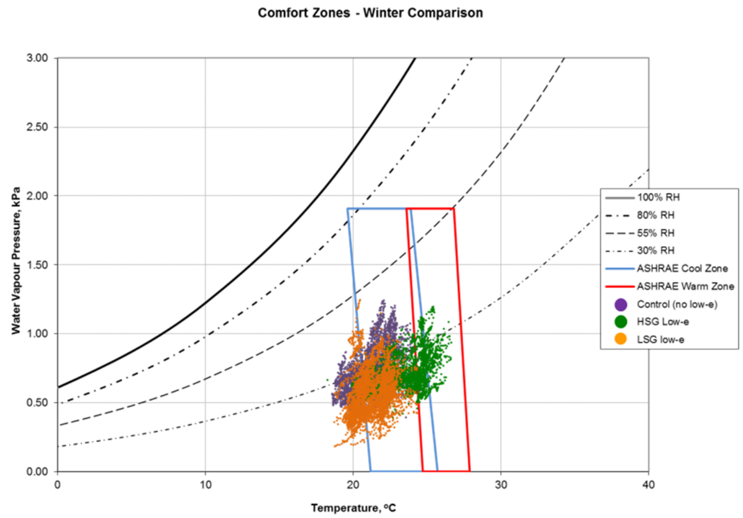

Figure 10: Measured indoor air temperature and relative humidity for all three study apartments, winter period.

In the winter (Figure 10), the resident of the Control apartment reported acceptable thermal comfort until March when it became warm and "stuffy" indoors. Radiator thermostats were set higher during the coldest part of the winter and set lower as spring approached. The resident of the HSG apartment continued to report conditions that were too cool and used supplementary heat sources (plug-in electric heaters during the day, electric blanket in bed at night) to maintain comfort. Radiator thermostats were set at maximum. The resident of the LSG apartment continued to report comfortable conditions, better than those experienced in the previous winter before refit of glazing, although radiator thermostats were set at maximum. Air temperature and relative humidity data points measured in the Control and LSG apartments generally coincided with the ASHRAE 55 cool weather zone whereas in the HSG apartment data points straddled cool and warm weather zones reflecting attempts by the resident to maintain higher indoor temperatures.

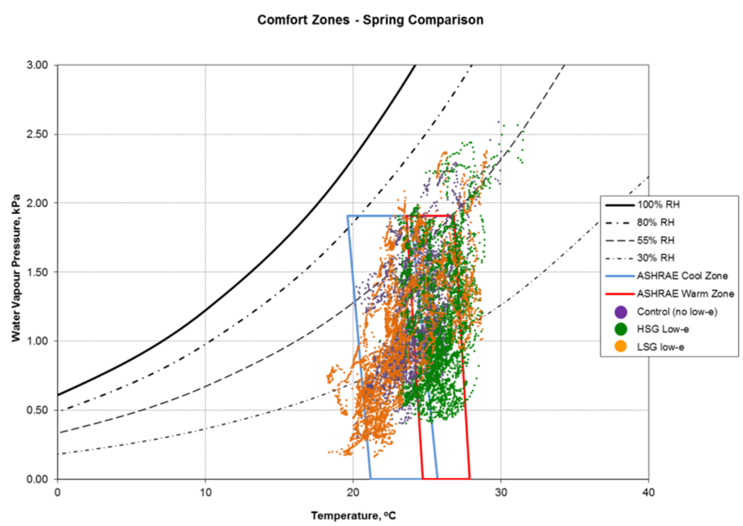

Figure 11: Measured indoor air temperature and relative humidity for all three study apartments, spring period.

In the spring (Figure 11), the residents of the Control and LSG apartments reported comfortable conditions until the arrival of hot, humid weather at the end of the period. The resident of the HSG apartment reported conditions changed from cool to comfortable. Thermostats were set to minimum in the Control apartment, at maximum in the HSG apartment, and progressively reduced from maximum to minimum in the LSG apartment. In all apartments, windows and/or the balcony sliding door were often found open during warm weather. The building space heating system was de-energized in mid-May. For all apartments, indoor air temperature and relative humidity data points were scattered across both ASHRAE comfort zones, reflecting the change from comfort to discomfort for residents of the Control and LSG apartments but conversely, a change from general discomfort to comfort in the HSG apartment resident.

In the summer (Figure 12), the residents of the Control and LSG apartments reported indoor conditions were uncomfortably warm. Windows and doors were opened and fans were used for cooling. The resident of the HSG apartment reported generally comfortable conditions. All residents advised there was no appreciable change compared to the previous summer, before the study began. Air temperature and relative humidity data points were frequently beyond the ASHRAE warm weather comfort zone, reflecting the considerable discomfort reported by the residents of the LSG and HSG apartments but conversely, increasing comfort for the resident of the HSG apartment.

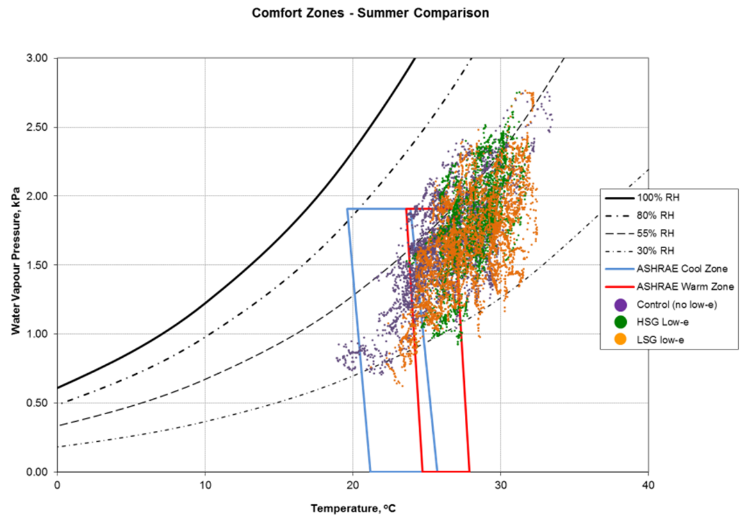

Figure 12: Measured indoor air temperature and relative humidity for all three study apartments, summer period.

Solar Radiation

The effect on control of solar radiation by LSG and HSG low-e coated glass on resident comfort can be discerned by examining incident solar radiation in the vertical position and transmitted solar radiation with the test apartments on clear sunny days in the fall and spring, winter and summer (Figures 13 through 15). Hourly maximum solar radiation (height of curves) changes little from winter to spring but decreases by about half from spring to summer. However, measured total daily solar radiation (area under the curves) increases from winter to spring before decreasing to about half of the winter value in the summer.

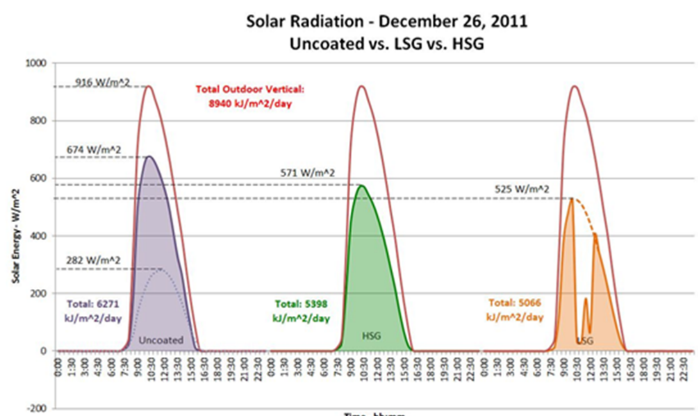

Figure 13: Incident (outdoor) solar radiation (red lines) and transmitted (indoor)solar radiation in the three test apartments on December 26, 2010. Purple, green and red colours represent the Control, HSG and LSG apartments.

The measured variations in solar radiation received in the test apartments shows consistency with the measurements of indoor air temperature and relative humidity and with resident reports of comfort and discomfort. In the fall and spring when the residents of the Control and HSG apartment reported uncomfortably warm conditions but the resident of the LSG apartment reported comfortable conditions, solar radiation received indoors was higher in the Control and HSG apartments than in the LSG apartment. In the late fall, winter and spring, space heating usage was higher in the HSG and LSG apartments which received less solar radiation indoors than the Control apartment. This suggests that too much solar energy can contribute to discomfort but that some solar energy is beneficial for reducing building space heating requirements during the winter months. In the summer, when solar radiation is much lower, all residents reported discomfort. This suggests that in the summer, solar heat gain contributes much less to resident comfort or discomfort.

The amount of solar radiation received through window glass is primarily affected by transmission, reflection and absorption characteristics of the glass and applied coatings. The combined effect of these characteristics is represented by the Solar Heat Gain Coefficient (SHGC) which ranges from 1, when all solar energy striking a window is transmitted (angle of incidence of 0˚), to 0 when no direct solar energy is transmitted (angle of incidence of 90˚). The relationship between angle of incidence and SHGC is not linear. There is little decrease in SHGC from 0˚ to about 50˚ then a rapid decrease to zero at 90˚ angle of incidence (Figure 16).

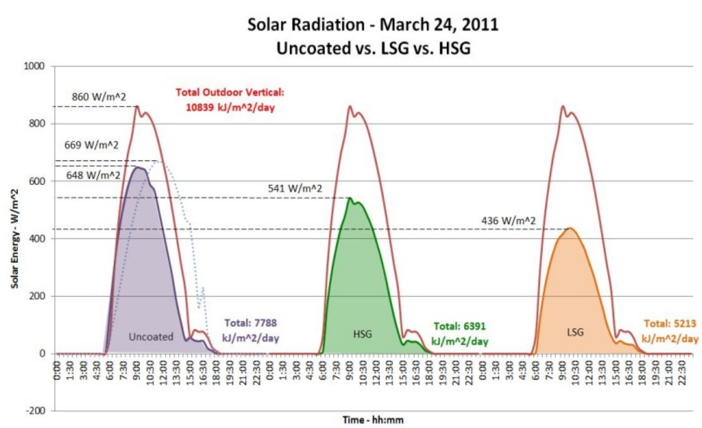

Figure 14: Incident (outdoor) solar radiation (red lines) and transmitted (indoor) solar radiation in the three test apartments on March 24, 2011.

Angle of incidence and SHGC varies during the day as the altitude (vertical angle above the horizon) and azimuth (horizontal angle measured from south) of the sun changes with the apparent motion across the sky. At sunrise, for a south-facing window, a combination of low altitude but high azimuth results in a large angle of incidence and therefore, a low SHGC and thus, low solar gain. At solar noon, altitude is higher but azimuth is lower, resulting in a lower angle of incidence and therefore, higher SHGC and higher solar heat gain.

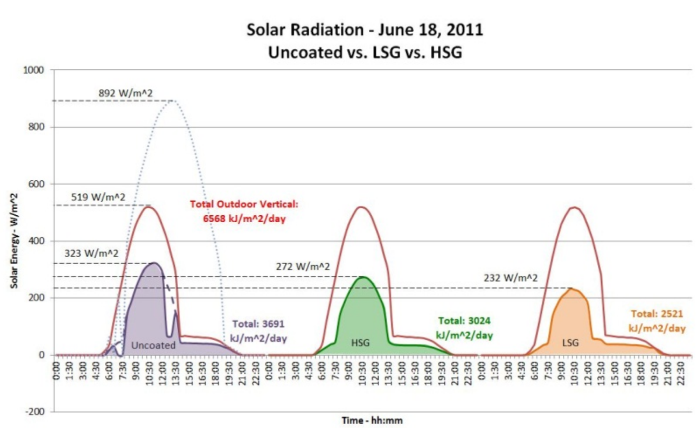

Figure 15: Incident (outdoor) solar radiation (red lines) and transmitted (indoor)solar radiation in the three test apartments on June 18, 2011

This gives rise to the distinctive bell-shaped curves of maximum hourly solar radiation shown in Figures 13, 14 and 15. In a northern location such as Ottawa, the tilt of the earth's axis causes seasonal variations in altitude and azimuth and consequently, seasonal variations in the range of angle of incidence. In Figure 16 the coloured bars represent the seasonal ranges of angle of incidence for the same three days as Figures 13, 14 and 15. The bars overlap so that in winter, the angle of incidence ranges from 90° to about 15°, in spring and fall from 90° to about 40° and in summer, from 90° to about 60°.

The range of angle of incidence is broader in winter than in spring and fall but the additional range is from about 40° to 15° over which there is little increase in solar gain (SHGC) so there is not much more potential for solar gain. In Figures 13 and 15, this is represented by only a small difference in maximum solar gain. Duration of exposure is longer in spring and fall compared to the winter so the total amount of solar radiation during the day is higher. This is represented by the curves being wider in spring and fall compared to winter.

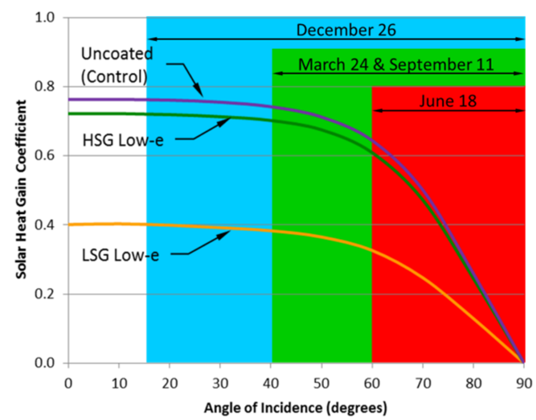

Figure 16: Solar Heat Gain Coefficient for glazing in the Control, HSG and LSG apartments and ranges of angle of incidence for winter, spring, fall and summer.

The range of angle of incidence is narrowest in summer so the potential for solar gain is lowest, so that comparing Figures 13, 14 and 15, the maximum solar radiation is about half. Duration is much greater in the summer but it cannot compensate for reduced angle of incidence.

Solar radiation gain is also affected by building shape and orientation. The study building faces about 31˚ east of south (Figure 17). Consequently, all year, maximum solar radiation increases rapidly in the morning to a maximum before noon. In addition, in the summer the sun rises slightly behind the plane of the exterior wall of the test apartments and in the spring, summer and fall it sets well behind plane of the exterior walls so that in the early morning and late afternoon and evening there are periods of low, indirect solar radiation. During these early morning and late afternoon times, radiation is still received indirectly by reflection from neighbouring buildings and from the sky. This is represented by the hat brim like projections for the fall/spring and summer solar radiation curves (Figures 14 and 15. This radiation is included in the total amounts shown and appears to be unaffected by HSG or LSG low-e coatings.

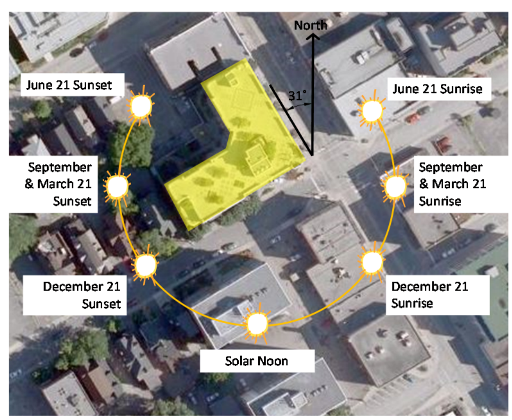

Figure 17: Aerial photo of test building (coloured yellow) with sunrise and sunset positions at solstices and equinoxes. Photo source: Bing.com.

Heat Loss (U-Factor)

The three glazings had different centre-of-glass U-factors, decreasing from Control to HSG to LSG (refer to Table 1). U-factor measures heat loss (nominally from indoors to outdoors) and includes effects of conduction, convection and radiation. Resident's reported comfort and discomfort was not as well correlated to U-factor as it was to solar radiation received indoors.

In the fall, the resident of the LSG apartment (lowest U-factor, 38% lower than in the Control apartment, comparing sealed, insulating glass unit performance data) reported comfortable indoor conditions and space heating usage was low (thermostats set to minimum). However, the resident of the Control apartment (highest U-factor) reported conditions that ranged from too warm at the beginning of the period to more comfortable at the end of the period; throughout, thermostats were set to minimum. The resident of the HSG apartment in (U-factor 30% lower than Control, only 8% higher than LSG for sealed, insulating glass units) reported comfort ranging from initially too warm to too cool. Considering U-factor (that is, heat loss) only, it would be reasonable to expect that later in the period, as outdoor weather cooled, indoor conditions in the HSG apartment would be comfortable because of reduced heat loss, similar to the LSG apartment since U-factors are fairly close. However, discomfort was reported.

In the winter, reported conditions in the Control apartment continued comfortable until outdoor weather became warmer; indoor conditions were then reported as "stuffy". Radiator thermostat settings correspondingly ranged from high to low. Reported conditions in the HSG apartment continued too cool (discomfort) with some improvement as outdoor weather became warmer; space heating usage was high. In contrast, conditions in the LSG apartment continued comfortable although radiator thermostats were set at maximum. Considering U-factor alone, reported conditions in the Control apartment seem reasonable (high heat loss countered by high space heating usage); less so I the LSG apartment (lowest heat loss but similar heating energy usage as Control apartment) and contradictory in the HSG apartment (low heat loss yet very high space heating usage).

In the spring, the residents of the Control and LSG apartments reported comfortable conditions until the arrival of hot, humid weather at the end of the period, even though U-factors were differed considerably. Comfort conditions were improved in the Control apartment during warm spring weather by reducing space heating to a minimum; in the LSG apartment, space heating was progressively reduced. Considering U-factor alone, this is somewhat counterintuitive: space heating demand should have been lower in the LSG apartment. The resident of the HSG apartment reported conditions changed from cool to comfortable; space heating usage decreased progressively, similar to the LSG apartment although thermostat settings remained high. Again, considering U-factor alone, reported discomfort due to indoor conditions being too cool in the winter is contrary to what should be experienced.

In the summer, the residents of the Control and LSG apartments reported indoor conditions were uncomfortably warm. The resident of the HSG apartment reported generally comfortable conditions. All residents advised there was no appreciable change compared to the previous summer, before the study began and glazing was changed in the HSG and LSG apartments. In the summer months, heat transfer would often occur from outside to inside; lower U-factor in the LSG apartment did not appear to give any benefit, although greater comfort was reported by the resident of the HSG apartment which had a similarly low U-factor.

The modes of heat transfer included in U-factor – conduction, convection and radiation – are affected by the amount of difference between indoor and outdoor conditions. As weather cools, the air temperature difference increases which results in higher rates of conduction and convection. Convection heat loss at the outdoor face of glazing is also directly affected by wind speed which generally is higher in the winter. Radiation heat loss is affected by the surface temperature and emissivity of objects in direct line-of-sight of the outside surface of glazing; in winter snow cover has high emissivity but snow and other object surfaces are also cold so radiation heat loss can be higher. Generally, the reverse occurs in warmer spring and summer weather. Consequently, improved (lower) U-factor can be expected to have a greater effect in fall, winter and spring than in the summer. The resident of the LSG apartment reported corresponding comfort and discomfort although compared to the Control apartment, energy usage appeared to be higher in the winter months as determined by a longer period of above minimum thermostat settings. The resident of the HSG apartment reported the opposite: decreasing comfort despite longer duration of high thermostat settings and using additional plug-in space heaters and electric blankets. All residents reported no noticeable difference in the summer months compared to the pre-study condition, before low-e glazing was installed in the LSG and HSG apartments. It would appear, therefore, that thermal comfort and energy usage can be positively affected by reduced U-factor but the effect of solar radiation, particularly increased duration while angle of incidence is low during the late winter/early spring 'shoulder' season, is greater.

Resident Preference

One of the drawbacks of performing a comparative study in an occupied building is the potential for results to be skewed by the behavior of building occupants. Attempts were made to control this affect by selecting three apartments, each occupied by a single person. However, no control could be exercised over the residents, such as ensuring all were the same age, sex and had the same usage patterns (ie. number of hours spent indoors, activities indoors, etc.). Resident preferences also could not be controlled.

As the study progressed, it became apparent that the resident of the HSG apartment experience discomfort and comfort conditions that were roughly opposite to residents of the Control and LSG apartments. As outdoor weather cooled and through the winter, the resident reported indoor conditions were too cool despite high thermostat settings for longer time than the other residents and using supplemental heat (plug-in electric heaters during the day and an electric blanket at night). The resident advised that she preferred warmer indoor conditions. As weather warmed in the spring and through the summer, not surprisingly the resident reported greater comfort although in the summer, comfort was not noticeably improved over the pre-study condition, with glazing the same as the Control apartment (ie. no HSG low-e). A window-mounted air conditioner was used by the resident in the summer for cooling but the resident reported it was used sparingly, only when guests were present and for their comfort, so the air condition is unlikely to be related to that resident's reports of greater comfort during summer weather.

The preference of the HSG apartment resident for warm indoor conditions makes it harder to determine if HSG low-e could provide improvement in resident thermal comfort. Comparison of solar radiation received indoors in the three study apartments reveals that solar gain was reduced by the HSG coating, approximately half as much as by the LSG coating (Figures 13, 14 and 15). This parameter could not be affected by resident behavior. The amount of reduction is greater than would be expected from available performance data (in Table 1, HSG low-e solar heat gain coefficient is only about 5% lower than the as-is condition with uncoated glass in the Control apartment whereas the LSG low-e solar heat gain coefficient is about 47% lower than in the Control apartment). As discussed, U-factor for the HSG low-e glass was very close to the U-factor for the LSG low-e glass (comparing sealed, insulating glass unit performance data only, Table 1). One would expect, therefore, that reported thermal comfort in the two apartments would have been similar, with 'shoulder season' conditions more similar to the Control apartment than the LSG apartment. This was not the case. No conditions were observed in the HSG apartment that would indicate some other cause for the reported cool indoor conditions. This discrepancy cannot be explained. It is impossible to know if the resident of the HSG apartment would have experienced greater comfort had the apartment windows and balcony sliding door been refitted with the LSG low-e glass which had a U-factor lower than the HSG low-e glass. It appears that reduction in solar gain by the HSG coating in the fall, winter and spring was sufficient to cause discomfort to the resident who prefers warmer indoor conditions than the other residents.

CONCLUSIONS

HSG and LSG low-e coatings cause decreased solar radiation in the study apartments. Reduced solar radiation corresponds to observed and reported increased usage of space heating (higher thermostat settings and for longer time) indicating that in apartment buildings, solar radiation gain can contribute to space heating and therefore, is potentially beneficial. The effect of solar gain appears to outweight the benefits of reduced U-factor. However, higher levels of solar radiation can cause discomfort, such as experienced in the Control and HSG apartments in the fall and spring. Factors contributing to reduction of SHGC include transmission, reflection and absorption characteristics of glass and HSG and LSG low-e coatings modified by building shape and orientation.

In apartments with sunny exposures, LSG low-e coated glass can improve resident thermal comfort in the spring and fall. However, to counter increased space heating use, compensating actions should be considered, such as glazing with sealed, insulating glass units incorporating a warm-edge spacer and argon gas fill in the insulating glass unit cavity. Glazing with sealed, insulating glass units also allows use of sputter coated LSG low-e coated glass. Thermally-efficient frame materials and window and door layouts (ie. fewer intermediate frame members) would further help reduce heat loss. It may be difficult to include compensating actions to reduce heat loss in existing buildings unless windows and doors and completely replaced. However, new buildings, such features can be built in.

Solar radiation received in the apartments is lowest in the summer, generally less than half of winter values. Nevertheless, residents reported discomfort in the summer, especially in the Control and LSG apartments. It appears that HSG or LSG low-e glazing provides little benefit to alleviating summer discomfort, at least in northern locations.

Resident preferences for indoor conditions different from the norm can result in unexpected outcomes, such as, in this case, discomfort when low-e glass coating performance parameters would suggest otherwise. More research is required to understand the situation that occurred during this study. It may be that compensating effects to offset reduced solar gain described previously may help with such situations.

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