Introduction and Overview

The building construction industry is in a state of flux. In particular, the building design process is attracting attention because of public concern about the environmental impact and cost of the very large amount of energy consumed in the built environment. In pursuit of better practice conservation is invariably the first and most cost-effective step, so significant attention is being devoted to the thermal resistance of the building envelope. Only a century ago a building might have been built without any insulation at all. Nobody would design that way now. Over the last few decades the code requirement for residential cold-climate wall insulation has increased substantially, to R-20\(^1\) or more. Even now high efficiency homes, some designed to be net-zero buildings, are being built with R-50 (or R-60 or higher) walls despite the fact that added thermal resistance offers a diminishing economic return. More often the investment is driven by the desire for environmental and social responsibility. Whether the motive is economic or not, it is well understood that high thermal resistance is a very good thing.

The thermal performance of windows has also increased appreciably. The mechanisms of heat transfer and solar gain at play in windows are well understood and good simulation models are available. It is convenient that the influences of heat transfer and solar gain can be segregated using R-value (or U-factor) and Solar Heat Gain Coefficient (SHGC).

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\(^1\) R-value is presented in the familiar IP units, \(\frac{\text{hr} \cdot \text{ft}^2 \cdot \text{F}}{\text{BTU}}\).
Two very noteworthy changes have taken effect in the window industry over the last twenty-five years - the widespread application of low emissivity (low-e) coatings and the use of argon fill gas. Even though the window is still a weak component in the building envelope, these two innovations represent a remarkable step forward, roughly tripling the thermal resistance across a 1/2 inch glazing cavity, from about R-1 to about R-3. Low-e/argon has become the standard in the residential sector whether the primary purpose of the coating is the reduction of cold-climate heat loss or hot-climate solar control.

Frame/sash and edge-seal (i.e., spacer) components have also evolved. Twenty-five years ago only two styles of edge-seal were widely used and the aluminum box spacer held a large majority of the edge-seal market. At that time very little was known about the thermal resistance of edge-seals but as data became available it became clear that the aluminum box spacer represents a serious short-circuit. Now many thermally-improved edge-seals are available. Similarly, new techniques have been devised to assess the thermal performance of frame and sash cross-sections, and many improved frame designs have been brought to market.

Low-e coatings are almost always used on surface 2 or surface 3, in the cavity, of double-glazed Insulated Glazing Units (IGUs). A low-e coating is very effective in this location because most of the heat transfer across a glazing cavity will take place by means of longwave radiant exchange if the glass is uncoated. Similarly, in parallel with natural convection, longwave radiation represents the larger component of heat transfer between the window and the conditioned space. This presents the possibility of also using a low-e coating on surface 4, the indoor surface, to boost thermal resistance. The addition of 4th surface low-e will push center-glass R-value up by approximately 0.9, say from R-4.0 to R-4.9. The 4th surface low-e will also improve thermal comfort by disconnecting the longwave radiant exchange between the window and the occupants of the building. This approach to increased thermal resistance and added comfort merits serious consideration because a durable low-e coating can be applied with little cost, with no additional weight and without modification to framing sections or mounting hardware.

However, the use of 4th surface low-e presents a trade-off. In a cold climate the added thermal resistance of the 4th surface low-e will lower the temperature of the indoor glass surface, decreasing the condensation resistance of the window. Consequently, it is necessary to develop some guidelines that can be applied to the use of 4th surface low-e. At first glance this appears to be a difficult task. Reasons for this impression include: (a) Condensation has an on/off
characteristic. The consumer will not perceive a difference between two well-designed windows whether the surface temperature exceeds the dew point temperature ($T_{dp}$) by a little or a lot. So there is little incentive to increase production cost to raise surface temperatures significantly above $T_{dp}$. (b) People are accustomed to seeing condensation and are largely willing to tolerate it, even on a repeated basis, unless it is excessive and especially if it runs/pools and threatens to damage the frame or wall. (c) The presence of condensation is subject to the variability of the weather. As outdoor temperature decreases the severity of condensation increases and the wetted area increases. Condensation is not generally a problem during sunlit hours when solar radiation warms the window. (d) There is a trend toward higher indoor relative humidity (RH) as buildings are tightened, and as people avoid the discomfort and health difficulties associated with dry air. Occupancy level and type of activity both have a strong influence on indoor RH. In turn indoor RH has a strong influence on the severity of condensation. Increased RH increases $T_{dp}$. In the extreme, any building envelope component, even a well-insulated wall, will be susceptible to condensation if RH is high.

So how much condensation resistance is enough, and at what cost? These questions require careful thought, particularly in light of the variabilities associated with weather and occupancy – all of which are beyond the manufacturer's control. More specifically, is it possible to draw conclusions about the use of 4th surface low-e coating? The key is to segregate the science from the weather/people-related factors. This idea leads to a two-step approach. First, quantify the thermal performance of the window (i.e., determine surface temperatures) and evaluate a condensation resistance index and, second, use this index to see how a 4th surface low-e window compares to the windows currently being marketed. It is important to realize that there is a wealth of knowledge about the suitability of existing products, including their condensation resistance, and the influence of pertinent weather/people-related variabilities is an integral part of this knowledge base.

In pursuit of insight regarding the use of 4th surface low-e, Guardian industries has sponsored a series of environmental chamber tests and a set of computer simulations. Both projects were undertaken by independent agencies. The experimental work was done by the Exova Building Performance Centre (Mississauga, Canada) and the simulations were done at the University of Waterloo (Waterloo, Canada). More specifically, measurement and simulation were used to explore the indoor surface temperatures of a very common cold-climate residential window (a double-glazed low-e/argon glazing system with insulating edge-seals in a double-hung vinyl sash and frame) with the goal of
resolving the influence of 4th surface low-e coatings. The project outcomes include straightforward recommendations on the use of 4th surface low-e plus some observations about condensation resistance in general. However, some background material is needed to better understand the process.

Background – What causes condensation on windows?

Condensation forms most readily at the perimeter of the view area (i.e., at the sightline). This is a direct visual indication that condensation is caused by edge-seal conduction and the edge-seal is widely, and correctly, recognized as a thermal short-circuit. It is a difficult challenge to devise an edge-seal that can match the performance of a good glazing system. The glass-to-glass resistance of the center-glass area (low-e, 1/2 inch argon), \( R \approx 3 \), can only be approached by the best rigid foam insulation, \( R \approx 6 \) per inch. This type of insulation is a material with approximately the conductivity of air, well below the conductivity of the structural materials currently used in spacer assemblies, and orders of magnitude below the conductivity of metals. So, even modern warm-edge spacers represent a thermal short circuit.

Although edge-seal conduction is the primary cause of perimeter condensation it is not the only culprit. Edge-glass temperature is also suppressed because the indoor glass surface is not flush with the wall and/or frame. In the recessed corner at the sightline the surface heat transfer coefficients between glass and room, both convective and radiant, are reduced because air motion is restricted and because of self-viewing between window surfaces, respectively.

It is also known that condensation forms most readily at the bottom edge of the view area. See Figure 1. This happens primarily because fill gas motion cools the bottom of the indoor glass. In winter, at night, fill gas flows upward adjacent to the warm indoor glass and downward near the cold outdoor glass. The descending gas becomes progressively colder. At the bottom of the cavity the cold fill gas turns and as it starts its ascent it cools the indoor glass. The result is that the bottom edge of the indoor glass is preferentially cooled by the fill gas.

Background – Computer Simulation

Numerical models have been developed for predicting the temperature field in a window assembly. It is an ambitious undertaking to distinguish between head and sill sections because the conduction and radiant exchange models needed for the more straightforward energy analysis must be augmented by models that account for fill gas motion. Several research comparisons between
measurement, usually surface temperature profiles obtained by thermography, and simulation have been used to refine analysis techniques and establish confidence in the associated software. Simulation has been used to reproduce the detail of measured edge-glass temperature profiles including a good estimate of minimum surface temperature at the bottom sight line. Simulation can be used reliably to compare the thermal performance of alternate designs and offers insight regarding the heat transfer mechanisms at play. This is a valuable tool.

Figure 1: Edge-glass condensation photographed shortly after sunrise. There is much more condensation at the sill than at the jamb.

Less effort has been devoted to the prediction of frame surface temperatures. The frame attracts less interest because condensation is not generally found on the surfaces of a well-insulated frame. Comparisons on this topic have been met with mixed success but, more to the point, the prediction of frame temperatures is unimportant in the context of the current study where the focus is on the role of the 4th surface low-e coating and how that coating will influence condensation resistance at the glass surfaces. The center-glass temperature will be influenced only by the characteristics of the glazing system – by definition. The area of greatest interest is the bottom edge-glass area. The temperature profile in this location will be influenced largely by the
characteristics of the glazing system (including the emissivity of the 4th surface),
conduction in the vicinity of the edge-seal, and fill-gas motion – and reliable
models have been established for all three of these influences. Frame
temperature will be largely unaffected by a 4th surface low-e coating.

Background – Condensation Resistance Index

The next step in the process is to transform surface temperature information
into an index that quantifies condensation resistance. Alternate methods have
been proposed and discussed but no consensus has been reached. This situation
might be expected because there is no underlying principle by which
condensation resistance can be defined. In contrast, the definitions of U-value
and SHGC are unambiguous – they must be assessed such that each satisfies an
energy balance. The definition of a condensation resistance index must be
based on ideas that are less amenable to quantification: For example, surface
temperatures below Tdp will cause condensation, large areas of condensation are
bad, low sightline temperature is bad.

In North America methods of evaluating a condensation resistance index are
offered by AAMA, CSA and NFRC. A common thread is to normalize surface
temperature, Ts , with respect to the indoor and outdoor temperatures, T in and
T out . This operation is specified by CSA to calculate Condensation Index (I)
and by AAMA to calculate Condensation Resistance Factor (CRF). The
calculation of I or CRF is shown in Equation 1.

\[
I \text{ or CRF} = \frac{T_s - T_{\text{out}}}{T_{\text{in}} - T_{\text{out}}} \times 100
\]

Values of I or CRF range from zero to one hundred, higher values being
associated with higher, more desirable, surface temperatures. This type of
normalization allows for a meaningful comparison of different products even if
those products were tested using different values of T in and T out . Of course, test
conditions should be similar if possible.

The AAMA and CSA methods are both formulated for use with measured
surface temperatures but differ because AAMA specifies T s for the glass area
by averaging the measurements of six thermocouples at specified locations
whereas the CSA methods specifies T s as the coldest glass temperature.

A much more intricate scheme is prescribed by NFRC to calculate a
Condensation Resistance (CR) index. The calculation of CR for each
component area, A x (x=frame, edge-glass, center-glass), is of the form shown in
Equation 2. Note that a penalty is applied in the CR calculation only if surface temperature falls below \( T_{dp} \) and this penalty is weighted in proportion to both temperature suppression below the dew point temperature \( (T_{dp} - T_i) \) and the amount of subcomponent area \( (A_{x,i}) \) involved. This combined consideration of condensation area and condensation severity represents a distinct difference with respect to the AAMA and CSA procedures.

\[
CR_x = 1 - \frac{1}{3} \sum_{j=1}^{3} \left( \frac{\sum_{i=1}^{j} (T_{dp,j} - T_i)A_{x,i}}{(T_{dp,j} - T_c)A_x} \right)^{1/3} \times 100 \quad (2)
\]

The NFRC procedure also differs from the other procedures because a module for converting simulation results to CR is included in the Window/Therm software package. This module can only be executed if Therm is run in "condensation mode", meaning that a model for fill gas motion has been invoked. Therm also accounts for self-viewing of the window surfaces. These features closely correspond to procedures used in previous research comparisons and provide an expectation of good engineering accuracy.

The current project was undertaken as a combination of simulation and measurement but the bulk of the analysis related to the quantification of condensation resistance relies on simulation. Therefore, for the combination of suitable heat transfer models and convenience, CR was chosen as the working tool to quantify condensation resistance.
The Test Samples

Six double-hung, vinyl, windows (overall size 47 inches x 59 inches) were used in this study. The frame and sash were of a conventional, currently marketed, residential design. Each IGU (23 inches x 40.5 inches) was built from two sheets of 3 mm clear float glass and one of two insulating edge-seals, either a composite butyl or a tin-plated steel U-channel. The pane spacing was 15.9 mm (5/8 inch) in each case and argon fill gas was used in each case (presumed to be 90% argon, 10% air). One of two different low-e coatings was used in each glazing cavity (ClimaGuard 70/36 on surface 2 or ClimaGuard 80/70 on surface 3, emissivity = 0.036 and 0.095, respectively). Three windows were built with ClimaGuard IS-20 low-e coating (emissivity = 0.2) on the 4th surface for comparison with three otherwise identical windows built with no 4th surface coating. The edge-seal and coating combinations are listed in the left-hand portion of Table 1.

Table 1: Test Sample Configurations and Selected Simulation Results

<table>
<thead>
<tr>
<th>Edge-Seal</th>
<th>Coating(s)</th>
<th>( R_{\text{center-glass}} )</th>
<th>( R_{\text{window}} )</th>
<th>Bottom Edge CR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite</td>
<td>70/36 (surface 2)</td>
<td>3.9</td>
<td>3.8</td>
<td>61.7</td>
</tr>
<tr>
<td>Butyl</td>
<td>70/36 + IS-20</td>
<td>4.8</td>
<td>4.3</td>
<td>50.6</td>
</tr>
<tr>
<td>U-channel</td>
<td>70/36 (surface 2)</td>
<td>3.9</td>
<td>3.5</td>
<td>53.1</td>
</tr>
<tr>
<td></td>
<td>70/36 + IS-20</td>
<td>4.8</td>
<td>4.0</td>
<td>43.9</td>
</tr>
<tr>
<td>Composite</td>
<td>80/70 (surface 3)</td>
<td>3.7</td>
<td>3.6</td>
<td>60.2</td>
</tr>
<tr>
<td>Butyl</td>
<td>80/70 + IS-20</td>
<td>4.6</td>
<td>4.1</td>
<td>48.0</td>
</tr>
</tbody>
</table>

Note: simulation results correspond to NFRC specifications for CR calculation

The Test Conditions

Six sets of tests were undertaken using an environmental test chamber. During each set of tests each window was exposed to a variety of conditions. On the indoor side the temperature was held constant at \( T_{\text{in}} = 70^\circ F \) but each test was repeated with RH=30%, 40% and 50%. On the outdoor side the wind speed was held constant at 12.3 mph and each test lasted 18 hours with \( T_{\text{out}} \) ramped down through the profile shown in Figure 2. No solar radiation was present during any of the tests so the profile shown in Figure 2 mimics a cold winter
night. The last four hours of the profile corresponds to an extremely cold winter night. Photographs and thermal images were taken periodically during each test. Figure 3 shows a photograph of one of the test windows mounted in the mask wall.

![Figure 2: Outdoor temperature time/ramp profile](image)

Figure 3: Test window mounted in mask wall
The tubes used to create the outdoor-side wind can be seen through the window. (CG 70/36 + IS-20, composite butyl edge-seal, $T_{\text{out}} = 0^\circ\text{F}$ (initial), RH=30%)
Environmental Chamber Tests

Early in the program of environmental chamber tests it was necessary to adjust the configuration of the warm-side chamber. For example, when the CG 70/36 window with composite butyl spacer and IS-20 coating was tested at $T_{\text{out}} = -10^\circ\text{F}$ and RH=50% condensation was observed only at the perimeter of the glass even though, based on simulation, the center-glass surface was expected to be colder than $T_{\text{dp}}$. It was found that the air circulation loop used to maintain $T_{\text{in}}$ was causing forced air movement in the vicinity of window and mask wall, and although this air movement was weak it did raise the surface temperature of the window. Consequently, a curtain was installed near the back wall of the chamber to prevent the supply vents from directing air at the window. This modified configuration was used for all window tests.

![Figure 4: Thermal images of windows without (left image) and with (right image) 4th surface low-e (CG 70/36, composite butyl edge-seal, $T_{\text{out}} = 0^\circ\text{F}$)](image)

Figure 4 shows thermal images of two windows that are identical except that the window shown on the right has a 4th surface low-e coating. The most immediate observation is that the thermal camera cannot correctly measure the temperature of the low emissivity surface. This surface is highly reflective in the longwave band so the reported surface temperature is close to room temperature because most of the radiation received by the camera is reflected from the background. Nonetheless, the thermal images show the cold areas...
caused by edge-seal conduction at the perimeter of each IGU. The coldest edge of each IGU is at the bottom because of fill gas motion. The coldest point is in the bottom corner because of the combined effect of two edge-seals and fill gas motion. The bottom edge above the meeting rail is colder than the bottom edge at the sill. This difference occurs because the bottom section of the upper sash has a relatively short conduction path to the outdoor side with two sash surfaces exposed to the outdoor air. The CR numbers reported in this study apply to the edge-glass area that is most susceptible to condensation – the edge-glass above the meeting rail.

A conventional camera was used to photograph the indoor side of the test window during each test run. Figure 1 provides an example. It was also possible to make observations by eye during the experiments. The photographs were later checked in order to estimate the width of the condensation band above the meeting rail. A summary of the observed condensation amounts can be found in Table 2. Note that the data listed in Table 2 are approximate because the condensation front is difficult to see in some instances and because the field of view includes the entire window, not just the edge-glass area. The visualization described by Table 2 provides a variety of useful observations:

- As $T_{out}$ decreases condensation first appears at the bottom sightline and the condensation band gets wider. Eventually, when $T_{out}$ is very low and when the condensation band is at its widest, possibly covering the center-glass area, frost and ice may appear at the sightline.
- At lower values of RH every window showed less condensation, and stayed free of condensation to lower values of $T_{out}$.
- Windows with the composite butyl spacer produced less condensation than windows with the U-channel spacer. It is not possible to draw quantitative conclusions about the relative performance of the two spacers, because of the coarse nature of the photographs, but there is a clear difference both in the width of the condensation band and the number of instances in which frost occurs.
- The choice of low-e coating used in the glazing cavity (i.e., CG 70/36 versus CG 80/70) had little influence on the amount of condensation observed. In the most severe condition, $T_{out} = -15^\circ$F, the CG 70/36 coating seems to perform better, and this might be expected because of its lower emissivity, but at other outdoor temperatures the reverse seems to be true.
- The 4th surface low-e coating is accompanied by a wider condensation band in most cases, and this is expected, but one should resist the
temptation to reject the use of 4th surface coatings purely on the basis of this observation (The same train of thought could be used to reject the use of edge-seals for example.) because it is possible to develop logic by which condensation resistance can be retained and, in fact, such procedures are described in subsequent passages of this document. The different amounts of condensation are illustrated by comparing the two photographs shown in Figure 5. In this case the 4th surface low-e causes an extra inch of condensation, approximately. This is typical of many of the cases listed in Table 2 although the amount of extra condensation differs from one situation to the next. Certainly, the introduction of 4th surface low-e would be much more dramatic if the center-glass area of the window were otherwise on the verge of falling below Tdp. This idea can be reinforced by using Table 2 to make the same comparison shown in Figure 5 but switch from RH=40% to RH=50%.

During the course of the experimental work a number of comparisons were made and the equipment operators were satisfied that the surface temperatures and condensation patterns observed were in good agreement with simulation results. This agreement, as well as agreement found in previous research comparisons, provides the freedom to examine the thermal performance of the test windows in more detail using computer simulation. Simulation results provide insight that cannot be obtained by experiment.

**Figure 5:** Condensation band on windows without and with 4th surface low-e (CG 70/36, composite butyl edge-seal, T_{out} = 0°F (8 hours), RH=40%)
Table 2: Measurement Summary - Width of Condensation Band (inches) Above Meeting Rail Sightline

<table>
<thead>
<tr>
<th>IGU Coating</th>
<th>Edge-Seal</th>
<th>Indoor RH</th>
<th>Indoor Coating</th>
<th>Outdoor Temperature (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Width of Condensation Band (inches)</td>
<td>40</td>
</tr>
<tr>
<td>70/36 on #2 surface</td>
<td>Composite Butyl</td>
<td>30%</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IS-20</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40%</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IS-20</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50%</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IS-20</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>U-Channel</td>
<td>30%</td>
<td>none</td>
<td>none</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>IS-20</td>
<td>none</td>
<td>none</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>40%</td>
<td>none</td>
<td>none</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>IS-20</td>
<td>none</td>
<td>none</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>none</td>
<td>none</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>IS-20</td>
<td>none</td>
<td>none</td>
<td>0.5</td>
</tr>
<tr>
<td>80/70 on #3 surface</td>
<td>Composite Butyl</td>
<td>30%</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td>IS-20</td>
<td>none</td>
<td>none</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>40%</td>
<td>none</td>
<td>none</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>IS-20</td>
<td>none</td>
<td>none</td>
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</tr>
<tr>
<td></td>
<td>50%</td>
<td>none</td>
<td>none</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>IS-20</td>
<td>none</td>
<td>none</td>
<td>1</td>
</tr>
</tbody>
</table>

Notes: (f) = frost observed on at least part of the glass surface, full = entire glass surface covered with condensation.
Computer Simulation - Center-Glass Condensation Resistance

Figure 6 shows the indoor center-glass surface temperatures calculated for five glazing systems, plotted as a function of $T_{\text{out}}$. Four of the glazing systems match the systems studied in this project. The fifth system consists of two sheets of uncoated clear glass with a 5/8 inch air-filled glazing cavity (i.e., conventional double glazed, labelled CDG). In addition, dashed lines mark $T_{dp}$ for RH=30%, 40% and 50% (at $T_{in} = 70^\circ F$).

The two uppermost curves in Figure 6 correspond to the two glazing systems that do not have a 4th surface low-e coating. The only difference between these two systems is the different low-e coating in the glazing cavity. The CG 70/36 coating produces a slightly higher center-glass temperature because its emissivity is lower than the emissivity of the CG 80/70 coating. Working downward, the next two curves correspond to the same two glazing systems except that the 4th surface low-e coating has been added. It is encouraging that the center-glass area, with 4th surface low-e present, will be free of
condensation at $T_{\text{out}}$ as low as $0^\circ\text{F}$ with RH=40% and at $T_{\text{out}}$ even as low as about -25°F with RH=30%. These observations are well supported by anecdotal evidence. Center-glass condensation is rare.

To better understand why center-glass condensation is rare it is worth remembering that low $T_{\text{out}}$ almost always coincides with low indoor RH. This is because cold outdoor air can hold very little water vapor even if its RH is very high. As cold outdoor air enters the building, mechanically or otherwise, it is heated to room temperature and its RH drops dramatically. So high indoor RH in combination with low $T_{\text{out}}$ only occurs in unusual circumstances. For example, indoor RH will be high in an exceptionally tight building with no heat recovery ventilator (HRV), or it may be caused by unusual occupant loading, or high indoor RH may simply be maintained mechanically. Regardless, the connection between low outdoor temperature and low indoor RH generally applies and this connection represents a natural safety factor.

Figure 6 includes a line showing indoor RH levels recommended as a function of $T_{\text{out}}$. This particular recommendation is offered by the EPA. Clearly, the recommended RH levels are intended to avoid moisture-related problems at the indoor surfaces of the building envelope; the similarity between the slopes of the various lines is unmistakable. All five glazing systems shown in Figure 6, including systems with 4th surface low-e, will have no problems with center-glass condensation if the recommended indoor RH levels are maintained.

Now let’s look at Figure 6 from a different perspective, a perspective that removes weather and people, and even recommended RH levels, from the argument. The consequence of adding the 4th surface low-e is clear. At $T_{\text{out}} = 0^\circ\text{F}$, for example, the 4th surface low-e suppresses the center-glass surface temperature by about $7^\circ\text{F}$. This is a noticeable difference but it is important to recognize that both glazing systems with 4th surface low-e have higher center-glass temperature than the CDG glazing system. Important information can be extracted from the CDG comparison because CDG systems have been marketed for many years and the condensation resistance of the CDG glazing system is well understood. Specifically, if the CDG system is known to be satisfactory in a given market (Remember, our focus is on center-glass condensation at the moment.) then a low-e/argon + 4th surface low-e system will also be satisfactory. It should be emphasized that this comparison applies to the same market. Taking this point of view, by testing alternatives with respect to the CDG glazing system in the same market, the variabilities associated with weather and people have been removed from the comparison, and an opportunity to make clear design and marketing decisions is available.
A similar approach will be used in the following section where the more crucial topic of bottom edge condensation resistance is discussed.

However, as an aside, let's consider another question that may be raised by Figure 6. Noting that the 4th surface low-e suppresses surface temperature by about 7°F, it is natural to ask whether the 4th surface low-e will actually decrease or increase heat transfer between the window and a building occupant. There are two things that change when the 4th surface low-e is added. First, the potential that drives the heat transfer, T^4 (not T), increases by about 20%. Second, a simple hand calculation shows that the resistance controlling radiant exchange will increase by about 50% when the emissivity of the 4th surface is reduced from 0.84 to 0.2. The net effect is a decrease in radiant heat transfer, between a window and a nearby occupant, of about 20%. So, yes, the 4th surface low-e coating will increase occupant comfort.

Computer Simulation - Bottom Edge Condensation Resistance

The edge-glass area, particularly the bottom edge-glass area, easily merits the most attention and effort when designing for condensation resistance. Examined from the perspective of a window supplier the message is consistent. When a homeowner is concerned about window condensation it is almost always edge-glass condensation. This is because bottom edge-glass condensation occurs more readily, and with greater severity, so it is seen and noticed more frequently.

Figure 7 shows bottom edge indoor surface temperature profiles, based on computer simulation, for the six windows studied in this project. The three curves grouped on the left correspond to the windows with 4th surface low-e. The corresponding temperature profiles of the uncoated 4th surface, but otherwise identical, windows are grouped on the right.

Again, it is clear that the 4th surface low-e supresses glass surface temperature. In contrast, the choice of CG 70/36 versus CG 80/70 in the glazing cavity makes relatively little difference and this difference diminishes toward the sightline where the glass temperature is more strongly influenced by edge-seal conduction. The choice of edge-seal has a much stronger influence on the edge-glass temperature profile. The minimum edge-glass temperature, at the sightline, changes by about 10°F when one edge-seal is replaced by the other. Considering the common situation with RH=30% the results shown in Figure 7 predict a small condensation band with U-channel edge-seals (about 1/2 or 1/4 inch without or with 4th surface low-e, respectively) and no condensation with composite butyl edge-seals (with or without 4th surface low-e). If RH is
increased to 40% all six windows can be expected to have bottom edge condensation and the severity of this condensation spans a wide range with the situations aggravated by both edge-seal conduction and 4th surface emissivity.

Figure 7: Calculated indoor edge-glass surface temperature (horizontal axis) versus distance above the sightline, above the meeting rail (vertical axis). Dashed lines show $T_{dp}$ corresponding to $T_{in} = 70^\circ F$

Again, it is useful to remove the weather/people variabilities from the decision process by making a comparison with an existing product. Say a manufacturer produces a window that is currently marketed and known to perform well in a given location/climate. Specifically, the current window is well-liked by customers with regard to condensation resistance. If this window is modified by adding a 4th surface low-e its CR value will decrease. Table 1 shows that the bottom edge CR values of the windows studied in this project all decrease by about 10 units when the IS-20 coating is added. Therefore, to retain the condensation resistance of the original product, along with the level of customer satisfaction attached to the original product, it is necessary to make a design change that will offset 10 CR units. The most direct means of making this adjustment is to use an edge-seal with more thermal resistance.
The comparison exercise described above can be illustrated with reference to Figure 7 and Table 1. Use the CG 70/36 window with U-channel edge-seal as the "original" design. When the IS-20 coating is added to the 4th surface CR drops from 53.1 to 43.9 but some of this decrease can be offset by switching to the composite butyl edge-seal, pushing CR back up to 50.6. Now examine the corresponding temperature profiles in Figure 7. The result is encouraging. The original window produces condensate (albeit a small amount) at RH=30% but the modified window produces none. The modified window outperforms the original window up to about 35% RH and the modified window doesn't produce appreciably more condensate until RH approaches 40%. If the edge-seal had been modified to the extent that the original bottom edge CR had been recovered the comparison would be even more favorable.

The same example can be used to emphasize a few details regarding climate and indoor RH. In this example the 4th surface low-e decreases bottom-edge CR from about 53 to about 44 but CR is pushed back up over 50 by switching to a different edge-seal. This should not be interpreted to mean that the edge-seal must be changed if 4th surface low-e is added to a particular window. In some instances the original edge-seal will still be suitable. For instance, in a warmer climate a manufacturer may know that CR=44 is sufficient so, with reference to the numbers listed above, it is not necessary to switch out the edge-seal. But in a colder climate a higher CR will be needed and an edge-seal with more thermal resistance should be used. A similar comment can be made about the influence of indoor RH. An older (i.e., leaky) house with low RH represents a situation where lower CR is sufficient but a well-sealed house with higher RH will need a higher level of CR performance. So, it is important to have a careful look at the numbers. The bottom-edge CR number provides a lot of guidance about choice of edge-seal and the suitability of 4th surface low-e coating in a particular climate and application.
Summary and Recommendations

In summary, a number of useful comments and recommendations can be made regarding this study of 4\textsuperscript{th} surface low-e coatings. The broad overview is that any window design that includes a proposed 4\textsuperscript{th} surface low-e coating must have sufficient thermal resistance to compensate for the fact that the 4\textsuperscript{th} surface coating will lower the temperature of the indoor glass surface. A satisfactory level of thermal resistance can be assessed by comparison with existing products. This comparison can be done in such a way that the variabilities of weather and people are removed from the argument. The detail of providing sufficient thermal resistance differs between center-glass, edge-glass and frame areas. The bottom edge-glass area is the location most likely to produce condensation so this is the area that requires the most attention. Comments pertaining to each of the three component areas are included below.

The first concern is that 4\textsuperscript{th} surface low-e may cause the center-glass temperature to drop below $T_{dp}$ allowing condensation to form across the entire view area of the window. The simplest advice in this regard is that it is safe to use 4\textsuperscript{th} surface low-e with a modern glazing system (i.e., low-e/argon) in any application where a conventional double glazed (clear/clear, 1/2 inch air, no coatings) window does not have problems with center-glass condensation. However, there may be exceptions to the rule. For example, this study was completed by examining a 4\textsuperscript{th} surface coating with emissivity of $e=0.2$. A coating with higher emissivity will be less susceptible to condensation but a coating with lower emissivity may cause problems. Also, a conventional double glazed window may not provide sufficient center-glass condensation resistance to be used as a reference system in exceptionally cold climates or in situations where indoor RH is unusually high. So here is a more generic procedure. Start by looking at the products that are used in the location of interest and for the application of interest. Identify a glazing system, as a reference, that provides sufficient center-glass condensation resistance for the given situation. In many cases this satisfactory glazing system will be conventional double glazing but in some cases it may be quite different. Use the center-glass CR value of this reference glazing system as a threshold value that represents satisfactory performance. Then, make sure the proposed glazing system matches or exceeds that center-glass CR threshold.

The mechanisms of heat transfer that govern edge-glass and center-glass surface temperatures are appreciably different. Generally, windows are most susceptible to condensation at the bottom edge-glass area. Nonetheless, a logical approach to having satisfactory edge-glass condensation resistance,
while adding a 4th surface low-e coating, matches the procedure described above. First, identify a window that provides satisfactory bottom-edge condensation resistance in the location and application of interest. Use the bottom edge-glass CR number of this reference window as a threshold CR value. Then, make sure the bottom edge-glass area of the proposed window meets or exceeds that CR threshold. If the reference and proposed windows happen to be identical, except for the 4th surface low-e coating, it will be necessary to improve the edge-seal to recover the original condensation resistance. This edge-seal improvement will need to increase the edge-glass CR value by about 10 CR units.

To complete the exercise, condensation resistance of the frame should also be considered, even though the use of a 4th surface coating has little influence in this area. The recommendation is similar. Determine the CR number for an existing frame that has sufficient condensation resistance and match its frame-area CR value with the proposed frame.

The procedures presented above show how CR values can be used to guide design decisions by making the correct comparisons. Each procedure uses the CR index to make comparisons. The CR index is not used in an absolute sense. Therefore, on the assumption that each of the three available indices (I, CRF and CR) is formulated well enough to distinguish between, or correctly rank, the condensation resistance of different products, any one of the three indices can be used to undertake the design procedures described. However, it is crucial that the condensation resistance index being used can be applied separately to the different component areas of the window, especially the bottom edge-glass area.

To finish, a comment about triple glazing is worthwhile. This study shows that opportunities exist for the design of double glazed windows with 4th surface low-e. The topic of 4th surface low-e has attracted attention because this approach is seen as a possible alternative to making the shift from double glazed to triple glazed windows. However, these two possibilities should not be seen as mutually exclusive. If a manufacturer chooses to produce triple glazed windows, the use of an indoor low-e coating, 6th surface low-e in this case, should be seen as a very safe way to deliver extra thermal resistance and improved thermal comfort. The extra center-glass thermal resistance of a triple glazed system, presumably with a low-e coating and argon fill gas in each glazing cavity, and the extra-long conduction path through the double edge-seal will provide more than enough thermal resistance to permit the use of 6th surface low-e in all but the most extreme operating conditions.
References

References have not been included in the body of this paper in order to make the text more readable. Nonetheless, there are a number of technical publications that support the background material presented. The following references are offered as worthwhile reading. Of course, any one of the references listed below is likely to include references to related material that is also of interest.

Simulation and Thermography:


* five papers, all part of the same comparison project
Fill Gas Motion


Edge-Seal Thermal Resistance


Recommended Indoor RH Levels
http://www.epa.gov/mold/moldresources.html

Acknowledgments

Appreciation is extended to Jordan Church (Exova Building Performance Centre), Christine Rogalsky (UW/Mech. Eng. BASc and MASc graduate) and Dave McClean (formerly of Guardian Industries). These three people enthusiastically devoted extra time and effort, and considerable expertise, to make sure the simulation and measurement processes were completed properly.