THE EFFECTS OF #4 SURFACE LOW-E COATINGS ON FENESTRATION CONDENSATION RESISTANCE

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ABSTRACT

As the focus on improving building envelope thermal performance continues to grow so too have alternative solutions for improving the thermal transmittance (U-factor) of glazed fenestration systems. Lately, particular attention has been paid to achieving "R5" performance in glazed window systems; these systems having U-factor ≤ 1.14 W/m^2-K (0.20 BTU/hr-ft^2-°F) for fixed units and ≤ 1.25 W/m^2-K (0.22 BTU/hr-ft2-°F) for operable.

The traditional solution for achieving this level of performance is through the use of triple glazed insulating glass. Such construction utilizes two glazing cavities and can incorporate multiple low-e coatings for significantly improved thermal performance. An alternative is to use a suspended low-e film inside the IGU construction for similar performance results. Recently introduced is a dual glazed IGU construction that utilizes a high performance, soft-coat low-e coating on surface #2 and a hard-coat, pyrolytic low-e coating on surface #4. This construction is designed to reflect long wave infrared radiation back to the interior environment thereby decreasing thermal transmittance and achieving a U-factor approaching 1.14 W/m^2-K (0.20 BTU/hr-ft^2-°F).

This infrared reflection of heat to the interior environment also reduces significantly the surface temperature of the interior surface of the interior glass lite. In an environment having exterior air temperature of -18ºC/0°F and interior air temperature of 21ºC/70°F the interior edge-of-glass temperature can fall well below 0ºC/32°F. Such a situation creates a condition whereby any ambient humidity, regardless of interior relative humidity level, will condense on the perimeter of the glazing system; as water or, potentially, as ice. This is counterintuitive to what is being utilized as a high performance glazing system.

This paper highlights the degradation of condensation resistance performance of #4 surface low-e insulating glass configurations of a variety of coating and spacer constructions. It raises awareness of how this specific performance improvement configuration can create a lesser performing system that can lead to confounding problems including water and ice damage to the fenestration system and the wall surround.

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INTRODUCTION: U-FACTOR VS. CONDENSATION RESISTANCE – THE BASICS

U-Factor Basics

U-factor is a measure of the heat flux (quantity of heat energy) that is transmitted from the air on the warm side of a fenestration system to the air on the cold side. It is, therefore, also known as air-to-air transmittance through a window, door or skylight. U-factor is represented in imperial units as BTU/hr-ft^2-°F and in metric units as W/m^2-K. Functionally, these represent the amount of heat energy transmitted through a product per hour, per degree temperature difference from the hot side to the cold side and averaged over the entire projected area of the system. While certain sections of a fenestration product may transmit more heat energy than others, the U-factor value represents the heat flux averaged over the entire area of the system.

This "area-weighted average U-factor" characterizes the impact of each component of the fenestration system based on the respective area percentage that the component represents relative to the projected area of the entire fenestration product as represented in the following simplified formula:

$$U_w = \frac{U_f * A_f + U_{cog} * A_{cog} + U_{eog} * A_{eog}}{A_w}$$

Where:

Uw = total window U-factor

Uf = frame components U-factor

Af = frame components projected area

Ucog = center-of-glass components U-factor

Acog = center-of-glass components projected area

Ueog = edge-of-glass components U-factor

Aeog = edge-of-glass components projected area

Aw = total window project area

Obviously in most fenestration products the glazing area, particularly the center-of-glass area, has the most significant influence on the product as it has the greatest percentage of projected area (Figure 1). The next area of greatest influence becomes dependent on a number of variables including type of window (e.g., casement, fixed, hung, etc.), frame material, frame reinforcement, frame cross-section, spacer/sealant system, location of spacer system in frame, etc.. Each of these may have multiple components of varying size and thermal conductivity and the individual effect of each on the overall U-factor can be marginalized as the relative projected area of the individual component relative to the entire window system becomes less and less.

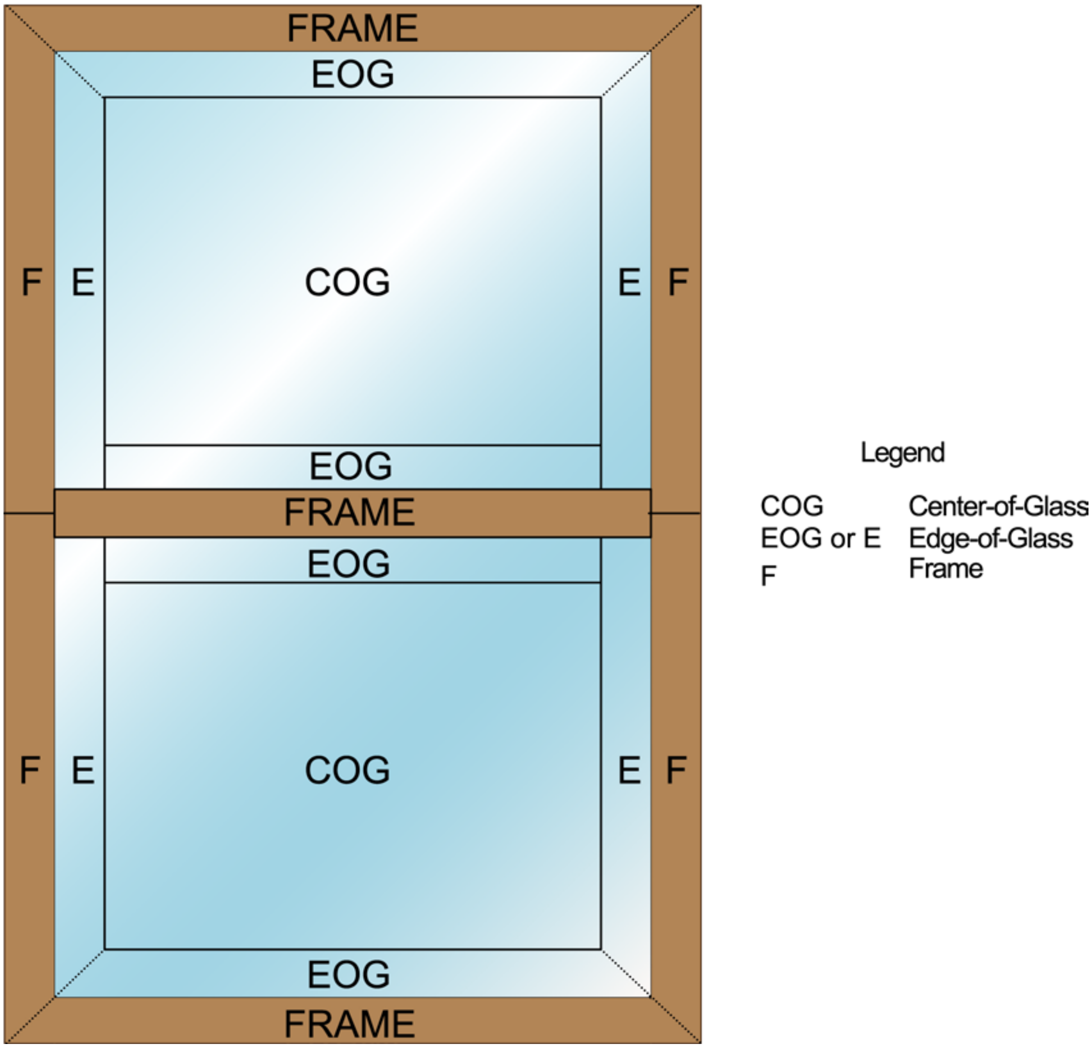


Figure 1: Area weighted sections for thermal analysis

Condensation Resistance Basics

The ability of a fenestration system to resist condensation formation on interior surfaces is directly related to interior surface temperatures and interior relative humidity. Once the interior surfaces of a fenestration system fall below the dewpoint temperature of the interior ambient air, moisture has the ability to condense on these surfaces. The area of the window system having the lowest surface temperature is most likely to create an opportunity for condensation to form.

As compared to U-factor, condensation resistance has far less to do with system performance vs. component performance. The determination of a fenestration system's ability to resist the formation of moisture condensation on interior surfaces, whether physically measured or computer simulated, is an evaluation of localized effects due to thermal conductivity differences of discrete components. A highly conductive material that 'reaches' from the warm side surface to the cold side surface will create a localized heat flux significantly greater than lower conductivity, insulating materials around it. Regardless of the component's projected area percentage relative to the overall window unit a thermal 'shortcircuit' will be introduced that, while perhaps having minimal influence on the system U-factor, may create significant problems concerning condensation.

Such thermal short-circuits can have a detrimental effect on the ability of a fenestration system to resist moisture condensation. In many cases, the impact can be so severe that frost and/or ice can form on the interior surfaces of the window. This can lead to a variety of problems including water damage and poor indoor air quality.

SYSTEMS FOR RATING PERFORMANCE

There are two primary organizations that rate the condensation resistance of fenestration systems: the National Fenestration Rating Council (NFRC) and the American Architectural Manufacturers Association (AAMA). Resistance to condensation formation is a relative rating and each organization has independent criteria for determining performance. Accordingly, **there is no correlation between NFRC and AAMA condensation resistance values**.

The following is a general comparison of the condensation resistance rating systems under each organization and is not intended to provide technical direction for product evaluation or comparison. Refer to the appropriate organizations for more information.

NFRC

Condensation Resistance: NFRC 500 also uses computer simulation through the same software to identify the Condensation Resistance rating of a fenestration product under the same exposure conditions. Condensation Resistance is based on a dimensionless scale of 1 – 100 with a higher number representing a greater resistance to condensation formation.

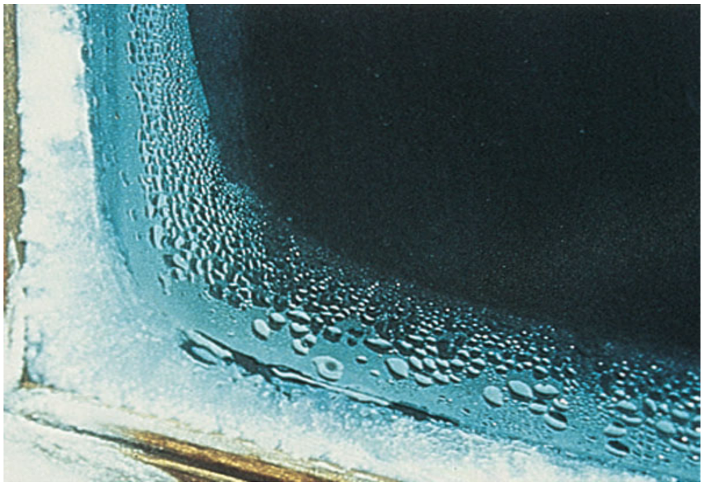
Condensation values are calculated for each the frame, COG and EOG at representative dew points correlating to interior relative humidities of 30%, 50% and 70%, respectively at an exterior conditions equal to -18°C (0°F) and interior conditions of 21°C (70°F). The Condensation Resistance for each area section is then derived from the average of the three relative humidity values and the fenestration system Condensation Resistance is the lowest of the frame, COG and EOG value.

AAMA

Condensation Resistance Factor: the Condensation Resistance Factor or CRF under AAMA it is based on a dimensionless scale generally in the range of 0 – 100 with a higher number representing a greater resistance to condensation formation. Physical testing under AAMA 1503 is performed on a baseline fenestration system exposed to exterior conditions of approximately -18°C (0°F) with a 6 m/s (15 mph) wind and interior conditions of approximately 21°C (70°F). Data from this baseline test is combined under AAMA1505 with test data from ASTM C518 measuring the thermal conductivity of the system components to obtain the CRF for each of the fenestration system glazing options.

EFFECTS OF CONDENSATION

Anyone who's lived in a temperate climate has experienced condensation on the interior surfaces of windows at one time or another. Whether due to over-humidification in a bathroom or old, single glazed aluminum window construction, moisture, water and sometimes even frost and ice on the sill or glass of a window were quite common at one time.



Ice formation on window sash

The significant improvements in fenestration design and construction for thermal performance have significantly improved the ability of fenestration products to resist condensation formation. Hand-in-hand with these improvements, however, have also been improvements in the construction of the building envelope and the tightening of the shell to resist air leakage. Tightening of the building envelope can exacerbate the effects of interior moisture as it has no way to easily escape the structure. While fenestration products used to be highly conductive, the buildings in which they were installed leaked air so much a natural air exchange took place to keep interior relative humidity in check (fortunately heating fuels were cheaper back then too…).

As the nature of man hasn't changed much over these years, we still take showers that are too long and too hot, design kitchens with windows over the sink and fail to consider humidity control and air exchange systems when designing new residences. These, inevitably lead to interior relative humidity levels that are too high for the design of the building envelope.

Lower Relative Humidity Isn't Always The Answer

As many might assume, the answer lies in keeping the interior relative humidity of the structure as low as possible. Everyone is familiar with the factors that accelerate mold growth; food, darkness and, of course, moisture. Mold control is an important concern for several reasons:

i. Molds and moisture can cause damage to window frames and wall surrounds that may accelerate the degradation of the building envelope.

ii. Tighter building envelope construction not only keeps moisture in but it reduces the air quality inside a structure if not properly ventilated. Molds release spores as they propagate that are also trapped in this environment. Many people can have allergic reactions to these spores that can create breathing problems and general discomfort.

iii. It's nasty to look at.

Moisture and mold damage to a wood window sash and frame

Condensation damage to wall surround (Building Envelope Forum – S. O'Brien)

As molds need moisture to grow and survive, the obvious answer might be “make it drier”. Unfortunately, molds aren’t the only culprit when concerns are raised regarding indoor air quality. There are a variety of air borne pathogens that can affect humans and not all like it wet. Some even prefer very dry air.

As illustrated in Figure 2, there is a range of indoor relative humidity that is most conducive to optimal indoor air quality relative to the propagation of a variety of pathogens. Some such as bacteria and viruses actually prefer either the moist or the dry extreme environments with generally reduced activity in a relatively narrow band of target indoor relative humidity. The “Optimum Zone” of relative humidity for indoor air quality is in a range of 30% - 55%. While optimal for the reduction of pathogen growth and air-borne irritant propagation this range of relative humidity can be a challenge for the prevention of moisture condensation on interior fenestration surfaces.

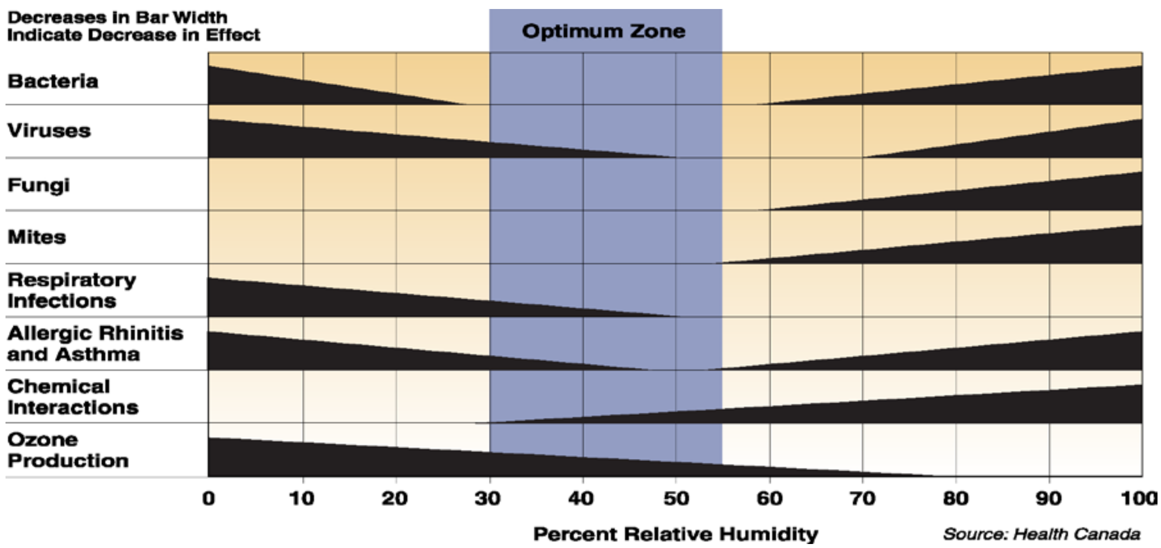
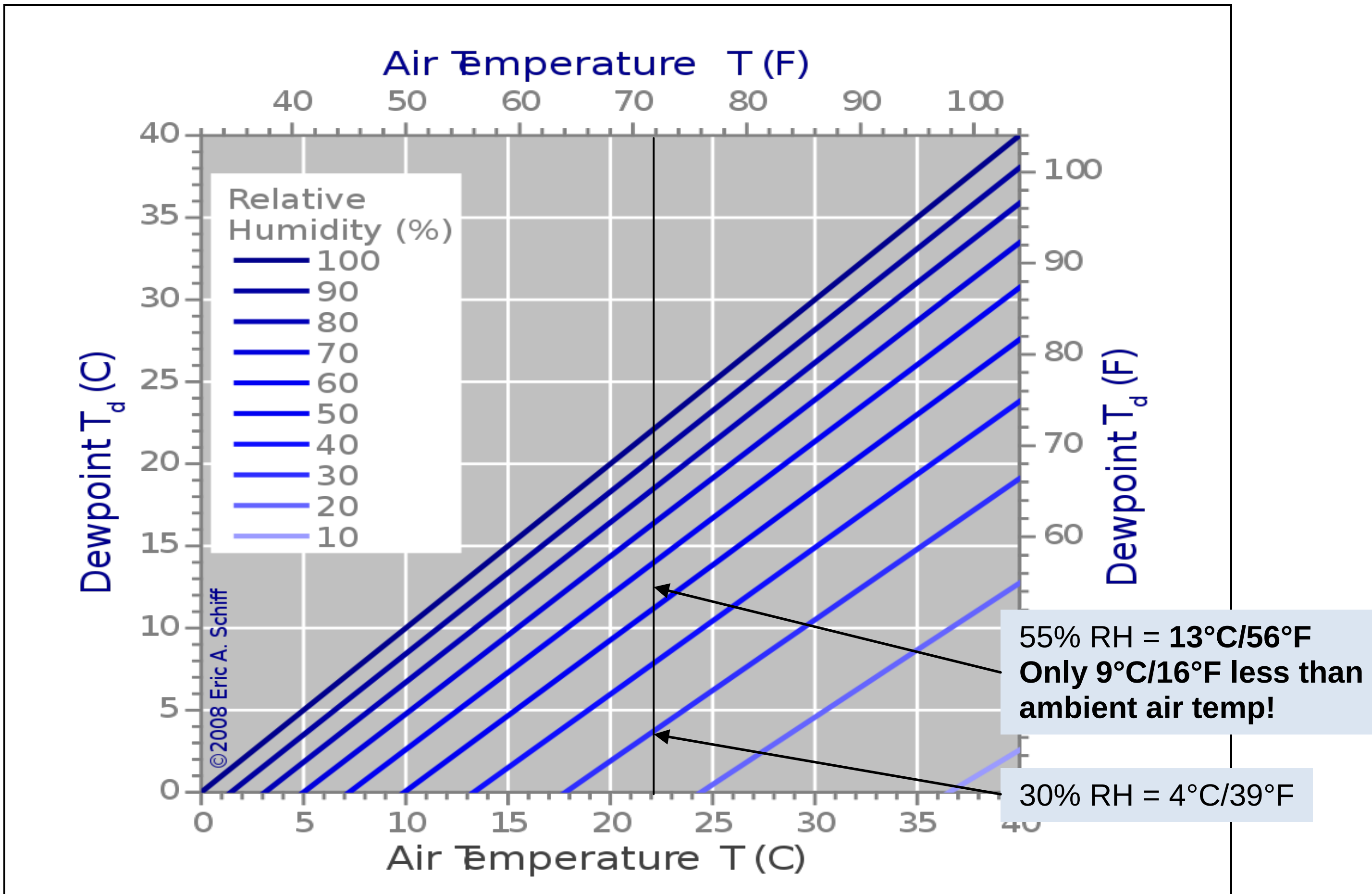


Figure 2: Optimal Indoor Relative Humidity

Graph 1 illustrates the relationship between air temperature, moisture dewpoint and relative humidity. The sloped lines represent varying percentages of relative humidity vs. coordinates of air temperature and dewpoint; being the point at which moisture will form. For an average indoor winter air temperature of 22°C (72°F) and relative humidity of 30%, the coldest point on any interior fenestration surface must be at least 8°C (46°F). At a relative humidity of 55% the coldest point on any interior fenestration surface must be at least **13°C (56°F)** to prevent condensation. This is only 9°C (16°F) less than the ambient air temperature and requires a fenestration system and relative components that have very low thermal conductivity. At these relative humidities it is imperative that a fenestration system utilize components of minimal thermal conductivity to prevent isolated ‘cold spots’ that may hasten condensation formation.



Graph 1: Dewpoint vs. Air Temperature at Varying Relative Humidities. Based on the Magnus-Tetens approximation (Schiff, E. A. 2008. Wikimedia Commons file Dewpoint-RH.svg)

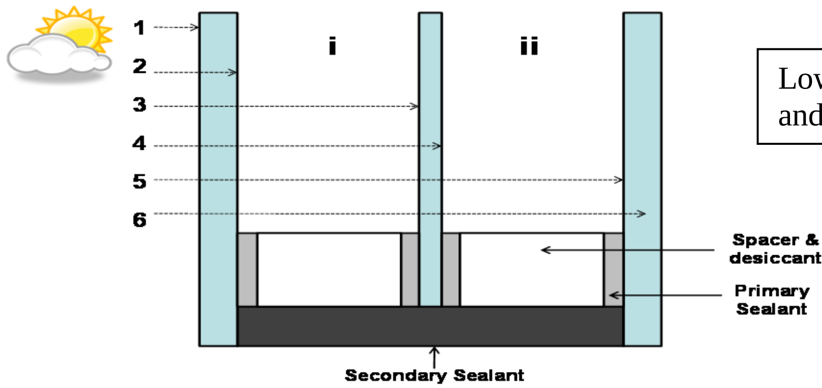
Lastly regarding moisture condensation on fenestration products, it conveys a perception of poor quality. When someone purchases a high-end fenestration system that has claims of excellent thermal performance (U-factor) only to find pools of water on the window sill when it gets cold outside it inevitably raises questions and concerns about the quality of the product.

DESIGN & CONSTRUCTION FOR IMPROVED THERMAL PERFORMANCE (U-FACTOR)

With the continual need for better thermally performing fenestration systems various insulating glass unit (IGU) constructions and component improvements are incorporated. Primary of these are:

1) Sputtered Low-e coatings (“soft-coat”) on internal IGU surfaces
2) Insulating gas infills (argon, krypton, etc.)
3) Low conductivity/”warm-edge” spacer systems
4) Triple glazed construction

Each of these has a relative impact on the U-factor of an IGU and most are used in combination with the others. Continued focus on very high performance IGU (<1.14 W-m^2/K or <0.20 Btu/hr-ft^2-ºF) has placed emphasis on designs for triple-glazed IGU incorporating multiple low-e coatings and insulating gas infills as detailed in Figure 3:



Low-e coatings on surfaces 2, 3, 4 and/or 5

Figure 3, Generic Insulating Glass Units Cross Section with Multiple Cavities (courtesy IGMA "DESIGN CONSIDERATIONS FOR MULTIPLE CAVITY INSULATING GLASS UNITS" draft 15)

Triple-glazed IGU construction has significant improvement in U-factor versus double glazed units. Incorporating properly configured triple-glazed IGU into fenestration systems can produce U-factors less than 1.0 W/m^2-K (0.18 Btu/hr-ft2-^{0}F). The addition of a third lite of glass, however, adds to the cost, weight and overall dimension of the IGU. Due to these factors significant resistance to the incorporation of triple-glazed IGU may exist unless specific market and/or legislative requirements demand it.

4TH SURFACE LOW-E COATINGS IN DOUBLE-GLAZED IGU

Concerns regarding the use of triple-glazed IGU has led to advances in coatings for use on the 4th surface of a traditional double-glazed IGU. In this configuration, a standard soft-coat low-e coating is placed on surface #2 inside the IGU. A second, pyrolytic or "hard-coat" low-e coating is applied to surface #4; the exposed interior glass surface as represented in Figure 4.

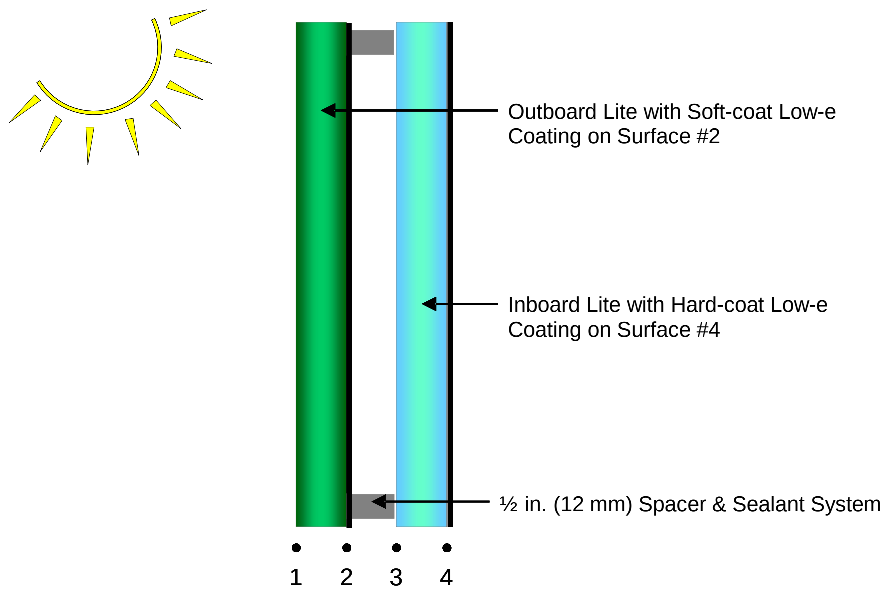


Figure 4: dual-glazed IGU with 4th surface low-e coating

The purpose of a 4th surface low-e coating is to reflect heat back to the interior of the building. Specifically, it reflects medium and short wave infrared radiation that is radiated by materials and components within the structure thereby reducing heat flow out through the glazing. Such glazing systems can achieve IGU U-factors approaching 1.14 W-m^2/K (0.20 Btu/hr-ft^2-ºF) without the incorporation of a third lite of glass.

4TH SURFACE LOW-E COATINGS AND REDUCED CONDENSATION RESISTANCE

A principal concern of 4th surface low-e coatings is the overall reduction in surface temperature of the interior lite of glass. Since this low-e coating is designed to reflect heat back to the interior, it inherently lowers the surface temperature of the glazing. The surface temperature reduction can be significant with edge-of-glass (EOG) temperatures **more than 14ºC/25ºF** lower than with clear glass**.** This represents a significant potential for condensation formation on the interior glazing of IGU that are specifically designed for improved thermal performance.

ANALYTICAL & EMPIRICAL COMPARATIVE METHODOLOGY

Twenty-five IGU's of varying configurations were prepared for a comparison of thermal performance (U-factor and Condensation Resistance) through both physical test and computer simulation. The construction of the evaluated unit constructions are as follows:

Test Specimen Number	Surface 2	Surface 4	Glazing Space	Fill	Spacer	Sealant Type	Sealant Thickness	Unit Size
19	Soft-coat low-e	Pyrolytic low-e	1/2"	air	aluminum	HMB	3/16"	24" x 24"
21	Soft-coat low-e	Pyrolytic low-e	1/2"	air	aluminum	HMB	3/16"	24" x 24"
23	Soft-coat low-e	Pyrolytic low-e	1/2"	air	aluminum	HMB	3/16"	24" x 24"
18	Soft-coat low-e	Pyrolytic low-e	1/2"	air	Tinplate steel	HMB	3/16"	24" x 24"
20	Soft-coat low-e	Pyrolytic low-e	1/2"	air	Tinplate steel	HMB	3/16"	24" x 24"
22	Soft-coat low-e	Pyrolytic low-e	1/2"	air	Tinplate steel	HMB	3/16"	24" x 24"
12	Soft-coat low-e	Pyrolytic low-e	1/2"	air	Tinplate steel	HMB	3/16"	24" x 24"
16	Soft-coat low-e	Pyrolytic low-e	1/2"	air	Tinplate steel	HMB	3/16"	24" x 24"
7	Soft-coat low-e	Pyrolytic low-e	1/2"	air	Stainless steel	HMB	3/16"	24" x 24"
8	Soft-coat low-e	Pyrolytic low-e	1/2"	air	Stainless steel	HMB	3/16"	24" x 24"
13	Soft-coat low-e	Pyrolytic low-e	1/2"	air	Foam	HMB	3/16"	24" x 24"
17	Soft-coat low-e	Pyrolytic low-e	1/2"	air	Foam	HMB	3/16"	24" x 24"
10	Soft-coat low-e	clear	1/2"	90% Ar	Tinplate steel	HMB	3/16"	24" x 24"
6	Soft-coat low-e	clear	1/2"	90% Ar	Stainless steel	HMB	3/16"	24" x 24"
25	Soft-coat low-e	clear	1/2"	90% Ar	Stainless steel	HMB	3/16"	24" x 24"
27	Soft-coat low-e	clear	1/2"	90% Ar	Stainless steel	HMB	3/16"	24" x 24"
29	Soft-coat low-e	clear	1/2"	90% Ar	Stainless steel	HMB	3/16"	24" x 24"
1	clear	clear	1/2"	90% Ar	Foam	HMB	3/16"	24" x 24"
2	Soft-coat low-e	clear	1/2"	90% Ar	Foam	HMB	3/16"	24" x 24"
4	Soft-coat low-e	clear	1/2"	90% Ar	Foam	HMB	3/16"	24" x 24"
11	Soft-coat low-e	clear	1/2"	90% Ar	Foam	HMB	3/16"	24" x 24"
15	Soft-coat low-e	clear	1/2"	90% Ar	Foam	HMB	3/16"	24" x 24"
24	Soft-coat low-e	clear	1/2"	90% Ar	Foam	HMB	3/16"	24" x 24"
26	Soft-coat low-e	clear	1/2"	90% Ar	Foam	HMB	3/16"	24" x 24"
28	Soft-coat low-e	clear	1/2"	90% Ar	Foam	HMB	3/16"	24" x 24"

Chart 1: IGU configurations for analysis

The primary differences between the units that result in differing thermal performance of similarly constructed units is the variation in the types of low-e coatings used and in differences in types of metal spacers. It is not the intent of this paper to compare the performance differences of specific products.

Each configuration was simulated in accordance with the procedures of NFRC 100 to calculate U-factor and with NFRC 500 for Condensation Resistance. Representative specimens were also physically tested in a guarded hot box in accordance with the setup of AAMA 1503 for thermal profile comparison as represented in Figures 5a and 5b.

Figure 5a: Exterior Test Installation

Figure 5b: Interior Test Installation

The represented simulation/test conditions are as follows:

Condition Number	Exterior Temperature (ºC/ºF)	Interior Temperature (ºC/ºF)	Interior Relative Humidity (test only)
1	-18/0	21/70	15%
2	4.5/40	21/70	25%
3	4.5/40	21/70	50%

SUMMARY ANALYSIS OF RESULTS

While traditional thermal analysis and testing is performed under Condition #1, this represents a worst case temperature profile across the IGU from interior to exterior. The ability of an IGU to resist condensation formation on interior surfaces should be less under these conditions than when the exterior temperature is great than -18ºC/0ºF. The interior IGU lite will be heated by the ambient interior, warm 21ºC/70ºF air. Due to the significant temperature differential heat energy flows from the #4 surface to the exterior of the unit. A dual-glazed IGU utilizing a low-e coating on surface #4 reduces heat flow to the exterior by reflecting heat back to the interior. As interior ambient heat energy is not absorbed by the interior glass lite, the #4 surface temperature stays inherently lower than if uncoated. This is the case <u>for all temperature profiles</u>; not simply under the Condition #1 profile.

But for desert geographies, as temperature rises in the environment so too, typically, does ambient relative humidity. As ambient relative humidity rises so too does the dew point at which condensation will form on surfaces. Since 4th surface low-e coatings minimize the heat exchange with the interior environment these low-e surfaces are always colder than uncoated glass under the same conditions; even at elevated exterior temperatures.

Figure 6 illustrates EOG temperatures for 25 IGU configurations including 4th surface low-e coatings, uncoated 4th surfaces, metal spacers and non-metal spacers having an exterior air temperature = -18ºC/0ºF, interior air temperature = 21ºC/70ºF and interior relative humidity = 15%. Even in this very dry, interior ambient air condition there are three IGU configurations that have simulated interior EOG temperatures below the interior air dew point temperature and four more that are within one degree Farenheit of it.

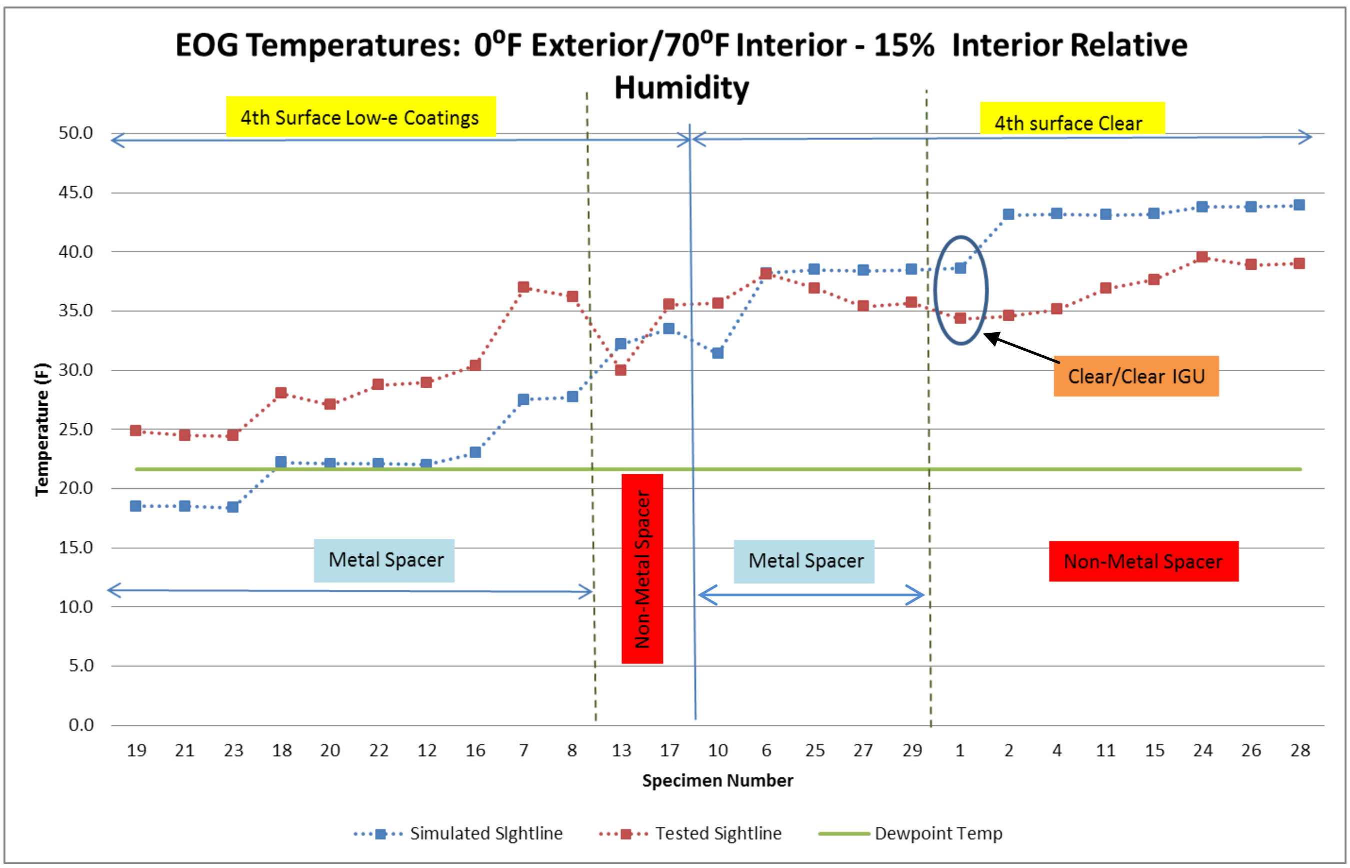


Figure 6: = -18ºC/0ºF exterior, 21ºC/70ºF interior temperature profile

Figure 7 is a similar temperature profile but representing Conditions #2 and #3 having exterior air temperature = 4.5ºC/40ºF and interior relative humidities of 25% and 50%, respectively. At condition #3, the ambient dew point of the interior air is approximately 10ºC/51ºF. In both the simulated and tested conditions, there are no less than six IGU configurations having 4th surface low-e coatings that have interior EOG temperatures at or below the dew point temperature. This illustrates a primary concern of #4 surface low-e configurations at higher exterior temperature and interior relative humidity conditions.

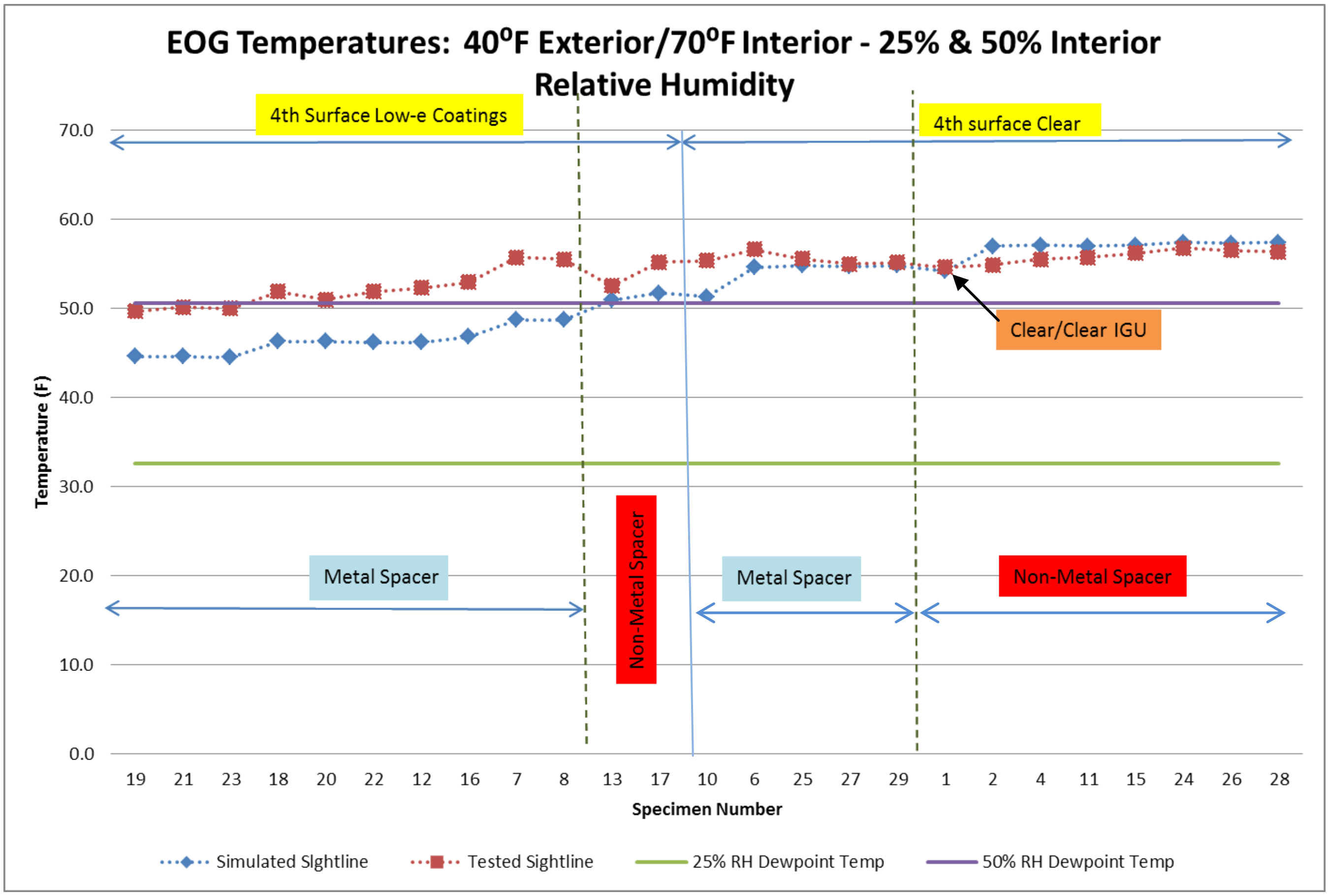


Figure 7: = 4.5°C/40°F exterior, 21°C/70°F interior temperature profile

As the key design benefit of 4th surface low-e configurations is improvement in U-factor without the addition of a third glass lite, Figure 8 compares U-factor vs. Condensation Resistance for Condition #1 temperature differential. With the exception of the clear/clear IGU construction, there is relatively minimal benefit to U-factor of #4 surface low-e coatings versus clear #4 surface units. The average U-factor of #4 surface low-e units is 1.54 W/m^2-K (0.271 Btu/hr-ft^2-^{0}F) as compared to an average U-factor of 1.61 W/m^2-K (0.283 Btu/hr-ft^2-^{0}F) for the clear units. This 4.3% improvement in U-factor comes with a significant reduction in the average Condensation Resistance rating from 67.7 for the clear #4 surface units including the clear/clear construction unit to 52.7 for the 4th surface low-e units.

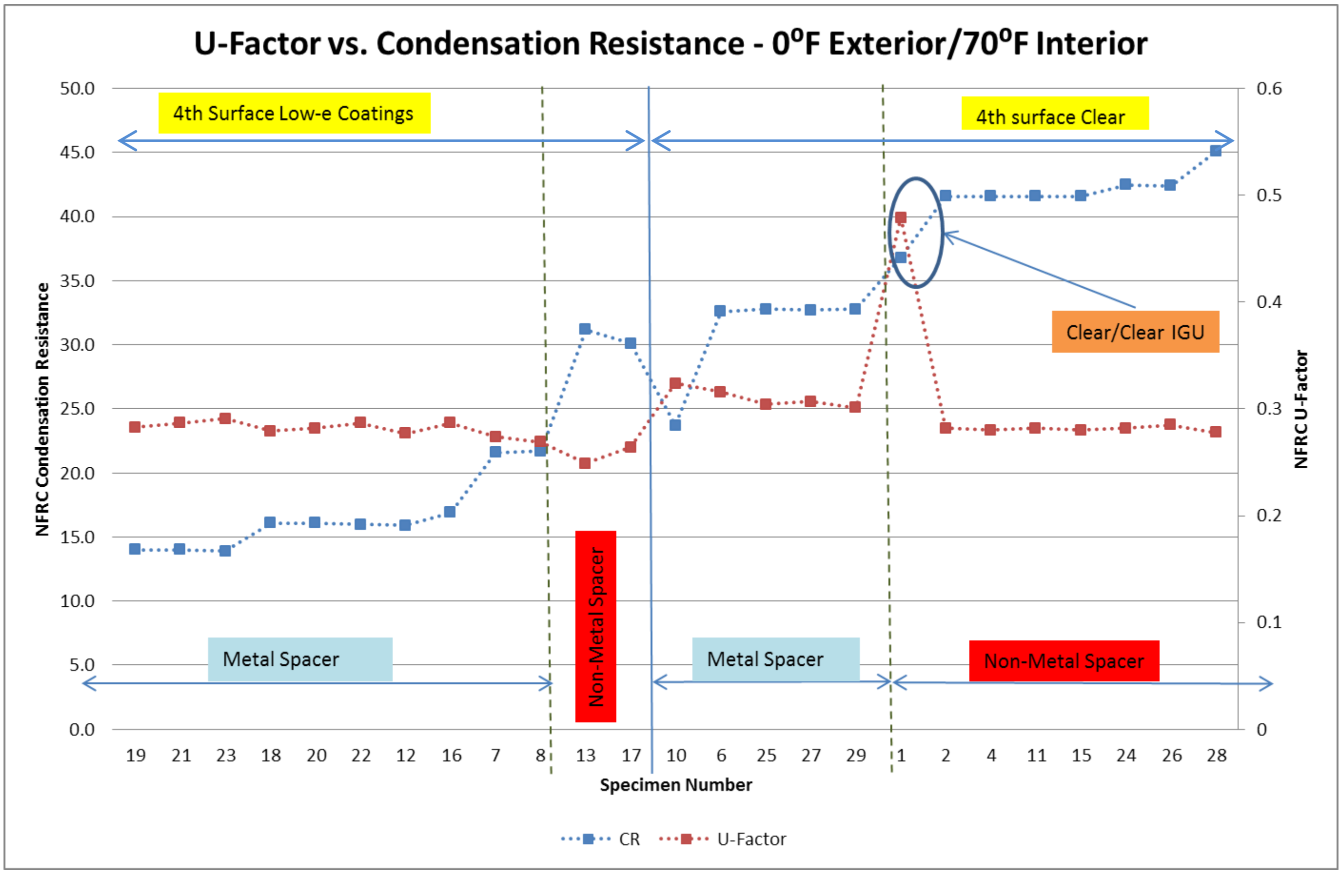


Figure 8: = U-Factor vs. Condensation Resistance rating

The benefits of incorporating 4th surface low-e coatings in dual-glazed IGU for improvement in U-factor/thermal transmittance are evident and well documented. When they are used, however, is it imperative that all additional available performance features are integrated into an IGU to minimize the negative impact on condensation resistance. Primary of these is improvement to EOG components to reduce heat flow through the edge-seal/spacer system.

As illustrated in the prior Figures, there is a significant impact on the EOG temperature profiles of each of the IGU configurations incorporating non-metal spacer systems. IGU configurations #19 and #13 represent comparable systems utilizing 4th surface low-e coatings. The use of a non-metal foam spacer ("warm-edge") versus an aluminum spacer system raised the EOG temperature by nearly 8°C/14°F. Identical IGU systems (#16 and #17) represent an EOG temperature elevation of 6°C/11°F when comparing a tinplate steel spacer system to a foam, warm-edge system. These systems also represent a 17 point (121%) and 13 point (78%) improvement in Condensation Resistance rating, respectively.

WARM-EDGE (WET) SPACER SYSTEMS

Traditional aluminum spacers are very effective for structural integrity but extremely poor for thermal resistance. In the mid-80's products known as "warm-edge" spacers were introduced to the market. Warm-edge essentially refers to anything that is warmer than aluminum and there is a broad range of products that are available as illustrated in Figure 9.

Warm edge spacer systems are designed to reduce the heat flux at the EOG.

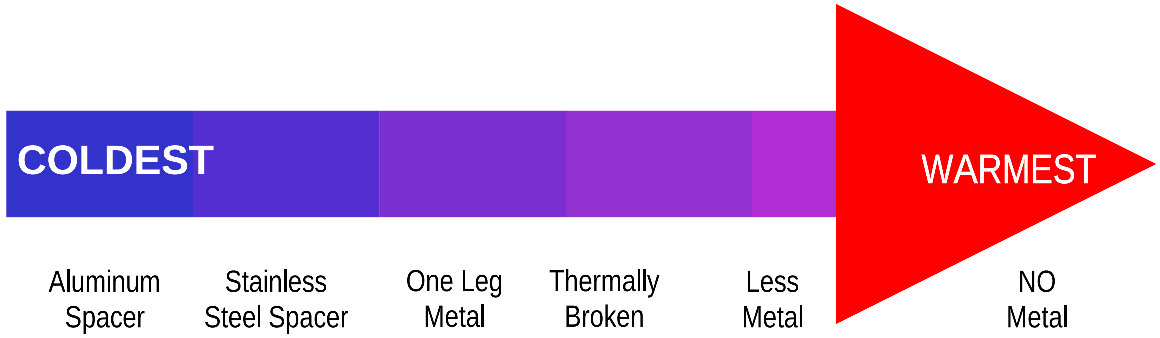
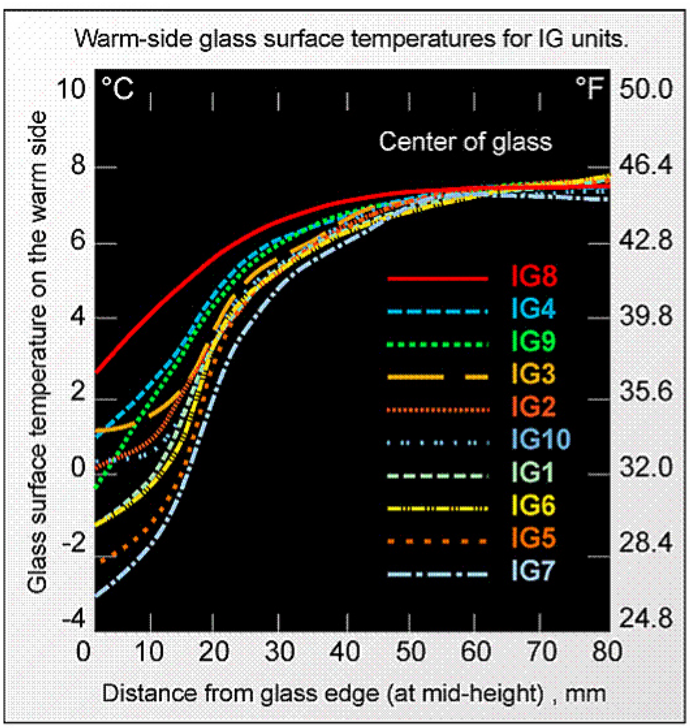
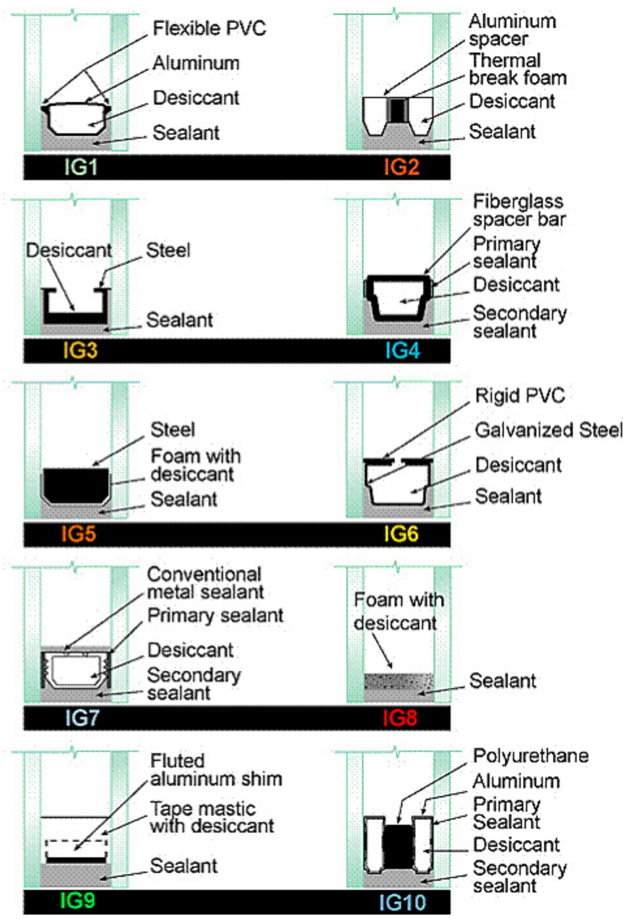


Figure 9: Warm Edge Spacers

Figure 10 illustrates the effect of different spacer constructions at the EOG on interior glass temperature. As is illustrated, once beyond the 63.5 mm (2-1/2 in.) EOG area all spacer systems are effectively the same. The nearer to the actual glass edge the greater the segregation between spacer types with a difference of up to 6°C (11°F) in surface temperature.





Information: A.H. Elmahdy, Institute for Research in Construction(IRC), National Research Council of Canada (NRC) 2004.

Figure 10: Glass edge temperatures of various warm edge spacer systems

A final representation of the importance of optimizing the spacer system to reduce condensation formation is illustrated in Figure 11 which presents three fixed PVC windows having identical construction but for the type of spacer system tested under the exact same conditions within the same test chamber. The full metal spacer system acts as an aggressive thermal bridge and interior condensation is readily evident. The system with a thermally broken metal spacer demonstrates significant reduction in surface condensation while the spacer having no metal has but a minute amount of condensation in one corner.

Full Metal Less Metal No Metal

Figure 11: Condensation resistance of different spacer systems

CONCLUSION

Utilization of 4th surface, pyrolytic coatings in dual-glazed insulating glass units can provide some degree of improvement on thermal transmittance performance (U-factor). The primary benefit of these coatings is to provide incremental thermal performance improvement over traditional dual-glazed units without the cost and weight penalties of triple-glazing. Users of this technology must understand the potential compromise that must be accepted on the ability of the IGU to resist condensation formation on interior surfaces.

The rejection of heat energy by 4th surface low-e coatings significantly lowers the interior surface temperature of the IGU and, accordingly, its Condensation Resistance rating. Warm-edge spacer technology can mitigate some of these effects by reducing heat flow through the edge-of-glass where the temperature profile reduction is most prevalent. It is imperative that this significant reduction in condensation resistance performance be understood when considering 4th surface low-e technology.

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