THE IMPACT OF GLASS SPACERS ON ENERGY PERFORMANCE AND RISK OF CONDENSATION IN AMERICAN WINDOWS

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THE IMPACT OF GLASS SPACERS ON ENERGY PERFORMANCE AND RISK OF CONDENSATION IN AMERICAN WINDOWS

New Risks and Opportunities for Fenestration Products Installed In Airtight Buildings

The thermal quality of glass spacers dramatically affect the physical properties of one of the most critical areas of the entire building thermal envelope - the interface between window frame and glass unit. The spacers influence the heat flow, resulting in higher heat losses, and consequently lower localized temperatures along the glass edge.

In everyone experience, the glass edge is one of the places condensation occurs sooner than anywhere else in a building.

Since its 2012 update, the International Energy Conservation Code (IECC) has been pushing buildings to be increasingly more airtight across America. This is great news for overall building durability (i.e. avoidance of exfiltration, and associated moisture-driven damages). Increased building air tightness also leads to significant improvements in energy efficiency, thanks to the reduction in heating and cooling.

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However, a more airtight building envelope leads to higher relative humidity inside buildings, as uncontrolled air leaks contribute to removing moisture water vapor from inside buildings. According to ASHRAE Standard 160, a family of 4 produces 2.5 gal of water vapor every single day. This means that regardless of how humid or dry a climate may be, moisture comes from within the building.

Proper moisture management in building has evolved into being an interdisciplinary field, bridging across from architectural detailing, window specs, to structural and mechanical engineering. The more buildings become air tight and insulated, the more they behave as one physical object where all parts are interrelated.

Today, the selection of a window product (including glass spacers) has consequences on the mechanical system in the effort to avoid mold/ condensation, and vice versa.

Unfortunately, the evolution of Building Code (until the 2018 IECC update, at least) still fails in mandating this interdisciplinary approach, resulting in manufacturers and professionals being incrementally more exposed to liability.

Even the 'Condensation Resistance' method established by the National Fenestration Rating Council does not provide a conclusive method to prevent condensation in fenestration products.

Given these circumstances, the impact of different glass spacers on the performance of window products is assessed both in terms of heat flow (U-factors), as well as of surface temperatures to avoid condensation.

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Scope

The purpose of this report is to assess the effect of different glass edge spacers, in their application over a range of fenestration products available on the American market.

The analysis was executed by creating combinations five glass spacer products, and nine window frame profiles. The 45 resulting combinations are evaluated in terms of localized heat flow (i.e. frame and edge of glass U-factors), whole window heat losses (total U-factor), and glass edge temperatures.

Calculation Methods

Heat Flows

The thermal performance of windows (total U-factor, Uw) and window components frame included in this report (frame U-factor, Ufr, and edge of glass U-factor, Ueog) were calculated according to the following standards:

ANSI/NFRC 100-2017: *"Procedure for Determining Fenestration Product U-factors".*

NFRC 101-2017: *"Procedure for Determining Thermophysical Properties of Materials for Use in NFRC-Approved Software".*

ISO 15099: *"Thermal Performance of Windows, Doors and Shading Devices - Detailed Calculations".*

ISO 10211: *"Thermal Bridges in Building Construction. Heat Flows and Surface Temperatures - Detailed Calculations".*

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Condensation Risk

In assessing the risk for condensation, the following standards were evaluated:

NFRC 500-2017: *"Procedure for Determining Fenestration Product Condensation Resistance".*
ISO 13788: *"Hygrothermal Performance of Building Components and Building Elements - Internal Surface Temperature to Avoid Critical Surface Humidity and Interstitial Condensation - Calculation Methods".*
CSA A440.2:19: *"Fenestration Energy Performance".*

The Condensation Resistance (CR) method defined by NFRC assigns a score to the fenestration product. This is executed by averaging internal surface temperatures resulting from three separate simulations (i.e. @30%, 50%, and 70% relative humidity).

$$CR_f = \left\{ 1 - \left\{ \frac{\sum_k SS_{f_k} A_{f_k}}{A_f} \right\}^{1/3} \right\} \times 100$$

k=frame section

$$CR_c = \left\{ 1 - \left\{ \frac{\sum_k SS_{d_k} A_{d_k} + \sum_k SS_{deog_k} A_{deog_k} + \sum_k SS_{cog_k} A_{cog_k}}{\sum_k A_{d_k} + \sum_k A_{deog_k} + \sum_k A_{cog_k}} \right\}^{1/3} \right\} \times 100$$

Formulas 01-02: NFRC Condensation Resistance calculation method for frames (left), and for center of glass, edge of glass, and dividers (right). The mathematical nature of the CR as an average of values over area (A), and over multiple relative humidity values (RH 30%, 50%, and 70%) makes it unsuitable as a design tool for practical use in the professional practice.

The purpose of the CR score is to allow different products to be compared to one another, not to assess the actual risk of condensation on one specific product as part of the design process.

Due to its mathematical nature (i.e. average of average values), the CR score does not represent a tool to be used in the professional practice, in combination with other design parameters (design room temperature and RH, external temperature etc.).

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For this reason, for the purpose of calculating localized internal temperatures on the glass edge with the goal to avoid condensation, this report refers to the 'Temperature Factor' method (fRsi value) as described in ISO 13788.

$$fRsi = (Tsi\_min - Te) / (Ti - Te)$$

- fRsi: temperature factor (from ISO 13788 FEM modeling)
- Ti: room temperature
- Te: external temperature
- Tsi_min: localized lowest temperature on the model considered (e.g. frame/glass unit combination)

Formula 03: Definition of temperature factor (fRsi value), as described in ISO 13799.

Once the fRsi value is calculated via finite element method (FEM), the localized lowest temperature on the internal surface can be calculated by reversing Formula 3, as follows:

$$Tsi\_min = Te + fRsi * (Ti - Te)$$

Formula 04 (rev. of Formula 03): calculation method to determine the lowest localized temperature (Tsi_min), given any combination of internal/external temperature, and temperature factor fRsi.

The temperature factor described in ISO 13788 is the same as illustrated in CSA A440.2, with the only difference being that the CSA method relies on testing on physical specimen instead of FEM modeling.

Condensation Risk: Climate-Specific Benchmarking

The risk of condensation is associated to the combination of low localized temperatures on the internal surface of building components (Tsi_min), and to relative humidity inside buildings.

For the purpose of avoidance of mold/condensation inside airtight buildings, the International Passive House institute has developed a climate-specific criterion ('Hygiene Criterion') to benchmark the temperature factors against as part of the design/specification process.

With reference to the following sources, the minimum temperature factors to be met by climate to avoid mold/condensation by design are listed in Table 01.

> ASHRAE: *"Climatic Data for Building Design Standard".*
> International Passive House Institute (PHI): *"Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard - Hygiene Criterion".*
> Bonilauri, E: *"Better Climate Zone Mapping for Passive House in Different Countries".*

Table 01: Minimum Temperature Factors to Avoid Condensation

ASHRAE Standard 169 Climate Zone	PHI Climate (approx.)	Minimum Temperature Factor (fRsi_min) To Avoid Condensation
1	Very Hot	-
2	Hot	-
3	Warm	0.55
4	Warm, Temperate	0.65
5	Cool, Temperate	0.70
6	Cold	0.75
7	Cold	0.75
8	Arctic	0.80

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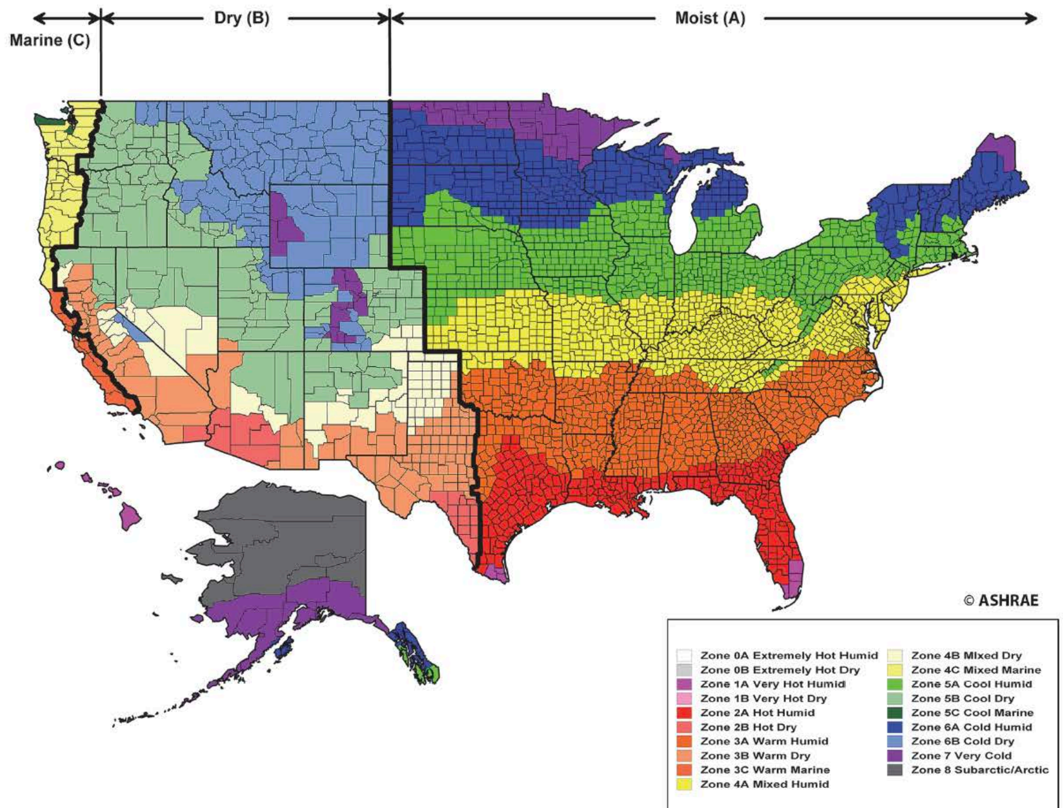

FIGURE B-1 Climate zones for United States counties.

Image 01: Climate zones of the US according to ASHRAE Standard 169.

Note that the boundary conditions used by PHI in calculating the temperature factors slightly vary from the ISO 13788 ones.

Physical Properties of Materials

Physical properties of materials, including thermal conductivity (λ value) and emissivity (ε) were sourced from the following standards:

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NFRC101-2017: *"Procedure For Determining Thermophysical Properties of Materials For Use in NFRC-Approved Software".*
ASHRAE: *"Handbook of Fundamentals, 2017 edition".*
ISO 10456: *"Building Materials and Products: Hygrothermal Properties. Tabulated Design Values and Procedures for Determining Declared and Design Thermal Values"*

Software

The energy modeling of the window frame/ glass spacer/ glass unit combinations was executed via finite element software (FEM) Dartwin Frame Simulator v.5 for the heat flow portion of the analysis. The results were used to determine the U-factors illustrated later. While being validated according to the same ISO 10211 standard as Therm, Dartwin Frame Simulator is not an NFRC-approved software. Differences in the results between the two softwares should be limited to the admissible margin allowed for software validation.

The modeling of the temperature factors (fRsi values) according to ISO 13788 was executed with Dartwin Mold Simulator v.5.

Modeling Combinations

Window Frames

Nine different window frame profiles were selected as part of this study, with the intention to cover a range of frame types, materials, and operation, glass units, and overall energy performance.

While the list of frames included does not cover all options available on the American market, it can be considered to be significantly representative for the scope of this report.

Table 02: Window Frames Used in Modeling

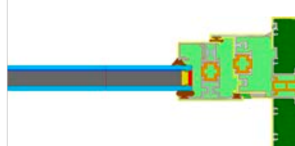
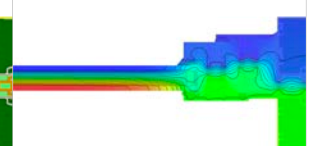
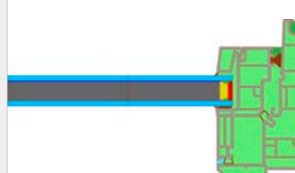
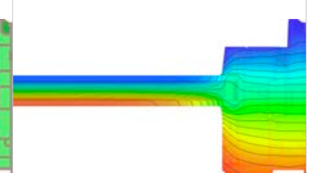
#	Frame	Glass Unit	Type	Section View	Isotherm View
D-111	Th. Broken Aluminum	Double Pane	Casement Outswing		
D-112	PVC	Double Pane	Casement Outswing		

Table 02: Window Frames Used in Modeling

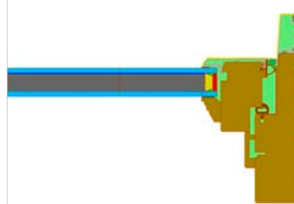
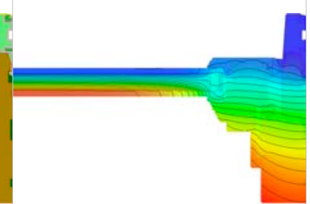
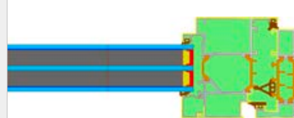
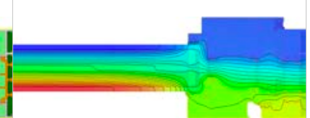
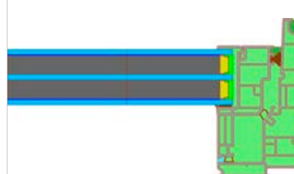
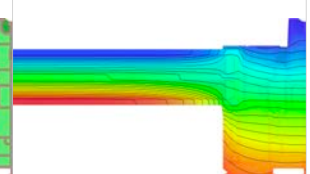
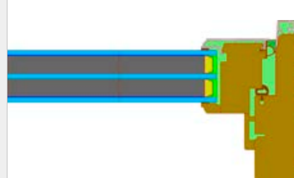
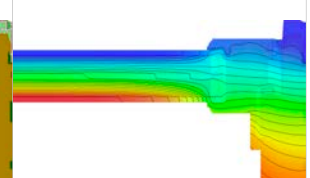
#	Frame	Glass Unit	Type	Section View	Isotherm View
D-113	Timber	Double Pane	Casement Outswing		
D-121	Th. Broken Aluminum	Triple Pane	Casement Outswing		
D-122	PVC	Triple Pane	Casement Outswing		
D-123	Timber	Triple Pane	Casement Outswing		

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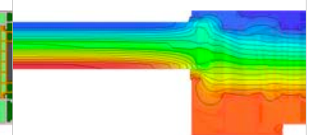
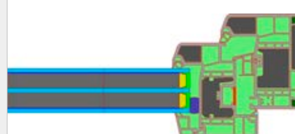
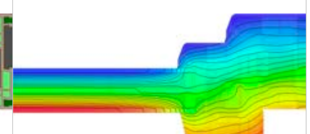
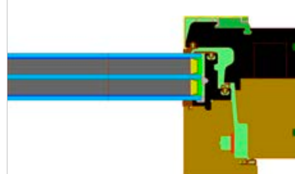
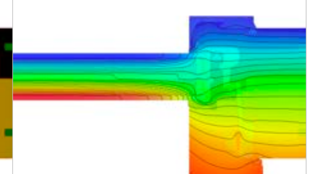
Table 02: Window Frames Used in Modeling

#	Frame	Glass Unit	Type	Section View	Isotherm View
D-131	Th. Broken Insulated Aluminum (phC-grade Passive House window)	Triple Pane	Dual Action (tilt/turn)		
D-132	Insulated PVC (phB-grade Passive House window)	Triple Pane	Dual Action (tilt/turn)		
D-133	Insulated Timber (phA-grade Passive House window)	Triple Pane	Dual Action (tilt/turn)		

Glass Spacers

Five types of glass spacers were used in the modeling, in order to provide a wide enough range of performance for the analysis.

Information for the spacers was sourced from:

> LBNL: *"Window Spacers and Edge Seals in Insulating Glass Units: A Stage-of-the-Art Review and Future Perspectives"*

For greater accuracy, the spacers were modeled according to their actual materials and geometry, i.e. not via the 2-box model.

Table 03 summarizes the list of glass spacers, including main spacer materials, and section drawing.

Table 03: Glass Spacers Used in Modeling

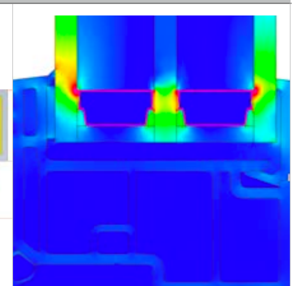
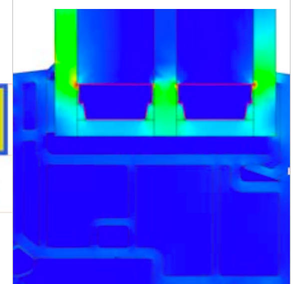
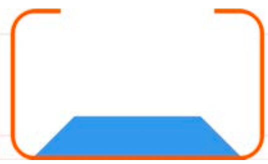
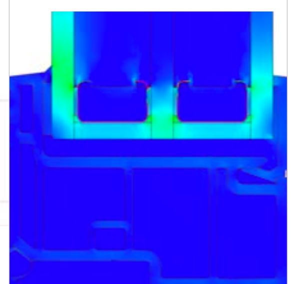
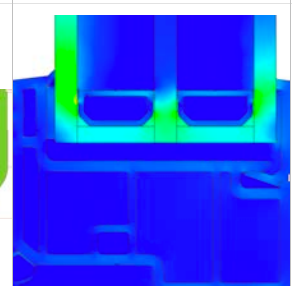
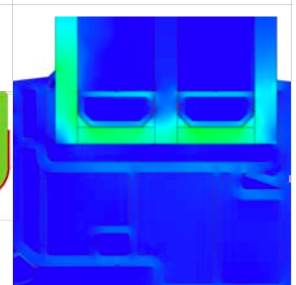
#	Material	Type	Section View	Heat Flow Rate (On D-122)
1	Aluminum	Standard		

Table 03: Glass Spacers Used in Modeling

#	Material	Type	Section View	Heat Flow Rate (On D-122)
2	Stainless Steel	Standard		
3	Stainless Steel	Improved		
4	Plastic + Aluminum Seal	Warm Edge		
5	Plastic	Warm Edge		

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Glass Units And Sealants

Two types of insulated glass units were considered for the modeling, as shown in Table 02:

- Double Pane Glass: 4mm LoE272 on #2/14mmAr90/4mm Clear (COG U-factor 0.251 BTU/h*ft2*F)
- Triple Pane Glass: 4mm LoE272 on #2/14mmAr90/4mm Clear/14mmAr90/4mm LoE272 on #5 (COG U-factor 0.123 BTU/h*ft2*°F)

All glass units were modeled sealed with hot melt butyl.

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RESULTS

Interpretation of Results

The modeling results are provided in the following pages in terms of absolute values (U-factors), improvement over the baseline (i.e. the aluminum spacer), as well as resulting internal surface temperatures.

The results also include average values per data point. Those values are linear mean values across the results listed in the individual tables. This is intrinsically inaccurate, as the values refer to significantly different types of window frames. However, the number and diversity of the frames modeled was considered broad enough, and diverse enough, so that the resulting averages can provide valuable feedback. As inaccurate as linear averages may be, simplicity was given priority rather than looking for a more sophisticated, just as disputable weighing method.

Color Coding

Tables listing U-factors for different combinations of window frames, glass spacers, and glass units are provided without color coding.

Tables listing results in improvements (%) in U-factors, as well as temperature factors (fRsi) and internal temperatures are shown with automatic color coding of the cells background. This is executed on an algorithm basis across individual tables, in order to enhance results readability.

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U-factors

Tables 04-06 summarize the U-factors of window frames (Ufr), edge of glass (Ueog), and whole window (Uw) for the combinations of frame, glass unit, and glass spacer.

Frame U-factor (Ufr Thermal Transmittance, BTU/h*ft2*°F)

According to ISO15099 Alternative Method, and NFRC Conditions			Glass Spacer				
Glass Unit	Case	Window Frame	Aluminum	Stainless Steel, Standard	Stainless Steel, Improved	Swisspacer Advance	Swisspacer Ultimate
Double Pane	D-111	Thermally Broken Aluminum Frame, Casement Outswing	0.4366	0.4243	0.4149	0.4169	0.4037
	D-112	Vinyl Frame, Casement Outswing	0.1945	0.1812	0.1698	0.1706	0.1537
	D-113	Wood Frame, Casement Outswing	0.2587	0.2434	0.2310	0.2335	0.2162
Triple Pane	D-121	Thermally Broken Aluminum Frame, Casement Outswing	0.3290	0.3067	0.2939	0.2943	0.2809
	D-122	Vinyl Frame, Casement Outswing	0.1831	0.1599	0.1442	0.1456	0.1264
	D-123	Wood Frame, Casement Outswing	0.2238	0.2035	0.1907	0.1930	0.1768
	D-131	Thermally Broken Insulated Aluminum Frame, Dual Action (phC)	0.2283	0.1998	0.1822	0.1847	0.1630
	D-132	Insulated Vinyl Frame, Dual Action (phB)	0.1437	0.1337	0.1290	0.1272	0.1181
	D-133	Insulated Wood Frame, Dual Action (pHA)	0.1551	0.1373	0.1255	0.1271	0.1120

Table 04: Frame U-factors resulting from the combination of window frames, glass unit, and glass spacers listed in tables 02 and 03.

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Edge of Glass U-factor (Ueog Thermal Transmittance, BTU/h*ft2*F)							
According to ISO15099 Alternative Method, and NFRC Conditions			Glass Spacer				
Glass Unit	Case	Window Frame	Aluminum	Stainless Steel, Standard	Stainless Steel, Improved	Swisspacer Advance	Swisspacer Ultimate
Double Pane	D-111	Thermally Broken Aluminum Frame, Casement Outswing	0.4003	0.3793	0.3663	0.3630	0.3456
	D-112	Vinyl Frame, Casement Outswing	0.3928	0.3658	0.3448	0.3429	0.3110
	D-113	Wood Frame, Casement Outswing	0.4392	0.3991	0.3699	0.3689	0.3296
Triple Pane	D-121	Thermally Broken Aluminum Frame, Casement Outswing	0.3507	0.3049	0.2822	0.2795	0.2532
	D-122	Vinyl Frame, Casement Outswing	0.3045	0.2567	0.2288	0.2274	0.1906
	D-123	Wood Frame, Casement Outswing	0.3268	0.2706	0.2394	0.2380	0.1988
	D-131	Thermally Broken Insulated Aluminum Frame, Dual Action (phC)	0.2680	0.2295	0.2097	0.2066	0.1818
	D-132	Insulated Vinyl Frame, Dual Action (phB)	0.2706	0.2306	0.2081	0.2047	0.1707
	D-133	Insulated Wood Frame, Dual Action (pHA)	0.2765	0.2340	0.2099	0.2080	0.1758

Table 05: Edge of Glass U-factors.

Whole Window U-factor (Uw Thermal Transmittance, Total Fenestration, BTU/h*ft2*°F)							
Per NFRC requirements, whole window standard sizes: Casement 600x1500 mm, Dual Action 1200x1500 mm			Glass Spacer				
Glass Unit	Case	Window Frame	Aluminum	Stainless Steel, Standard	Stainless Steel, Improved	Swisspacer Advance	Swisspacer Ultimate
Double Pane	D-111	Thermally Broken Aluminum Frame, Casement Outswing	0.3673	0.3571	0.3500	0.3503	0.3405
	D-112	Vinyl Frame, Casement Outswing	0.2702	0.2601	0.2519	0.2517	0.2394
	D-113	Wood Frame, Casement Outswing	0.2977	0.2832	0.2722	0.2728	0.2578
Triple Pane	D-121	Thermally Broken Aluminum Frame, Casement Outswing	0.2617	0.2420	0.2315	0.2311	0.2195
	D-122	Vinyl Frame, Casement Outswing	0.1832	0.1653	0.1544	0.1544	0.1402
	D-123	Wood Frame, Casement Outswing	0.2042	0.1842	0.1726	0.1731	0.1585
	D-131	Thermally Broken Insulated Aluminum Frame, Dual Action (phC)	0.1736	0.1600	0.1522	0.1524	0.1427
	D-132	Insulated Vinyl Frame, Dual Action (phB)	0.1514	0.1423	0.1374	0.1363	0.1284
	D-133	Insulated Wood Frame, Dual Action (pHA)	0.1553	0.1438	0.1368	0.1370	0.1279

Table 06: Whole window U-factors.

U-factors Improvements

Tables 07-09 illustrate the improvement on U-factors (frame, edge of glass, and window, respectively) resulting from upgrading individual frames to better performing spacers.

Improvements are illustrated by individual row, and referred to the baseline of the aluminum spacer. The only variable that change in the modeling is the actual glass spacer.

Improvement: Frame U-factor (Ufr Thermal Transmittance)							
Baseline: Aluminum Spacer			Glass Spacer				
Glass Unit	Case	Window Frame	Aluminum	Stainless Steel, Standard	Stainless Steel, Improved	Swisspacer Advance	Swisspacer Ultimate
Double Pane	D-111	Thermally Broken Aluminum Frame, Casement Outswing	0.0%	-2.8%	-5.0%	-4.5%	-7.5%
	D-112	Vinyl Frame, Casement Outswing	0.0%	-6.8%	-12.7%	-12.3%	-21.0%
	D-113	Wood Frame, Casement Outswing	0.0%	-5.9%	-10.7%	-9.7%	-16.4%
Triple Pane	D-121	Thermally Broken Aluminum Frame, Casement Outswing	0.0%	-6.8%	-10.7%	-10.5%	-14.6%
	D-122	Vinyl Frame, Casement Outswing	0.0%	-12.7%	-21.2%	-20.5%	-31.0%
	D-123	Wood Frame, Casement Outswing	0.0%	-9.1%	-14.8%	-13.8%	-21.0%
	D-131	Thermally Broken Insulated Aluminum Frame, Dual Action (phC)	0.0%	-12.5%	-20.2%	-19.1%	-28.6%
	D-132	Insulated Vinyl Frame, Dual Action (phB)	0.0%	-7.0%	-10.3%	-11.5%	-17.8%
	D-133	Insulated Wood Frame, Dual Action (pHA)	0.0%	-11.5%	-19.1%	-18.0%	-27.8%
		Average	0.0%	-8.3%	-13.9%	-13.3%	-20.6%

Table 07: Improvement on frame U-factors, compared to the aluminum spacer baseline.

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Improvement: Edge of Glass U-factor (Ueog Thermal Transmittance)							
Baseline: Aluminum Spacer			Glass Spacer				
Glass Unit	Case	Window Frame	Aluminum	Stainless Steel, Standard	Stainless Steel, Improved	Swisspacer Advance	Swisspacer Ultimate
Double Pane	D-111	Thermally Broken Aluminum Frame, Casement Outswing	0.0%	-5.2%	-8.5%	-9.3%	-13.7%
	D-112	Vinyl Frame, Casement Outswing	0.0%	-6.9%	-12.2%	-12.7%	-20.8%
	D-113	Wood Frame, Casement Outswing	0.0%	-9.1%	-15.8%	-16.0%	-25.0%
Triple Pane	D-121	Thermally Broken Aluminum Frame, Casement Outswing	0.0%	-13.1%	-19.5%	-20.3%	-27.8%
	D-122	Vinyl Frame, Casement Outswing	0.0%	-15.7%	-24.8%	-25.3%	-37.4%
	D-123	Wood Frame, Casement Outswing	0.0%	-17.2%	-26.7%	-27.2%	-39.2%
	D-131	Thermally Broken Insulated Aluminum Frame, Dual Action (phC)	0.0%	-14.4%	-21.8%	-22.9%	-32.2%
	D-132	Insulated Vinyl Frame, Dual Action (phB)	0.0%	-14.8%	-23.1%	-24.3%	-36.9%
	D-133	Insulated Wood Frame, Dual Action (pHA)	0.0%	-15.4%	-24.1%	-24.8%	-36.4%
		Average	0.0%	-12.4%	-19.6%	-20.3%	-29.9%

Table 08: Improvement on edge of glass U-factors, compared to the aluminum spacer baseline.

Improvement: Whole Window U-factor (Uw, Total Fenestration, NFRC)							
Baseline: Aluminum Spacer			Glass Spacer				
Glass Unit	Case	Window Frame	Aluminum	Stainless Steel, Standard	Stainless Steel, Improved	Swisspacer Advance	Swisspacer Ultimate
Double Pane	D-111	Thermally Broken Aluminum Frame, Casement Outswing	0.0%	-2.8%	-4.7%	-4.6%	-7.3%
	D-112	Vinyl Frame, Casement Outswing	0.0%	-3.7%	-6.8%	-6.9%	-11.4%
	D-113	Wood Frame, Casement Outswing	0.0%	-4.9%	-8.6%	-8.4%	-13.4%
Triple Pane	D-121	Thermally Broken Aluminum Frame, Casement Outswing	0.0%	-7.5%	-11.5%	-11.7%	-16.1%
	D-122	Vinyl Frame, Casement Outswing	0.0%	-9.8%	-15.8%	-15.8%	-23.5%
	D-123	Wood Frame, Casement Outswing	0.0%	-9.8%	-15.4%	-15.2%	-22.4%
	D-131	Thermally Broken Insulated Aluminum Frame, Dual Action (phC)	0.0%	-7.9%	-12.4%	-12.2%	-17.8%
	D-132	Insulated Vinyl Frame, Dual Action (phB)	0.0%	-6.0%	-9.2%	-9.9%	-15.2%
	D-133	Insulated Wood Frame, Dual Action (pHA)	0.0%	-7.4%	-11.9%	-11.8%	-17.7%
		Average	0.0%	-6.6%	-10.7%	-10.7%	-16.1%

Table 09: Improvement on whole window U-factors, compared to the aluminum spacer baseline.

Risk of Condensation

Condensation occurs as a combination of localized low temperatures (Tsi_min), and relative humidity inside the building (RHi).

NFRC Condensation Resistance is purely an averaged score over multiple data points, and it is designed to allow comparisons between different window products. However, it is not of use when trying to assess the risk of condensation on one specific product.

ISO 13788 temperature factor method is designed specifically to estimate the risk of condensation on the internal surface of building components, including fenestration products. The localized lowest localized temperature (Tsi_min) on the internal surface of the combination of window frame/ glass unit/ glass spacer is calculated with Formula 04, based on the fRsi value, and internal/ external temperatures Ti, Te.

Table 10 shows the minimum temperature factors (fRsi_min) necessary to avoid condensation at different combinations of internal relative humidity (RHi), and external temperature (Te) - room temperature Ti is assumed to be 70˚F.

Table 11 lists the temperature factors (fRsi values) resulting from the FEM modeling of the combinations of window frame/ glass unit/ glass spacer. By comparing the values with Table 10, it can be assessed which combinations result safer in preventing condensation by granting higher glass edge temperatures.

Tables 12-19 list glass edge temperatures based on the fRsi values shown in Table 11, at different steps of external temperatures (i.e. 30, 15, 0, and -15 ˚F).

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Minimum Temperature Factors (fRsi_min) To Avoid Condensation										
Room Temp.	Room Rel. Humidity	Notes		Dewpoint Temp.	Safety Buffer	Safety Design Temp.	Minimum fRsi Value to Avoid Condensation At Different External Temperatures (Te)			
Ti	RHi									
°F	%			°F			Te = 30 °F	Te = 15 °F	Te = 0 °F	Te = -15 °F
70	20	Too Dry For Comfort		24.8	2	26.8	-	0.215	0.383	0.492
	30	Optimal Range		35.2		37.2	0.181	0.404	0.532	0.615
	40		Range Expected Inside Airtight Buildings	43.2		45.2	0.379	0.548	0.645	0.708
	50			49.3		51.3	0.532	0.660	0.733	0.780
	60	Risky For Moisture-Driven Damages		54.5		56.5	0.663	0.755	0.807	0.841

Table 10: Minimum temperature factors (fRsi_min) required to avoid condensation at different combinations of internal relative humidity, and external temperature.

Glass Edge Temperature Factor (fRsi Value)							
The fRsi value is a pure number calculated from FEM modeling, which describes the physical relationship between room temperature Ti, external temperature Te, and coldest temperature on a window, as fRsi = (Tsi_min - Te) / (Ti - Te)							
By reversing the equation above, the coldest temperature on the internal surface of a window frame and glass combination can be calcuated as Tsi_min = Te + fRsi * (Ti - Te)			Glass Spacer				
Glass Unit	Case	Window Frame	Aluminum	Stainless Steel, Standard	Stainless Steel, Improved	Swisspacer Advance	Swisspacer Ultimate
Double Pane	D-111	Thermally Broken Aluminum Frame, Casement Outswing	0.557	0.606	0.629	0.630	0.644
	D-112	Vinyl Frame, Casement Outswing	0.537	0.596	0.652	0.645	0.715
	D-113	Wood Frame, Casement Outswing	0.433	0.525	0.602	0.593	0.716
Triple Pane	D-121	Thermally Broken Aluminum Frame, Casement Outswing	0.608	0.685	0.718	0.713	0.731
	D-122	Vinyl Frame, Casement Outswing	0.572	0.662	0.724	0.718	0.787
	D-123	Wood Frame, Casement Outswing	0.553	0.662	0.733	0.726	0.783
	D-131	Thermally Broken Insulated Aluminum Frame, Dual Action (phC)	0.668	0.741	0.788	0.787	0.834
	D-132	Insulated Vinyl Frame, Dual Action (phB)	0.639	0.713	0.768	0.761	0.827
	D-133	Insulated Wood Frame, Dual Action (pHA)	0.629	0.708	0.764	0.757	0.820

Table 11: Temperature factors (fRsi values) resulting from ISO 13788 FEM modeling of the different combinations of window frame/ glass unit/ glass spacer.
The combinations having fRsi > fRsi_min result save from a condensation avoidance point of view (i.e. glass edge temperature > dewpoint temperature).

Glass Edge Temperature (Tsi_min, ˚F)							
Based on the Glass Edge Temperature Factor (fRsi Value), and on room temperature Ti, external temperature Te, listed on the right.			Ti	70.0		Te	30.0
			Glass Spacer				
Glass Unit	Case	Window Frame	Aluminum	Stainless Steel, Standard	Stainless Steel, Improved	Swisspacer Advance	Swisspacer Ultimate
Double Pane	D-111	Thermally Broken Aluminum Frame, Casement Outswing	52.3	54.2	55.2	55.2	55.8
	D-112	Vinyl Frame, Casement Outswing	51.5	53.8	56.1	55.8	58.6
	D-113	Wood Frame, Casement Outswing	47.3	51.0	54.1	53.7	58.6
Triple Pane	D-121	Thermally Broken Aluminum Frame, Casement Outswing	54.3	57.4	58.7	58.5	59.2
	D-122	Vinyl Frame, Casement Outswing	52.9	56.5	59.0	58.7	61.5
	D-123	Wood Frame, Casement Outswing	52.1	56.5	59.3	59.0	61.3
	D-131	Thermally Broken Insulated Aluminum Frame, Dual Action (phC)	56.7	59.6	61.5	61.5	63.4
	D-132	Insulated Vinyl Frame, Dual Action (phB)	55.6	58.5	60.7	60.4	63.1
	D-133	Insulated Wood Frame, Dual Action (pHA)	55.2	58.3	60.6	60.3	62.8
		Average	53.1	56.2	58.3	58.1	60.5

Table 12: Lowest temperature on the glass edge (Tsi_min), resulting from the combination of the temperature factors, room temperature (Ti = 70˚F), and external temperature (30˚F).

Temperature Difference on Glass Edge (dTsi_min, ˚F)							
Based on the Glass Edge Temperature Factor (fRsi Value), and on room temperature Ti, external temperature Te, listed on the right.			Ti	70.0		Te	30.0
Baseline: Aluminum Spacer			Glass Spacer				
Glass Unit	Case	Window Frame	Aluminum	Stainless Steel, Standard	Stainless Steel, Improved	Swisspacer Advance	Swisspacer Ultimate
Double Pane	D-111	Thermally Broken Aluminum Frame, Casement Outswing	0.0	2.0	2.9	2.9	3.5
	D-112	Vinyl Frame, Casement Outswing	0.0	2.4	4.6	4.3	7.1
	D-113	Wood Frame, Casement Outswing	0.0	3.7	6.8	6.4	11.3
Triple Pane	D-121	Thermally Broken Aluminum Frame, Casement Outswing	0.0	3.1	4.4	4.2	4.9
	D-122	Vinyl Frame, Casement Outswing	0.0	3.6	6.1	5.8	8.6
	D-123	Wood Frame, Casement Outswing	0.0	4.4	7.2	6.9	9.2
	D-131	Thermally Broken Insulated Aluminum Frame, Dual Action (phC)	0.0	2.9	4.8	4.8	6.6
	D-132	Insulated Vinyl Frame, Dual Action (phB)	0.0	3.0	5.2	4.9	7.5
	D-133	Insulated Wood Frame, Dual Action (pHA)	0.0	3.2	5.4	5.1	7.6
		Average	0.0	3.1	5.3	5.0	7.4

Table 13: Temperature difference on glass edge (˚F), compared to the aluminum spacer (Te=30˚).

Glass Edge Temperature (Tsi_min, °F)							
Based on the Glass Edge Temperature Factor (fRsi Value), and on room temperature Ti, external temperature Te, listed on the right.			Ti	70.0		Te	15.0
			Glass Spacer				
Glass Unit	Case	Window Frame	Aluminum	Stainless Steel, Standard	Stainless Steel, Improved	Swisspacer Advance	Swisspacer Ultimate
Double Pane	D-111	Thermally Broken Aluminum Frame, Casement Outswing	45.6	48.3	49.6	49.7	50.4
	D-112	Vinyl Frame, Casement Outswing	44.5	47.8	50.9	50.5	54.3
	D-113	Wood Frame, Casement Outswing	38.8	43.9	48.1	47.6	54.4
Triple Pane	D-121	Thermally Broken Aluminum Frame, Casement Outswing	48.4	52.7	54.5	54.2	55.2
	D-122	Vinyl Frame, Casement Outswing	46.5	51.4	54.8	54.5	58.3
	D-123	Wood Frame, Casement Outswing	45.4	51.4	55.3	54.9	58.1
	D-131	Thermally Broken Insulated Aluminum Frame, Dual Action (phC)	51.7	55.8	58.3	58.3	60.9
	D-132	Insulated Vinyl Frame, Dual Action (phB)	50.1	54.2	57.2	56.9	60.5
	D-133	Insulated Wood Frame, Dual Action (pHA)	49.6	53.9	57.0	56.6	60.1
		Average	46.8	51.0	54.0	53.7	56.9

Table 14: Lowest temperature on the glass edge (Tsi_min), resulting from the combination of the temperature factors, room temperature (Ti = 70˚F), and external temperature (15˚F).

Temperature Difference on Glass Edge (dTsi_min, °F)							
Based on the Glass Edge Temperature Factor (fRsi Value), and on room temperature Ti, external temperature Te, listed on the right.			Ti	70.0		Te	15.0
Baseline: Aluminum Spacer			Glass Spacer				
Glass Unit	Case	Window Frame	Aluminum	Stainless Steel, Standard	Stainless Steel, Improved	Swisspacer Advance	Swisspacer Ultimate
Double Pane	D-111	Thermally Broken Aluminum Frame, Casement Outswing	0.0	2.7	4.0	4.0	4.8
	D-112	Vinyl Frame, Casement Outswing	0.0	3.2	6.3	5.9	9.8
	D-113	Wood Frame, Casement Outswing	0.0	5.1	9.3	8.8	15.6
Triple Pane	D-121	Thermally Broken Aluminum Frame, Casement Outswing	0.0	4.2	6.1	5.8	6.8
	D-122	Vinyl Frame, Casement Outswing	0.0	5.0	8.4	8.0	11.8
	D-123	Wood Frame, Casement Outswing	0.0	6.0	9.9	9.5	12.7
	D-131	Thermally Broken Insulated Aluminum Frame, Dual Action (phC)	0.0	4.0	6.6	6.5	9.1
	D-132	Insulated Vinyl Frame, Dual Action (phB)	0.0	4.1	7.1	6.7	10.3
	D-133	Insulated Wood Frame, Dual Action (pHA)	0.0	4.3	7.4	7.0	10.5
		Average	0.0	4.3	7.2	6.9	10.2

Table 15: Temperature difference on glass edge (˚F), compared to the aluminum spacer (Te=15˚).

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Glass Edge Temperature (Tsi_min, °F)								
Based on the Glass Edge Temperature Factor (fRsi Value), and on room temperature Ti, external temperature Te, listed on the right.			Ti	70.0		Te	0.0	
			Glass Spacer					
Glass Unit	Case	Window Frame	Aluminum	Stainless Steel, Standard	Stainless Steel, Improved	Swisspacer Advance	Swisspacer Ultimate	
Double Pane	D-111	Thermally Broken Aluminum Frame, Casement Outswing	39.0	42.4	44.0	44.1	45.1	
	D-112	Vinyl Frame, Casement Outswing	37.6	41.7	45.6	45.2	50.1	
	D-113	Wood Frame, Casement Outswing	30.3	36.8	42.1	41.5	50.1	
Triple Pane	D-121	Thermally Broken Aluminum Frame, Casement Outswing	42.6	48.0	50.3	49.9	51.2	
	D-122	Vinyl Frame, Casement Outswing	40.0	46.3	50.7	50.3	55.1	
	D-123	Wood Frame, Casement Outswing	38.7	46.3	51.3	50.8	54.8	
	D-131	Thermally Broken Insulated Aluminum Frame, Dual Action (phC)	46.8	51.9	55.2	55.1	58.4	
	D-132	Insulated Vinyl Frame, Dual Action (phB)	44.7	49.9	53.8	53.3	57.9	
	D-133	Insulated Wood Frame, Dual Action (pHA)	44.0	49.6	53.5	53.0	57.4	
		Average	40.4	45.9	49.6	49.2	53.3	

Table 16: Lowest temperature on the glass edge (Tsi_min), resulting from the combination of the temperature factors, room temperature (Ti = 70˚F), and external temperature (0˚F).

Temperature Difference on Glass Edge (dTsi_min, °F)								
Based on the Glass Edge Temperature Factor (fRsi Value), and on room temperature Ti, external temperature Te, listed on the right.			Ti	70.0		Te	0.0	
Baseline: Aluminum Spacer			Glass Spacer					
Glass Unit	Case	Window Frame	Aluminum	Stainless Steel, Standard	Stainless Steel, Improved	Swisspacer Advance	Swisspacer Ultimate	
Double Pane	D-111	Thermally Broken Aluminum Frame, Casement Outswing	0.0	3.4	5.0	5.1	6.1	
	D-112	Vinyl Frame, Casement Outswing	0.0	4.1	8.1	7.6	12.5	
	D-113	Wood Frame, Casement Outswing	0.0	6.4	11.8	11.2	19.8	
Triple Pane	D-121	Thermally Broken Aluminum Frame, Casement Outswing	0.0	5.4	7.7	7.3	8.6	
	D-122	Vinyl Frame, Casement Outswing	0.0	6.3	10.6	10.2	15.1	
	D-123	Wood Frame, Casement Outswing	0.0	7.6	12.6	12.1	16.1	
	D-131	Thermally Broken Insulated Aluminum Frame, Dual Action (phC)	0.0	5.1	8.4	8.3	11.6	
	D-132	Insulated Vinyl Frame, Dual Action (phB)	0.0	5.2	9.0	8.5	13.2	
	D-133	Insulated Wood Frame, Dual Action (pHA)	0.0	5.5	9.5	9.0	13.4	
		Average	0.0	5.5	9.2	8.8	12.9	

Table 17: Temperature difference on glass edge (˚F), compared to the aluminum spacer (Te=0˚)

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Glass Edge Temperature (Tsi_min, °F)							
Based on the Glass Edge Temperature Factor (fRsi Value), and on room temperature Ti, external temperature Te, listed on the right.			Ti	70.0		Te	-15.0
			Glass Spacer				
Glass Unit	Case	Window Frame	Aluminum	Stainless Steel, Standard	Stainless Steel, Improved	Swisspacer Advance	Swisspacer Ultimate
Double Pane	D-111	Thermally Broken Aluminum Frame, Casement Outswing	32.3	36.5	38.5	38.6	39.7
	D-112	Vinyl Frame, Casement Outswing	30.6	35.7	40.4	39.8	45.8
	D-113	Wood Frame, Casement Outswing	21.8	29.6	36.2	35.4	45.9
Triple Pane	D-121	Thermally Broken Aluminum Frame, Casement Outswing	36.7	43.2	46.0	45.6	47.1
	D-122	Vinyl Frame, Casement Outswing	33.6	41.3	46.5	46.0	51.9
	D-123	Wood Frame, Casement Outswing	32.0	41.3	47.3	46.7	51.6
	D-131	Thermally Broken Insulated Aluminum Frame, Dual Action (phC)	41.8	48.0	52.0	51.9	55.9
	D-132	Insulated Vinyl Frame, Dual Action (phB)	39.3	45.6	50.3	49.7	55.3
	D-133	Insulated Wood Frame, Dual Action (pHA)	38.5	45.2	49.9	49.3	54.7
		Average	34.1	40.7	45.2	44.8	49.8

Table 18: Lowest temperature on the glass edge (Tsi_min), resulting from the combination of the temperature factors, room temperature (Ti = 70˚F), and external temperature (-15˚F).

Temperature Difference on Glass Edge (dTsi_min, °F)							
Based on the Glass Edge Temperature Factor (fRsi Value), and on room temperature Ti, external temperature Te, listed on the right.			Ti	70.0		Te	-15.0
Baseline: Aluminum Spacer			Glass Spacer				
Glass Ur	Case	Window Frame	Aluminum	Stainless Steel, Standard	Stainless Steel, Improved	Swisspacer Advance	Swisspacer Ultimate
Double Pane	D-111	Thermally Broken Aluminum Frame, Casement Outswing	0.0	4.2	6.1	6.2	7.4
	D-112	Vinyl Frame, Casement Outswing	0.0	5.0	9.8	9.2	15.1
	D-113	Wood Frame, Casement Outswing	0.0	7.8	14.4	13.6	24.1
Triple Pane	D-121	Thermally Broken Aluminum Frame, Casement Outswing	0.0	6.5	9.4	8.9	10.5
	D-122	Vinyl Frame, Casement Outswing	0.0	7.7	12.9	12.4	18.3
	D-123	Wood Frame, Casement Outswing	0.0	9.3	15.3	14.7	19.6
	D-131	Thermally Broken Insulated Aluminum Frame, Dual Action (phC)	0.0	6.2	10.2	10.1	14.1
	D-132	Insulated Vinyl Frame, Dual Action (phB)	0.0	6.3	11.0	10.4	16.0
	D-133	Insulated Wood Frame, Dual Action (pHA)	0.0	6.7	11.5	10.9	16.2
		Average	0.0	6.6	11.2	10.7	15.7

Table 19: Temperature difference on glass edge (˚F), compared to the aluminum spacer (Te=-15˚)

CONCLUSIONS

The American construction industry is undergoing significant changes in terms of how quality is measured in buildings, and the expectations and liability that come with it.

Energy codes now require buildings to be airtight, yet they still fail in thoroughly addressing the consequences associated with this practice in terms of building science and proper moisture management. Design teams often still limit their work to traditional siloed scopes, without realizing how interrelated different portions of the building have become. For example, specifying a traditional aluminum glass spacer now has consequences on the building moisture management, and impacts other scopes of the design (e.g. the mechanical system).

This increase in risk of moisture-driven damages is still largely unknown to many American AEC professionals.

The purpose of this report was to assess the impact of different glass spacers on the performance of American fenestration products. The evaluation covered both energy performance, and avoidance of moisture-driven damages (specifically, condensation).

Table 09 illustrates the improvements on the whole window U-factors provided by using better glass spacers. Compared to the baseline of aluminum spacers, the use of warm edge spacers such as Swisspacer Ultimate allows to reduce the heat losses by up to over 22%, and about 16% in average across all window products considered.

However, the critical advantage of using warm edge glass spacers lays in the higher glass edge temperatures resulting from the heat loss reduction. Baseds on the temperature factor method, tables 12-19 list the lowest localized temperatures (Tsi_min). Warm edge spacers such as Swisspacer Ultimate

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provide considerably higher glass edge temperatures compared to the aluminum spacer baseline: from +7.4˚F temperature difference at 30˚F external temperature (Table 13), to +15.7˚F temperature difference at -15˚F external temperature (Table 19).

With buildings becoming more airtight and closer to zero energy consumption, accurate detailing and selection of climate-suitable components become critical steps towards ensuring project success. The results of the analysis summarized in this report clearly show how much of a difference warm edge glass spacers can make both in terms of energy efficiency, and prevention of condensation.

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