IMPROVING THERMAL PERFORMANCE IN STRUCTURAL FENESTRATION PRODUCTS

ABSTRACT

The manufacturers of fenestration products (windows and doors) for use in a building facade have many materials to choose from to produce their products. This paper discusses the use of aluminum with a structural thermal barrier as the material of choice for fenestration worldwide. It will offer fundamental facts about thermal barriers for commercial and residential applications. The structural longevity and design flexibility of such products is discussed. The cost of producing thermal barrier fenestration and processing techniques is presented.

Data will be provided which illustrates the ability to meet energy codes required for the architectural building industry. Comparison studies are also given on various types of systems that can be used for insulating aluminum windows and doors.

INTRODUCTION

Even today as we are securely into the twenty-first century the time proven attributes of aluminum make it the unparalleled choice for use in the world's structural windows. The properties of aluminum allow for the ease of manufacturing to be combined with reliability of structural performance. Aluminum windows have proven their worth in harshest of climates from the frigid cold of the Siberian peninsula to the extreme heat of the many deserts throughout the world to the some of the most stringent wind load requirements in the hurricane zones of the tropical climates. While the initial energy requirement for producing aluminum alloys is high, once the material is created the ability and number of times it can be recycled is unlimited.

Thermal barrier history, types and properties

With all of its intrinsic accolades, aluminum, when used for fenestration has a shortcoming. Thermal Conductivity is defined as "a measure of the rate at which heat flows through a material…. an insulating material is a poor conductor of energy and thus has a low thermal conductivity". PVC, wood and aluminum make up 95% of the worlds windows, the thermal conductivity of Vinyl/PVC is 0.17 W/m*K (1), that of a hardwood and/or maple is 0.16 W/m*K (1) and the thermal conductivity of aluminum alloys is 160 W/m*K (1). With the impressive insulating properties of these other materials and ever increasing energy requirements how can aluminum compete and maintain its popularity?

Table 1: The thermal conductivity of materials used in commercial fenestration products, taken from NFRC 101.

Aluminum	Stainless Steel	Polyamide	Polyurethane
160 W/m*K	14.3 W/m*K	0.30 W/m*K	0.12 W/m*K

The answer comes from a technology that has evolved from its conception over forty years ago. The Alaska State Courthouse in the United States was the first documented time that a

Patrick Muessig, is global technical manager for Azon USA Inc., Kalamazoo, Michigan – USA

Thermal barrier history, types and properties - cont.

Table 2: Structural properties of thermal barrier materials

Material Property	Polyamide	Polyurethane
Shear	439 g/m^2	1171 g/m^2
Impact Strength	1.0 ft/lbs/in	1.9ft/lbs/in
Flexural Strength	17,800 psi	19,000 psi
Shore D Hardness	79/81	84/86
Percent Elongation	8%	64%

polymer thermal barrier was inserted into an aluminum window in a commercial application. Those crude windows served as a forerunner for today's thermal barrier market. The engineers knew even at that day in age that with all of the benefits of aluminum windows, energy efficiency was still the missing ingredient. The material used at this time was a two part polyurethane system. The thermal conductivity of polyurethane is 0.12 W/m*K, that makes it over a 1,000 times more insulating than aluminum (see Table 1). This adaptation to the aluminum window now made it an energy efficient design; however, if aluminum windows with a thermal barrier option were to become common, all the attributes that made aluminum the material of choice for structural purposes had to be maintained.

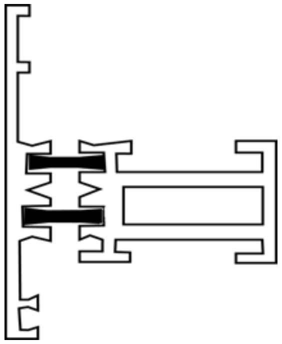
It would have to have the tensile and flexural strength properties that would compliment that of aluminum. It would require high shear strength properties so that a window could resist deflection and support lateral loads. It would also require the ability to maintain its properties when exposed to a wide range of temperature differentials. It would have to have a lifetime to match that of the current aluminum fenestration products.

In the some forty years of thermal barrier design refinement two dominant systems have prevailed. One is the polyurethane – pour and debridge system and the other is polyamide – the strip system. Both have their places of dominance in the world. In North America polyurethane is the material of choice and has over 90% of the thermal barrier market. In Eastern Europe polyamide has become the choice and has close to the same market share. Aside from the thermal conductivity other properties vary as well (Table 2).

Thermal barrier comparisons

The processing of the two systems varies as much as their material properties. The polyamide or strip system comes to the manufacturer in set lengths and widths. It is a pre-formed material with a clear adhesive strip on either side. The polyamide thermal barrier is used as a connector; two separate pieces of aluminum are slid onto two polyamide strips that sit on a top of one another (see Figure 1). Once the two pieces are joined by the polyamide a knurling wheel is run upon the top of each strip and it forces the aluminum clamps into the polyamide strips thus giving the product its shear strength. After this process the product is heated to melt the adhesive strips and prevent water infiltration and help secure the polyamide strips.

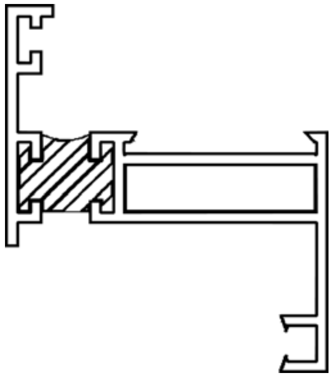
Figure 1: Aluminum polyamide – strip system thermal barrier profile



The polyurethane or pour and debridge system actually comes to the manufacturer in a liquid form. A mixing machine with two tanks, one Iso and one Resin hold the required materials separate until the time of processing. A single aluminum extrusion passes through the mixing machine and liquid polyurethane is poured in the desired cavity size. The material then hardens exothermically into a solid structural material.

Thermal barrier comparisons -cont

Figure 2: Aluminum polyurethane-pour and debridge thermal barrier profile.



The next step is using a mill to 'debridge' or remove the bottom of the aluminum cavity thus creating a thermal barrier (see Figure 2). The exact cost of the two systems varies. The polyamide material tends to be more costly to produce. For either system the total material cost added to a standard 1.2m x 1.2m aluminum window is close to 12 Euro. Using two computer programs one called Therm 5.0 and one called RESFEN 3.1 – Residential Fenestration the effects of a thermal barrier can be demonstrated in window performance and how that translates into annual energy savings.

Therm 5.0 is a state-of-the-art computer program developed at Lawrence Berkeley National Laboratories (LBNL) for use by building component manufacturers, engineers, architects and others interested in heat transfer. Using Therm one can model two-dimensional heat transfer effects in building components, this analysis allows the evaluation of a product's energy efficiency. The program uses a finite element analysis method that examines every material within a fenestration product and produces a rating of heat transfer (U-factor) and the solar heat gain effects (SHGC). It is through the use of this software that the effects of the low thermal conductivity of the thermal barrier materials are demonstrated.

By importing AutoCAD drawings and assigning material properties, Therm allows you to model almost any frame profile. Once the material properties are assigned, an Insulating Glass Unit is imported from another LBNL software program Window 5.0. Window allows the operator to design an IG unit with any low-e coating, gas fill, or size desired. Next the proper boundary and environmental conditions are assigned then the program assesses how much, how fast, and where the heat would flow through the profile. The operator is then given a rating for U-frame and U-edge, which are transferred back to Window 5.0, where the size and type of window are entered. Once this is accomplished two very important results are derived, the total fenestration product's U-Factor and SHGC (Solar Heat Gain Coefficient). These two ratings dominate the industry and when code officials decide what requirements need to be met these are the two that are chosen.

Table 3: Requirements for Document 'J' in Scotland

Frame Type	With gas or oil central heating having an efficient boiler	With electric heating, solid fuel central heating, or gas or oil central heating having an inefficient boiler
Aluminum or steel windows	2.2 W/m*K	2.0 W/m*K
PVC-U or timber windows	2.0 W/m*K	1.8 W/m*K

Therm provides more insight than just a number rating. It allows the operator to view how the heat flows through a profile using heat flux magnitude, infrared heat flow, flux vectors and isotherms. This ability to simulate versus physical testing allows the designer to optimize the fenestration product including placement, size and material required for thermal barriers before a single unit is ever built.

Thermal barrier comparisons -cont

Since many fenestration manufacturers now have global operations, it is imperative that they be able to meet all of the different and ever changing energy codes for given regions. In Scotland they are required to meet Document “J” (see Table 3), in England it is Document “L” and in fact its requirements are the first column of Document “J” and in the United States ‘Energy Star’ (see Figure 3) is dominating. (Note the conversion is 1.0 US unit = 5.7778 W/m*K)

When these requirements first appeared many aluminum manufacturers where concerned about the ability of their products to meet the required performance levels. They had to compile a myriad of information and interchangeable options that would allow them to comply and still be profitable. During this phase the thermal barrier for aluminum windows changed from an option to a requirement.

The manufacturers found that a standard aluminum window with a clear IG unit had an average U-factor of around 3.5 W/m*K. Adding a low-e hard coat to the IG unit took them down to around 2.7 W/m*K, which was still not enough. Adding a structural thermal barrier increased the window’s performance to below 2.2 W/m*K, thus meeting the Document ‘L’ requirements.

Figure 3: Current Energy Star Criteria

Zone	Approximate HDD/CDD Coverage	U-factor	SHGC
Northern	≥ 5,400 HDD	≤ 0.35	Any
North/Central	3,600 - 5,400 HDD	≤ 0.40	≤ 0.55
South/Central	6,300 - 4,500 CDD	≤ 0.40	≤ 0.40
Southern	≥ 6,300 CDD	≤ 0.65	≤ 0.40

Zone	Approximate HDD/CDD Coverage	U-factor	SHGC
Northern	≥ 5,400 HDD	≤ 0.60	Any
North/Central	3,600 - 5,400 HDD	≤ 0.60	≤ 0.40
South/Central	6,300 - 4,500 CDD	≤ 0.60	≤ 0.40
Southern	≥ 6,300 CDD	≤ 0.75	≤ 0.40

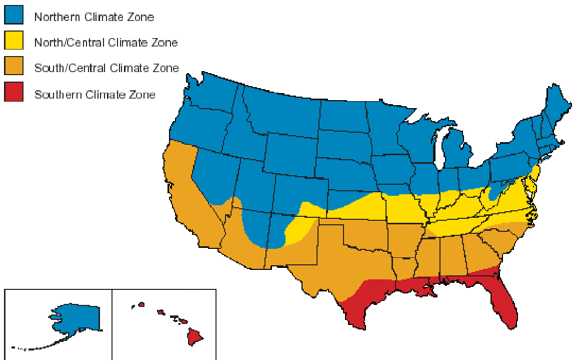
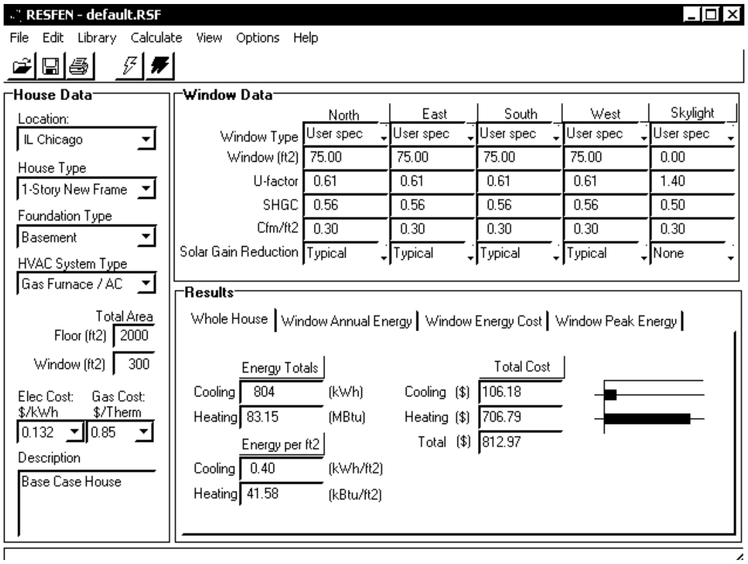


Figure 4: RESFEN calculations for annual heating and cooling costs of a dwelling in Chicago, Illinois USA



House Data

Location: IL Chicago
House Type: 1-Story New Frame
Foundation Type: Basement
HVAC System Type: Gas Furnace / AC
Total Area
Floor (ft2): 2000
Window (ft2): 300
Elec Cost: $/kWh: 0.132
Gas Cost: $/Therm: 0.85
Description: Base Case House

Window Data

	North	East	South	West	Skylight
Window Type	User spec	User spec	User spec	User spec	User spec
Window (ft2)	75.00	75.00	75.00	75.00	0.00
U-factor	0.61	0.61	0.61	0.61	1.40
SHGC	0.56	0.56	0.56	0.56	0.50
Cfm/ft2	0.30	0.30	0.30	0.30	0.30
Solar Gain Reduction	Typical	Typical	Typical	Typical	None

Results

Whole House | Window Annual Energy | Window Energy Cost | Window Peak Energy

Energy Totals		
Cooling	804	(kWh)
Heating	83.15	(MBtu)

Energy per ft2		
Cooling	0.40	(kWh/ft2)
Heating	41.58	(kBtu/ft2)

Total Cost	
Cooling ($)	106.18
Heating ($)	706.79
Total ($)	812.97

Thermal barrier comparisons -cont

But why is saving energy through improved fenestration products important and just how much energy is saved going from 3.5 U-factor to 2.2? To answer the first part, today it is widely accepted that 1/3 of all energy is consumed by commercial buildings of that 38% of that is attributed to the heating and cooling. To answer the second part we will utilize the previous mentioned LBNL software program RESFEN.

RESFEN or residential fenestration is a software program that allows the operator to calculate the heating and cooling costs of a residential dwelling in North America. By entering the location, square footage of the house, the square footage of the fenestration products, their orientation and the heating and cooling costs for the region RESFEN gives a simple dollar amount for the dwelling (see Figure4). In this example a U-factor of 0.61 was used, the equivalent of 3.50 W/m*K, representing a standard aluminum frame with a clear IG unit. The total annual heating and cooling costs for this home is $812.97 USD. If all of the windows are replaced with ones that meet the Document 'L' requirements of 2.2 W/m*K or .38 in IP units, the annual heating and cooling costs are now $716.44 USD. That represents a saving of $96.53 USD, for a single story home, when this scenario is applied to some of the taller commercial buildings having 80-100 stories the savings can reach into the millions. Unfortunately, at present time the software is limited to larger North American cities and only residential applications. There have been discussions to make a much more comprehensive commercial version 'COMFEN' for global use but the development period is forecasted to be at least 3-5 years.

We saw the savings of $96.53 when going from windows with a U-factor 3.5 W/m*K to a 2.2 W/m*K, but how much of that can be attributed to the use of a thermal barrier system? Previously we mentioned that with a low-e coating the windows performance was around 2.7 W/m*K, so actually the thermal barrier improvement was taking the window from 2.7W/m*K to below a 2.2 W/m*K. If the same RESFEN simulation was performed with windows whose U-factor was 2.7W/m*K the total annual heating and cooling costs were $755.21 USD. From before, we know that windows with a U-factor 2.2 W/m*K cost $716.44 USD. Therefore the annual heating and cooling savings attributed to the thermal barrier are $38.77 USD.

If you are following the calculations you probably have noticed that the addition of a low-e coating taking the window from 3.5 to 2.7 saved $57.76 USD which was more than the thermal barrier. While it is understood that both are required to meet energy standards, the true savings of each of the thermal options must be noted. In speaking with three aluminum pour and debridge thermal barrier window manufacturers in the United States, the average material cost per window to add a low-e coating was $55 USD. To add a thermal barrier to a window was $11 USD. Since our test home in Chicago, IL had 20 windows the total additional cost to add low-e to the windows was $1,100 USD and to add a thermal barrier was $220. When these numbers are divided by their respective annual energy savings the payback period becomes 19 years for the low-e coating and 5.7 years for the thermal barrier. As shown the thermal barrier becomes the most energy efficient material for the return on investment.

Improving insulated glass with warm-edge spacers

Once a structural aluminum window incorporates a thermal barrier, a low-e coating and gas fill now the spacer for the insulated glass (IG) unit thus becomes the weakest link. Warm-edge technology started making inroads in the mid-1990s. It was promoted as a way to reduce condensation and improve the comfort level associated with fenestration products used in the home.

Today there are many residential warm-edge spacers on the market from pre-desiccated foam, to butyl with corrugated steel to many PVC designs. They add not only the benefits from reduced condensation but also they improve the overall energy efficiency of the unit, while improving acoustical properties and ease of manufacturing. Due to these improvements it is estimated that the warm-edge market now represents 75% of all spacer material used in residential applications.

Improving insulated glass with warm-edge spacers -cont

As is often the case in the fenestration industry, products are introduced for residential use and once they have proven their efficacy, commercial applicators start asking for the same technology. There were few solutions for commercial use. Residential warm-edge spacers weren't designed to handle the deflection and windloads associated with a fifty-story building or a 15-foot span on a curtainwall. The window and glazing producers had limited options to meet the demands of commercial use.

Conveniently a warm-edge spacer is defined as anything less conductive than the standard aluminum box spacer. So a natural choice was stainless steel. While stainless steel had all of the intrinsic structural properties required it was still a highly conductive material. The thermal conductivity of stainless steel is 14.3 W/m*K, when this material replaces a standard aluminum spacer some benefits are noted, the sightline temperature increases 1-2C and the condensation resistance is increased 2-3 points. It also decreases the units overall U-factor around 0.02-0.05. While all of these are undoubtedly improvements, lost in the mix was an improvement in acoustical properties and many companies within the industry could not justify the increase in cost and the slower rates of production.

The slower rates of production stemmed heavily from two facts: The abrasive wheels required to cut the stainless steel spacer had to be added to the production line and were slower and more expensive than those used for aluminum. Additionally, many manufacturers who bend their aluminum spacers require a tight .093" radius; they could not meet this requirement using stainless steel. This added to the manufacturer's frustration as they already viewed the bending process a bottleneck in assembly line production.

The other option involved taking an aluminum spacer and incorporating a polyurethane thermal barrier in the middle of the profile. This technology —an adaptation taken from thermal barrier aluminum frames (see Figure 2) —had already proven itself in architectural windows in commercial markets. Through testing and thermal simulation, aluminum thermal barrier polyurethane warm-edge spacer proved it abilities. It demonstrated all of the attributes in commercial applications that have made warm-edge technology so attractive for residential applications.

Figure 5: How an aluminum thermal barrier warm-edge spacer works

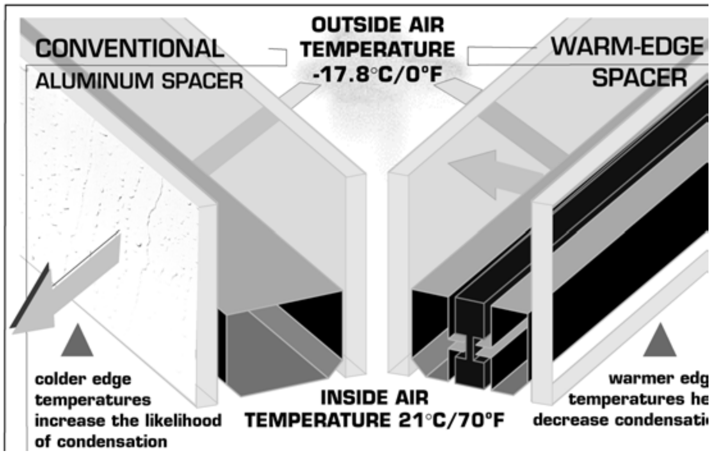


Table 4: Property comparison of aluminum, stainless steel and an aluminum polyurethane warm-edge spacer in the same aluminum thermal barrier, Low-e, dual IG unit

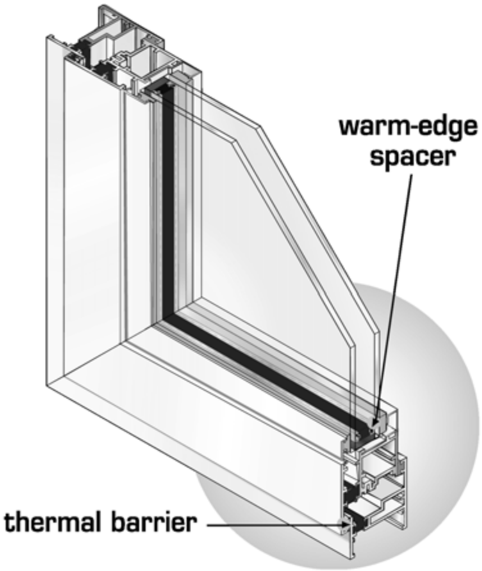
Spacer type	Aluminum	Stainless Steel	Aluminum Polyurethane
Sight Line Temp (C)	6.2 C	6.7C	8.7C
Sight Line CRF	31.0	33.5	43.5
Total U-Factor	2.34	2.31	2.18

Improving insulated glass with warm-edge spacers -cont

The sight-line temperature increased 2-5C, the Condensation Resistance increased 8-15 points, the overall U-factor was improved by 0.12-0.22 W/m*K and the additional benefits of acoustical improvements and overall comfort returned without the production difficulties associated with stainless steel. (see Table 4 for comparison)

The improvements are such that when required to produce a more efficient product manufacturers now have an option. Filling an IG unit with a low conductive gas such as Argon or Krypton was once a viable way to meet this request. However as this practice increased many manufacturers were displeased with added step of production or the cautions required for having such material on a production line. Additional questions surfaced about the percent of low conductance gas that was actually in the IG unit initially and what percent remained during the lifecycle of these units. Many manufacturers once faced with adding a low conductive gas fill to the IG units have turned to warm-edge technology as a practical replacement. The use of a structural thermal barrier warm-edge spacer does not require an additional production step and restrictive material handling codes no longer apply. The warm-edge spacer is now accepted as a part of an energy efficient commercial building.

Figure 6: A window incorporating a thermal barrier frame and a structural thermal barrier warm-edge spacer



Both the thermal barrier technology and the introduction of warm-edge spacers (see Figure 6) have allowed commercial window manufacturers to produce an energy efficient product that has never before been matched without sacrificing structural properties. It was estimated that in the later part of the twentieth century there were enough aluminum thermal barrier extrusions produced to encircle the globe nine times. Aluminum thermal barrier and the structural warm-edge technology are now combined in a fenestration product created for the commercial market that will allow the ever increasing demands of high performance energy and possibly more important those of the end consumer.

While the concept remains the same, many new developments in the chemical formulization of thermal barriers and the design of structural warm-edge spacers continue to evolve and as this happens these two products will remain a staple in the industry for all of the important reasons this paper has discussed.

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