DEVELOPMENT OF CONVECTION FLOW BARRIERS

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EXECUTIVE SUMMARY

In recent years, window energy efficiency has significantly been upgraded with the introduction of specialized super-window components, including low-e coatings, argon gas fill and insulating foam spacers. The combination of low-e coatings and argon gas filling increases center-of-glass temperatures and the substitution of insulating foam spacers increases average edge-of-glass temperatures. However, although these components increase average window-surface temperatures, their introduction is not the complete answer to window-condensation problems and bottom-edge condensation can still occur under extreme cold exterior temperatures and high indoor humidity conditions.

In order to minimize these bottom-edge condensation problems, Edgetech proposed the concept of a convective-flow barrier which blocks the simple convective loop within a double-glazed unit and specifically prevents the downward air flow in the cavity adjacent to the cold exterior lite from directly striking the warm interior lite.

In Phase One of the research project, the design concept of a convective flow barrier was demonstrated to be an effective mechanism for minimizing bottom perimeter-edge condensation problems. However, the first-generation barrier designs that were prototyped were cumbersome to manufacture on a commercial scale. For Phase Two, the key objective was to develop more cost-effective, second-generation barrier designs that can be readily commercialized in the immediate future. Specific tasks included: design development, condensation resistance testing, durability testing, thermal performance testing, field trials and production equipment development.

For the design development task, the Phase Two research focused on evaluating three alternative design strategies. The first design strategy involves fabricating the barrier as a bottom-edge glass strip slotted into a U-shaped perimeter metal cam. To ensure no cold-spot leakage, polyisobutylene (PIB) is extruded into the metal channel. The glass sheet is held in place using hidden side clips and for visual appeal, the top-edge of the glass strip is ground to a smooth-curved profile. Even though waste-glass material is used to fabricate this barrier-strip design, our general conclusion is that this design is too complicated and expensive to fabricate and therefore has limited commercial potential.

The second design strategy involves fabricating the barrier design as a decorative-glass insert consisting of a stained-glass perimeter with a center void. Marketed under the name of "deco-edge", this second design strategy avoids the problem of visually hiding the convective-flow barrier by making it a very attractive feature of the finished window. One company in Ontario, Centennial Home Renovations, has commercialized "deco-edge" units (See Edgetech newsletter Vol.3, No. 4) and because of the visual appeal of the final product and regardless of any benefits relating to condensation resistance, it is anticipated that other companies will follow Centennial's example.

The third design strategy involves moving away from the concept of a bottom-edge barrier design and instead extends the center-glass insert to the full-unit height. Although this design strategy is of course triple-glazing reinvented, the new product design differs from regular triple units in that the gas-filled cavity widths are somewhat narrower so that the units can be incorporated into existing window frames.

For PVC frames, the recommended cavity width is 3/8 inch with argon gas-filled units and for wood frames, the recommended cavity width is 3/16 inch for krypton-filled units. Based on thermographic analysis, our in-house testing has shown that these narrow-width, warm-edge triple-glazed units have the same bottom-edge temperatures as regular-width triples. Also computer energy analysis has shown that these narrow-width, plain triple-glazed units provide essentially the same thermal performance as low-e, argon-filled, double-glazed units.

Compared to double-glazed barrier designs, the key cost advantage of narrow-width triples is that incremental material and labor costs of the triple-glazed unit can be traded against the extra cost of the low-e coating required for a high performance double-glazed unit. If higher thermal performance is required, glazing efficiency can be further enhanced by the addition of one or even two low-e coatings.

For argon-filled triples, our preliminary cost analysis indicates that compared to low-e, argon-filled doubles and assuming full advantage is taken of automated unit production, there is essentially no cost premium for the argon-filled triples. However, because of higher gas costs, there is a cost premium of about 40 cents per square foot for the krypton-filled units. Even with these higher price slim-line krypton units, given the significantly improved condensation resistance, our conclusion is that consumers will be prepared to pay the additional costs involved.

In terms of edge-seal technology, these new narrow-width, warm-edge triples can be manufactured either with Edgetech's regular Super Spacer® product or alternatively by using a special U-shaped foam spacer which is wrapped around the center-glass lite. This new Super-U™ edge seal design can also be used for fabricating barrier-fence designs for double-glazed units.

For the Phase Two project, a major component of the research program involved detailed durability, thermal performance and condensation resistance testing of this new Super-U™ edge seal design. For efficiently laminating the U-shaped foam to insert metal-spacer frames, new semi-automated production equipment was also developed although this specialized production equipment needs to be further modified before the product can be commercialized on a wide-scale.

For extreme cold climates, a variety of different composite, multi-layer glazing/barrier designs were evaluated. Although adding a bottom-edge barrier to one or more of the cavity spaces of a triple-glazed unit does indeed improve performance, the trade-off again is whether to add an extra glass pane or incur the inconvenience of installing a barrier fence. As with double-glazed units, it was concluded that given the energy performance increase with quad-glazing, these composite multi-layer glazing/barrier designs are not likely to be cost-effective and the preferred design is a slim-line, argon or krypton-filled, quad-glazed unit.

As well as product development tasks, the research project also involved carrying out side-by-side field trials of double-glazed units with and without a bottom barrier fence. As predicted by our laboratory testing program, under extreme high indoor humidity levels and cold outdoor temperatures, the convection-flow barrier units were not completely effective in eliminating condensation and there was misting both at the bottom unit edge and immediately above the barrier fence. However, even though condensation was not completely eliminated, there was a surprisingly positive response from the occupants of the field-trial house. Our assumption is that because they could clearly see the unique double-band condensation pattern, they could appreciate that even though the barrier-strip fence might not be the complete answer, it was effective in increasing condensation resistance.

A second field-trial project demonstrated alternative triple-glazed designs, including both narrow-width and regular spaced units. Based on the record-breaking cold temperatures experienced in the 1993/94 winter, the narrow-width triples provided excellent condensation resistance, at least matching the performance of regular-width triples.

From the Phase One research program, one key conclusion was that existing condensation resistance test methods were inadequate and there was a need to develop a more accurate test procedure. As a result, a major focus of the Phase Two research program was on the development of an improved test procedure. As part of this task, Edgetech actively participated in the NFRC Condensation Resistance Technical Sub Committee of which Michael Glover, is the chairman. This US committee is developing both computational and laboratory test procedures for determining condensation resistance of fenestration products.

RÉSUMÉ À L'INTENTION DE LA DIRECTION

Au cours de ces dernières années, l'efficacité énergétique des fenêtres s'est considérablement améliorée avec l'apparition des composants spéciaux pour super-fenêtres, y compris les couches à faible émissivité, les lames d'argon et les profilés en mousse isolante. La combinaison des couches à faible émissivité et de l'argon fait augmenter la température moyenne au centre du verre et l'emploi de la mousse isolante fait augmenter la température moyenne au bord du verre. Cependant, même si ces composants font augmenter la température moyenne de surface des fenêtres, leur utilisation n'apporte pas une réponse complète au problème de la condensation car celle-ci peut se former sur le bord inférieur lorsque la température extérieure est très basse et que le taux d'humidité intérieur est très élevé.

Pour réduire la condensation sur le bord inférieur, Edgetech a proposé le concept de barrière au flux de convection qui bloque la boucle de convection dans un double vitrage et empêche précisément que le mouvement descendant de l'air au contact du panneau extérieur froid frappe directement le panneau intérieur chaud.

La phase Un du projet de recherche a permis de prouver que le concept de barrière au flux de convection était un mécanisme efficace pour réduire la condensation sur le périmètre inférieur. Cependant, les prototypes de barrière de la première génération étaient difficiles à fabriquer à une échelle commerciale à cause de leur encombrement. Dans la phase Deux, l'objectif clé était de développer des barrières de deuxième génération plus économiques et faciles à commercialiser rapidement. Les tâches portaient spécifiquement sur : le développement d'un prototype, les essais de résistance à la condensation, de durabilité, de rendement thermique, les essais sur le terrain et le développement de l'équipement de production.

Dans le cadre du développement du système, la phase Deux a porté sur l'évaluation de trois solutions. La première comprend la fabrication d'un prototype de barrière constitué par une bande de verre qui s'insère dans un profilé métallique en U situé sur le périmètre inférieur. Pour s'assurer qu'il n'y a pas de fuite par des points froids on extrude du polyisobutylène (PIB) dans le profilé en métal. Le verre est maintenu en place par des pinces latérales dissimulées et, pour des considérations d'esthétique, le bord supérieur de la bande de verre est arrondi et lissé. Même si on utilise des chutes de verre pour fabriquer la bande, notre conclusion générale est que ce type de conception est trop compliqué et trop coûteux à fabriquer et que son potentiel commercial est donc limité.

La deuxième solution consiste à faire de la barrière un élément décoratif comprenant un périmètre en verre teinté et un vide central. Commercialisé sous le nom de "deco-edge", ce système évite le problème du masquage de la barrière en en faisant un élément attrayant. Une entreprise ontarienne, Centennial Home Renovations, a commercialisé des produits "deco-edge" (Voir Edgetech newsletter Vol. 3, No. 4). À cause de l'aspect esthétique des produits, sans tenir compte de leur meilleure résistance à la condensation, on s'attend à ce que d'autres entreprises emboîtent le pas.

La troisième solution s'écarte du concept de barrière en partie inférieure et reprend le concept du panneau de verre central en l'appliquant à toute la hauteur de la fenêtre. Cela équivaut à un triple vitrage, sauf que la lame de gaz est plus mince, ce qui permet d'installer les panneaux sur les châssis existants.

La largeur recommandée pour la lame d'argon des châssis en PVC est de 3/8 po. Elle est de 3/16 po pour la lame de krypton des châssis en bois. En se basant sur des analyses thermographiques, les essais que nous avons effectués sur le terrain ont démontré que sur ces triples vitrages minces à bord chaud, le bord inférieur est à la même température que sur les triples vitrages de largeur normale. Des analyses énergétiques faites par ordinateur ont montré que ces fenêtres à triple vitrage

ordinaire de faible largeur ont en gros le même rendement thermique que les doubles vitrages à l'argon à faible émissivité.

Par rapport aux barrières par double vitrage, le principal avantage financier des triples vitrages minces est que le supplément de matériau et de main-d'oeuvre qu'ils exigent compense le surcoût de la couche à faible émissivité nécessaire pour un double vitrage à haut rendement. Si on veut un rendement thermique supérieur, on peut améliorer l'efficacité du vitrage en ajoutant une ou même deux couches à faible émissivité.

Selon notre analyse préliminaire, par rapport aux doubles vitrages à l'argon de faible émissivité, en admettant que la production soit entièrement automatisée, il n'y a virtuellement pas de surcoût pour les triples vitrages à l'argon. Cependant, à cause du coût plus élevé du gaz, les vitrages au krypton reviennent à environ 40 % de plus au pied carré. Mais, comme les vitrages minces au krypton ont une bien meilleure résistance à la condensation, nous pensons que les consommateurs accepteront de payer le supplément de coût.

Du point de vue de la technologie de l'étanchéité des bords, ces triples vitrages minces à bord chaud peuvent être fabriqués en utilisant le Super Spacer^{R} régulier d'Edgetech ou un profilé en U spécial en mousse sur le pourtour du panneau central. Ce nouveau joint étanche Super-U^{TM} peut aussi être utilisé pour des barrières par double vitrage.

Dans la phase Deux du projet, une des composantes essentielles du programme de recherche était les essais de durabilité, de rendement thermique et de résistance à la condensation de ce nouveau système Super-U^{TM} d'étanchéité des bords. Pour laminer de façon efficace le profilé en mousse et l'insérer dans des châssis métalliques, on a mis au point un nouvel équipement de production semi-automatique, mais cet équipement spécialisé a encore besoin d'être modifié pour que le produit puisse être commercialisé à grande échelle.

On a évalué, pour les climats extrêmement froids, différents types de barrières/vitrages multiples. Même si on ajoute une barrière au bord inférieur d'une ou deux lames de gaz d'un triple vitrage, on n'améliore pas le rendement. Là encore, la solution consiste à ajouter un vitrage supplémentaire ou à risquer l'inconvénient de poser un protège-barrière. Comme pour les doubles vitrages, on a conclu que, à cause du meilleur rendement thermique des quadruples vitrages, il peu probable que ces types de barrières/vitrages multiples composites valent la dépense. Un quadruple vitrage mince à l'argon ou au krypton est préférable.

En plus du développement du produit, le projet de recherche portait aussi sur la réalisation d'essais comparatifs, sur le terrain, de doubles vitrages avec ou sans barrière en partie inférieure. Comme le programme d'essais de notre laboratoire l'avait laissé entendre, avec un taux d'humidité intérieur très élevé et des températures extérieures très froides, les barrières au flux de convection n'étaient pas entièrement efficaces pour éliminer la condensation et il y avait de la buée sur la bordure inférieure et immédiatement au-dessus de la barrière. Cependant, même si la condensation n'était pas totalement éliminée, la réaction des occupants de la maison des essais était étonnamment positive. Selon nous, c'est parce qu'ils voyaient bien nettement la double bande de condensation et, même si le protège barrière n'était pas l'idéal, il était efficace pour augmenter la résistance à la condensation.

Un deuxième projet d'essais sur le terrain a permis d'éprouver d'autres modèles à triple vitrage, dont des modèles de faible épaisseur et d'épaisseur normale. En se basant sur les records de froid de l'hiver 1993-94, les tripes vitrages de faible épaisseur ont montré une excellente résistance à la condensation, au moins égale à celle des triples vitrages d'épaisseur normale.

L'une des constatations importantes du programme de recherche de la phase Un a été que le mode opératoire des essais de résistance à la condensation était inadéquat et qu'il fallait mettre au point une méthode plus précise. La phase Deux a donc mis surtout l'accent sur le développement d'une technique améliorée. Dans le cadre de cette tâche, Edgetech a participé activement au sous-comité technique de résistance à la condensation du NFRC dont Michael Glover est le président. Le comité US est en train de mettre au point des techniques informatiques et de laboratoire pour déterminer la résistance à la condensation des fenêtres.

1.0 INTRODUCTION

The evolution of high-performance glazing was initiated with the development and commercialization of low-e coating technology in the early 1980's. The low-e coating served to reduce radiative heat loss through the glazing unit. As a result of this reduced radiation heat loss, it then became worthwhile to reduce conductive heat loss by filling the glazing cavity space with a low conductivity gas such as argon.

With heat loss through the center glazing substantially reduced, the problem of heat loss through the conventional metal spacer at the perimeter of the insulating glass unit became even more pronounced and as a result our company pioneered the development and commercialization of the first high-performance, insulating-glass spacer for the North American market. Marketed under the name of Super Spacer®, the spacer typically achieves a 0.03 to 0.04 Btu/h/ft^2/°F (0.17 to 0.23 W/m^{2}C) overall window U-value improvement in average residential windows. This improvement is comparable to the improvement of argon gas filling. Another key advantage of the product is that the cold-weather problem of edge-of-glass condensation is diminished.

The performance of Super Spacer® in reducing conductive heat loss through the perimeter edge seal was graphically demonstrated in research performed at the NRC contained in the ASHRAE paper, "Heat Transfer at the Edge of Sealed Insulating Glass Units: Comparison of Hot Box Measurements with Finite-Difference Modelling". This study clearly shows that Edgetech's insulating spacer increases edge-of-glass temperatures. However, the paper only reports mid-height horizontal surface temperature profiles of sealed units without frames and is thus of limited value for predicting condensation resistance.

Experience has shown that under extreme cold weather conditions and high interior humidity levels, bottom edge-of-glass condensation can still occur and this problem is primarily caused by convective flow of the air or fill-gas within the double-glazed units. As shown in Figure 1, under cold-weather conditions, the cavity gas in a double-glazed unit flows downwards near the cold exterior glazing lite and upwards near the warm interior glazing lite. As the gas adjacent to the cold exterior glazing descends, it becomes progressively colder and at the bottom of the sealed-unit cavity, this cold gas turns and comes in direct contact with the bottom-edge region of the interior glazing sheet. As a result, the glass near the bottom-edge of the interior glazing sheet is cooled by the coldest fill gas within the sealed unit and this convective cooling effect contributes significantly to the potential condensation problem at the bottom edge-of-glass region. Though not the focus of this study, convection on the warm side can also aggravate this problem. Usually wind prevents natural convection from occurring on the cold side.

In order to prevent the descending cavity gas from reaching the bottom region of the interior glazing sheet, our company developed the product concept of a convective-flow barrier. As illustrated in Figure 2, a convective-flow barrier can be fabricated simply as a vertical fence which is positioned along the bottom edge of the double-glazed unit. This barrier is located approximately at the center of the cavity space between the glazing sheets which are typically spaced about 1/2 inch apart. By using the vertical-fence barrier to essentially block the flow path of the cold gas, the coldest area on the interior glazing is moved from the bottom edge of the double-glazed unit to a location just above the top edge of the vertical fence.

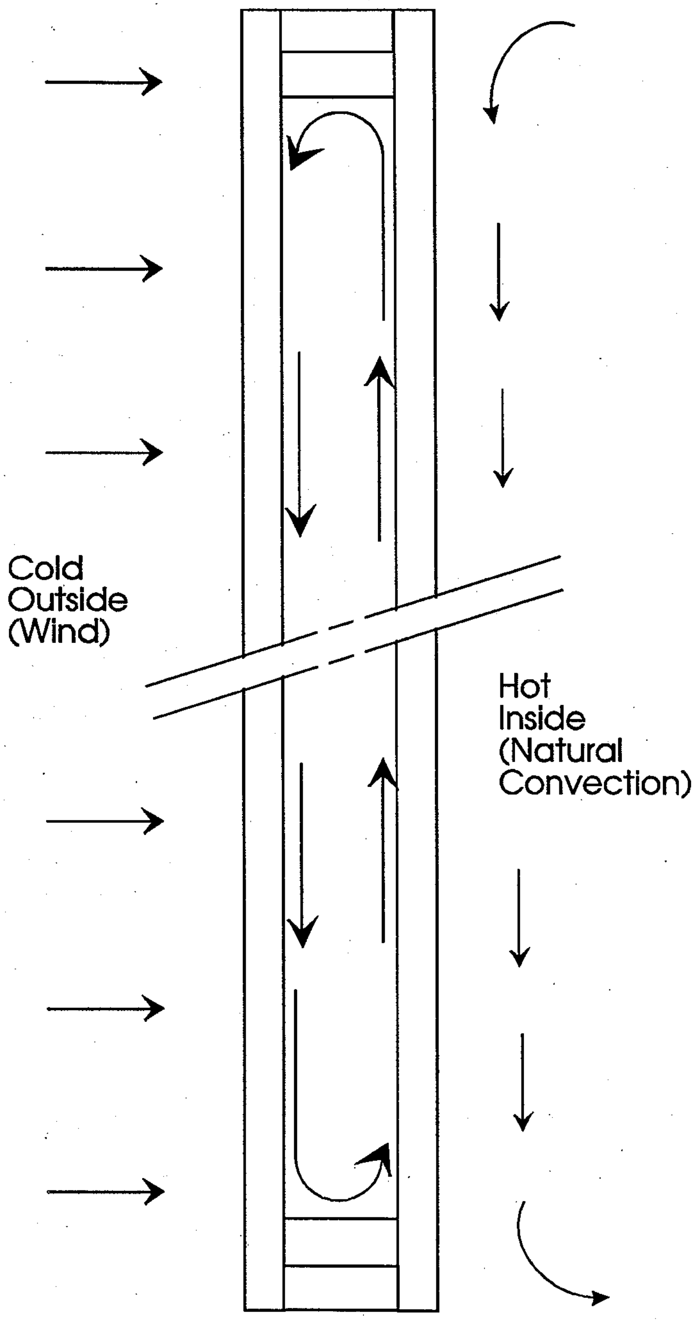


Figure 1 Natural Convection within Double-Glazed Unit

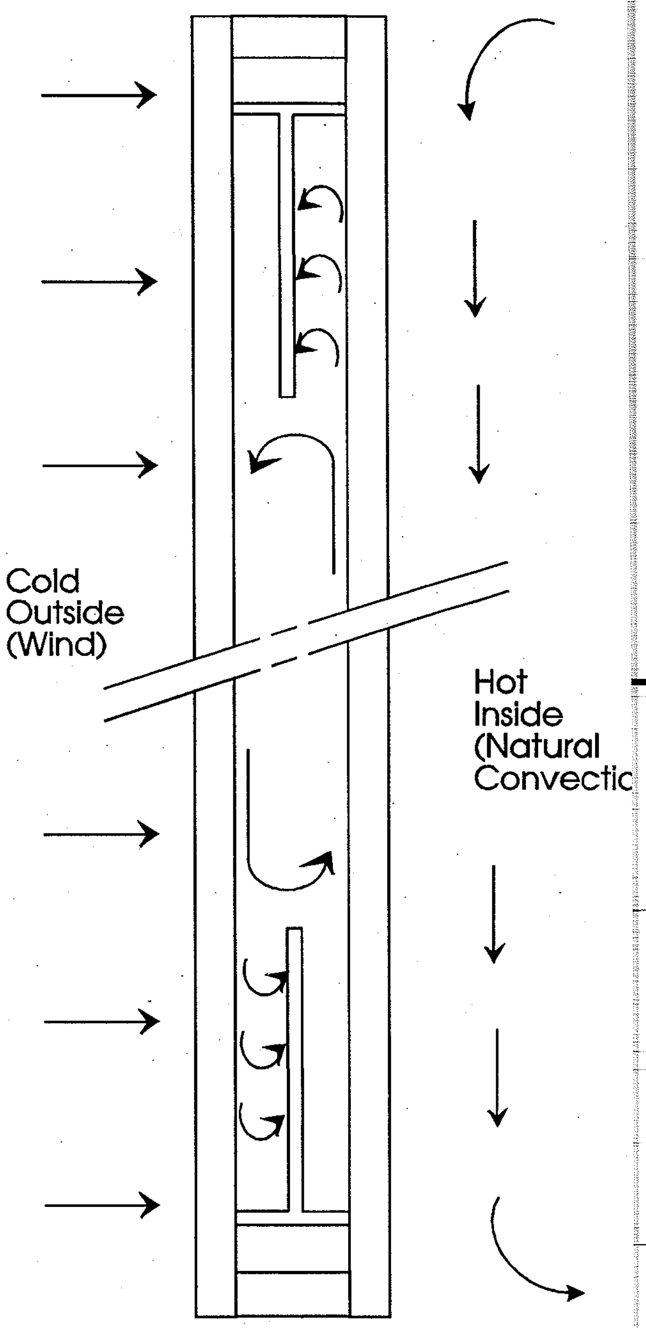


Figure 2 Double-Glazed Unit with Barrier Fence

1.1 Laboratory Testing of Convective Flow Barriers: Preliminary Evaluation

For Phase One, preliminary evaluation of the effectiveness of convective-flow barriers was carried out using different laboratory techniques, including thermographic, interferometric and visual observation.

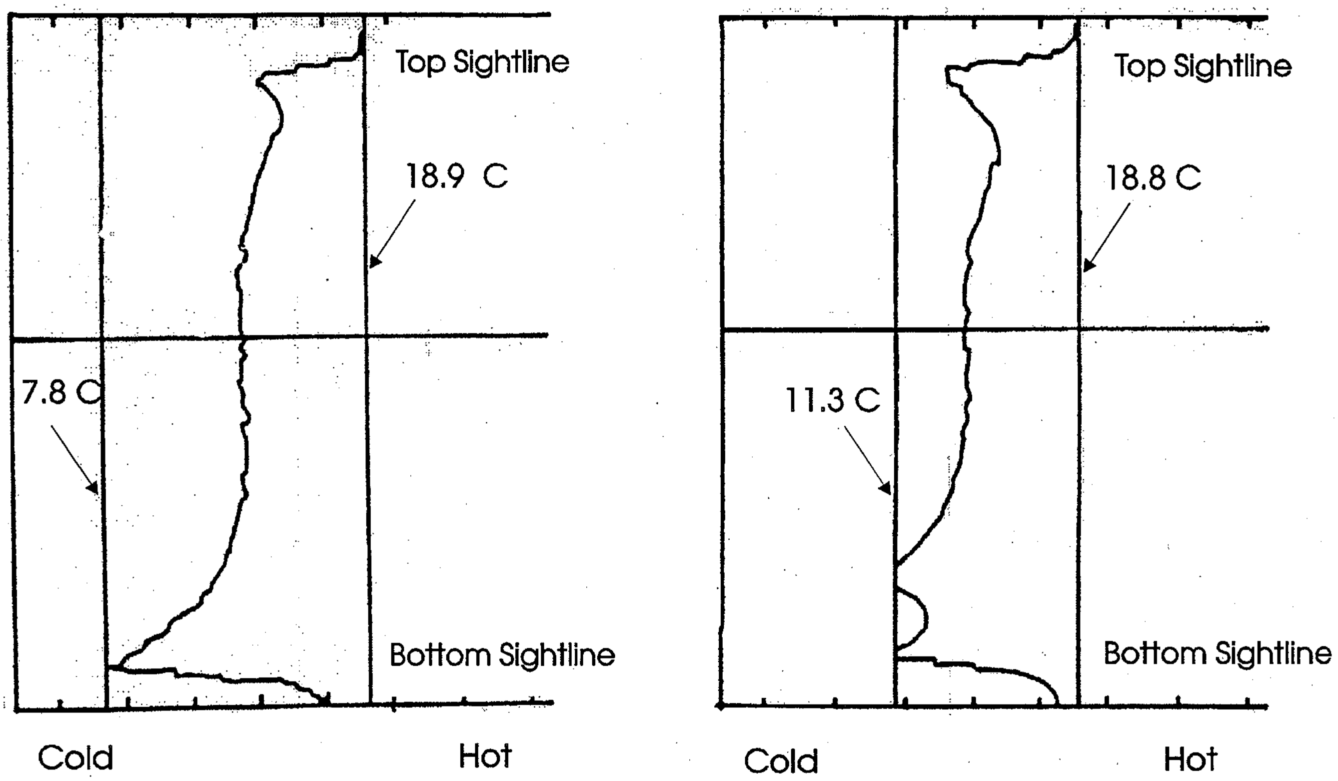
Preliminary thermographic testing at Lawrence Berkeley Laboratory demonstrated that simple convective-flow barriers are effective in increasing bottom edge-of-glass temperatures. The SESCI paper, "Convection-Flow Barriers for High Performance Glazing Units" (See Appendix E) summarizes the results of this preliminary work. As illustrated in Figure 3, the characteristic double peak temperature profiles obtained in these initial thermographic studies dramatically showed that the barriers are effective in separating the cold-edge effects due to convection from the cold edge effects due to conduction through the edge seal. During the thermographic testing, a range of different barrier heights were evaluated to determine the optimum height of the convective flow barrier and it was concluded that a height of about 2" was about optimum.

In addition to thermographic analysis, samples of convective-flow barriers were also provided to the Window Group at the University of Western Ontario and interferometric testing of these prototype barriers was carried out. Details of this study are contained in the CANMET report "Development of a Computer Based Calorimeter Interferometer Facility to Evaluate High Performance Windows". As shown in Figure 4, this testing provided very useful results and again the isotherm images that were produced graphically showed that the barrier is effective in moving the convective-flow vortex from the bottom of the glazing cavity to just above the barrier fence. Contrary to earlier thermographic analysis, this interferometric study also showed that there is not really an optimum height for the barrier fence and that the most effective solution is to fully extend the barrier so that the cavity space is divided up into two narrower spaces. Thus, due to the air films on the center lite as well as the inner sides of the outside lites, the natural convection loop cannot fully develop and the convection vortex is suppressed instead of just relocated.

To directly study visual condensation patterns, in-house high humidity/cold chamber testing was carried out of different convective-flow barrier designs. One conclusion from this visual testing program was that at extreme cold winter temperatures and high indoor humidity levels, the introduction of a barrier fence into a double-glazed unit can actually increase the glazing area where condensation can occur. This is due to the fact that instead of the condensation being focused in a small perimeter band along the bottom edge of the unit, the barrier evens out the temperatures over a larger area so that although the condensation formed may not be so severe, it is spread over a wider area. Further to completely eliminate bottom edge-of-glass condensation, this simple visual testing program showed that for extreme cold climate locations such as Winnipeg more radical design solutions were required if condensation was to be fully eliminated.

1.2 Development and Evaluation of Alternative Convective Flow Barrier Designs

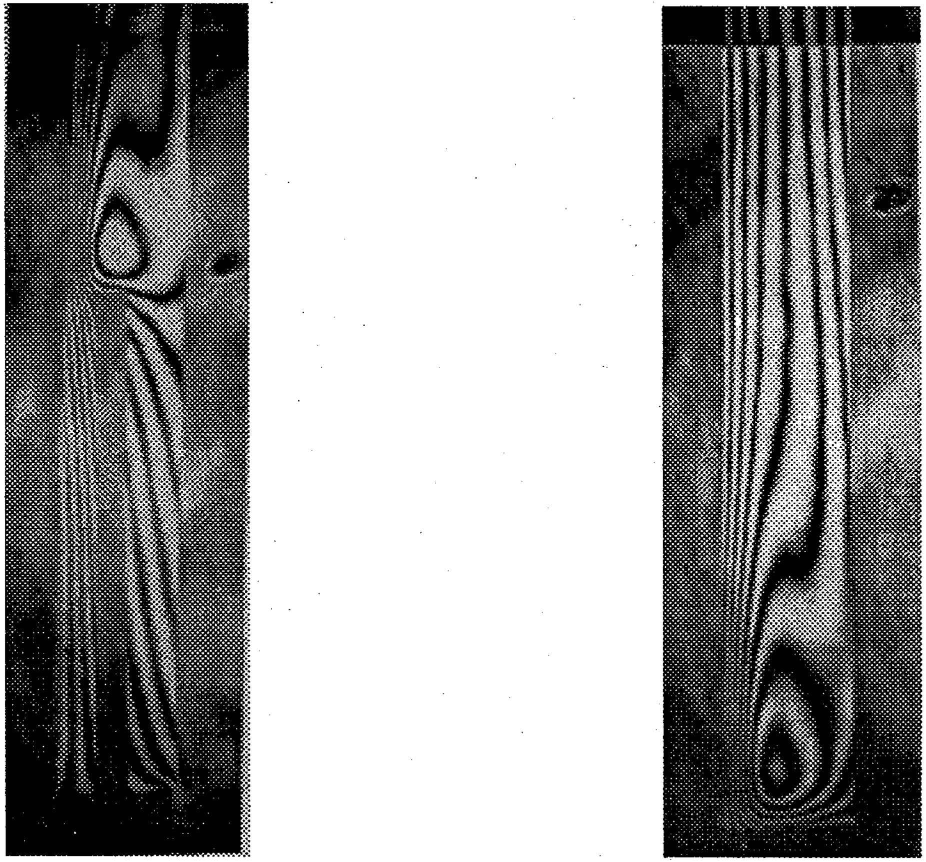
During Phase I, a wide range of first-generation convective barrier designs were developed and evaluated. One simple design option for fabricating the vertical-fence barrier is to use an inverted T-section plastic profile extrusion. In addition to the inverted T-section profile, a number of profile shapes were evaluated. One design option evaluated consisted of fabricating the convective-flow



Double-Glazed
No Barrier Fence

Double-Glazed
2" Barrier Fence

Figure 3 Side-by-Side Comparison of Temperature Profiles for Super Spacer® IG Units with and without a Vertical-Fence Barrier



Double-Glazed
½" Airspace
Cold-Side: -6°C
Warm-Side: 20°C
2" Barrier Fence

Double-Glazed
½" Airspace
Cold-Side: -6°C
Warm-Side: 20°C
No Barrier Fence

Figure 4 Interferometric Images: Barrier Fence vs Non-Barrier Fence barrier as a sloped-fence located at an inclined angle to the vertical. Another alternative design consisted of a horizontal strip or barrier which was located parallel to and extending along the full width of the sealed unit.

Preliminary cost analysis of these various extruded plastic-profile designs indicated that the comparatively high incremental costs of plastic extrusions would make these types of barrier too expensive for commercialization. As a result rather than fabricating the convective-flow barrier as an extruded profile, we came to the conclusion that it would be more cost effective to manufacture the barrier from transparent plastic or glass sheet material.

The principal initial design evaluated consisted of a vertical-glass fence held in position by slotted-support brackets or clips located on the bottom edge and on the sides. Based on thermographic analysis, a key design issue that was identified was that in order to prevent localized cold spots due to air leakage, effective sealing of the joint connection between the barrier and the edge seal was essential.

2.0 TECHNICAL DISCUSSION

2.1 Design Development of Hybrid Edge-Seal Design

Based on the Phase I research, it was concluded that for convective-flow barriers to be cost-effective, the key was to integrate the design of the insulating edge seal with the barrier design. Further, this new hybrid edge-seal design had to be capable of being manufactured using existing high-volume IG production equipment. In response to these two key requirements, a U-shaped silicone foam spacer design was developed that was capable of accommodating a wide rage of rigid inserts. Initial FRAME computer simulations of this second generation hybrid design indicated that the metallic inserts would not significantly downgrade the thermal performance of the edge seal.

By varying the slot width, the U-shaped silicone foam spacer can accommodate a wide range of inserts, including: (i) a simple barrier-strip glass fence inserted into a U-shaped metal came; (ii) a rectangular metal profile for rigid steel spacer dual-seal architectural IG units, (iii) a decorative brass-came for stained-glass lites, and (iv) thin glass panes for the wrap-around triple or quad designs. Because the inserts are rigid, polyisobutylene (PIB) can be conventionally applied to the spacer sides and the sealed units can be fabricated as traditional dual-seal units using a structural secondary sealant such as silicone. Or, with some unit designs, Edgetech's reverse dual seal design may be used. In the reverse dual seal design adhesive on the sides of the spacer supplies the unit's structural support while the secondary sealant acts as the barrier to moisture vapor transmission.

Our company has already commercialized this new Super U™ design and product information sheets on these different U-shaped spacer designs are contained in Appendix A. Because these designs are to be marketed to different segments of the insulating-glass industry, the new product is being marketed under a variety of trade names. Super U™ has a 3/16" slot capable of accepting a U-shaped metal cam into which the simple barrier fence can be inserted. Alternatively, Super U™ can be laminated to a conventional metal spacer frame fabricated from a rectangular steel rigid spacer. Super U™ Cushion Edge has a 1/4" slot to fit the common 1/4" cams of the decorative door-lite and stained-glass industries. Super U™ Triple has been designed with a narrow slot (1/16") to accommodate thin sheets of glass for the wrap-around triple design.

For the wrap-around triple design, the new Super U™ design offers the following six main advantages. First, by using a single extruded component, there are potential material and production labor savings. Second, for reduced unit weight, the center-glass lite can be fabricated from ultra-thin, chemically-tempered glass. Third, the flexible foam profile cushions the inner glass from breakage. Fourth, the vapor barrier film laminated to the back face of the spacer is continuous between the inner and outer glass lites reducing potential moisture and gas transmission. Fifth, for dual-seal units, the inner polyisobutylene seal is only applied on the two outer sides and so compared to conventional dual-seal units, quality assurance of the edge-seal can be more easily maintained. Sixth, where sensitive sputtered low-e coatings are applied to the center glass lite, there is no need for edge deletion.

2.2 Design Development of Narrow-Width, Triple-Glazed Units

As documented by the interferometric analysis, there is no real optimum height for the bottom-edge barrier design and the center-glass insert can be extended to the full-unit height. Although this design strategy is of course triple-glazing reinvented, the new product design differs from regular triple units in that the gas-filled cavity widths are very narrow so that the units can be incorporated into existing window frames.

For PVC frames, the recommended cavity width is 3/8 inch with argon gas-filled units and for wood frames, the recommended cavity width is 3/16 inch for krypton-filled units. Based on thermographic analysis, our in-house testing has shown that these narrow-width, warm-edge triple-glazed units have essentially the same bottom-edge temperatures as regular-width triples. Also computer energy analysis has shown that these narrow-width, triple-glazed units provide essentially the same thermal performance as low-e, argon-filled, double-glazed units.

Compared to bottom-edge barrier designs, the key cost advantage of narrow-width triples is that the incremental material and labor costs of triple-glazed units can be traded against the extra cost of a low-e coating required for high performance double-glazed units. For argon-filled triples, our preliminary cost analysis indicates that assuming full advantage is taken of automated unit production, there is no significant cost premium for the argon-filled triples. However, because of higher material gas costs, there is a cost premium of about 40 cents per square foot with the krypton-filled triples. Given the significantly improved condensation resistance, our conclusion is that consumers will be prepared to pay the additional costs involved.

These new narrow-width, warm-edge triples can be manufactured either with Edgetech's regular Super Spacer® product or alternatively by using the new Super U™ foam spacer which is wrapped around the center-glass lite.

2.3 Design Development of Composite Multi-Layer Glazing/Barrier Designs for Extreme Cold Climates

For buildings in extreme cold-arctic climate locations with high indoor humidity levels, even triple-glazed Super Spacer® units will not totally eliminate condensation. One solution is the combined use of barrier fences with triple-glazed units. A second solution is quad-glazing with two thin-glass center lites. As with double-glazed units rather than incur the inconvenience of installing convective-flow barriers, our conclusion is that the preferred solution is a narrow-width, quad-glazed unit. To minimize edge-seal stresses due to glass bowing under cold weather conditions, the overall unit width should be no more than 1 5/8" and for optimum thermal performance, the 3/8" cavity spaces in this type of unit need to be krypton gas-filled. As documented in the Edgetech Newsletter (See Volume 3, No. 3, "Loewen's R-16 quad wows Winnipeg crowd"), with the addition of three sputtered low-e coatings (e=0.04), these quad-glazed units can provide R-16 center-glass performance.

2.4 Drawbacks of Existing Condensation Resistance Test Methods

There are two main condensation resistance test methods in North America, The AAMA 1503 test and the CSA A440 standard. However, these condensation resistance test methods do not accurately assess the problem of bottom-edge condensation. In the case of the AAMA 1503 test, the condensation resistance factor (CRF) is calculated according to a complicated formula with the condensation resistance factor for the frame and glazing being calculated separately. The glazing CRF is based on the average of six thermocouple measurements in predetermined locations and the frame CRF is based on the average of fourteen predetermined thermocouple measurements and four roving thermocouple measurements that are given special emphasis because of a weighted-frame factor. Because these various thermocouple measurements are then averaged out, the CRF can provide the consumer with somewhat misleading information particularly in terms of bottom edge-of-glass condensation.

For example with a low-e gas-filled unit, the center-glazing temperature is much higher than edge temperatures, the top edge-of-glass temperature is also comparatively high because of convective flow within the unit and although the bottom edge-of-glass temperature is low, the problem of bottom edge condensation can to some extent be hidden from the consumer because the glazing CRF is calculated by averaging the three measured temperatures.

In the case CSA A440 standard, the temperature index for the glazing is also calculated separately from the temperature index for the frame. For the frame, instead of a complicated weighing factor, the temperature index is simply based on the minimum frame temperature measured. For the glazing, the temperature index is based on the average of three sensors which must be located 50 mm (2 inches) from the bottom. Again, by locating the sensors so far from the bottom-edge zone, the problem of bottom-edge condensation is again largely hidden from the consumer.

In the United States with the introduction of the new NFRC window rating program, there is an opportunity to improve and simplify the existing AAMA test procedure. Also, because of the need to harmonize product standards as part of the US/Canada free trade treaty, the work being carried out in the United States to develop an improved test procedure will also likely have an eventual impact on the Canadian standard.

In developing the new NFRC test procedures for condensation resistance, two alternative and complementary approaches are being examined. One approach is based on using improved convection models incorporated into existing 2D computer analysis programs and the second approach is based on cold-chamber testing.

At present, existing window-analysis programs such as the Vision or Window program, do not at present take into account local convection-flow effects and are therefore not suitable for evaluating bottom edge-of-glass condensation. However, improved convection correlations are under development and may be incorporated in such programs as FRAME 4.0 that will suitable for evaluating bottom-edge condensation. Although these new programs should be able to accurately determine bottom-edge temperatures in cases where air infiltration is negligible, there is still a need for laboratory test methods to determine the effects of air infiltration.

For cold chamber testing, thermocouple sensors are typically used to measure surface temperatures and these sensors must be located in a few prespecified positions. The use of thermocouples for surface temperature measurements is not ideal. First, the addition of the thermocouple sensors can modify the surface temperatures being measured. Second, special care must be taken in attaching the thermocouple sensors to the glass as inaccurate readings can easily result and this connection problem is a significant quality-control issue particularly when measuring bottom edge-of-glass temperatures. Third, thermocouple sensors only provide "spot" measurements and only a very limited number of thermocouples are used to determine glazing surface temperatures of an entire window.

To overcome the present drawbacks of thermocouple sensors, the use of an IR thermographic camera has been proposed as a means of measuring glazing surface temperatures. Compared to sensor measurements, there are three key advantages to using an IR thermographic camera. First, as a "non-contact" measurement system, surface temperatures are not modified by the thermographic measurement process. Second, the quality-control problems of sensor attachment are avoided. Third, surface temperatures are not based on a very few sensor locations but are based on full-surface temperature interpretation. At present, there is not recognized standard laboratory test procedure for thermographic surface measurements and as a result, significant time and effort has been spent in developing a new test procedure. An initial draft of the proposed standard is attached in Appendix B.

2.5 Development of Condensation Resistance Test Method

After submitting units for thermographic testing at a commercial laboratory, we came to the conclusion that although the basic theory for carrying out thermographic analysis is well known, there is a general lack of expertise in using infra-red thermography for measuring window-surface temperatures. Consequently, significant time and effort was spent in developing a new test procedure for IR thermographic measurements. A related task was the need to construct a cold-chamber test facility specifically designed for carrying out thermographic measurements.

(i) Identification of Critical Factors for Thermographic Testing

In the development of the thermographic test method, the first step was to identify the environmental conditions critical to infra-red thermographic testing of windows. For the warm-side conditions, these factors include: bulk air temperature, humidity, natural convection and background temperature/radiation. For the cold-side conditions, the two key factors are bulk-air temperature and air film coefficient on the test sample.

(ii) Construction of Cold-Chamber Facility

The cold chamber facility has been constructed as a separate, sealed and well-insulated room within our existing heated laboratory space. By using this double-shell design strategy, imposed thermal loads on the cold-chamber facility are minimized and this ensures that critical warm-side conditions such as bulk air temperature, natural convection, and background temperature/radiation can be easily controlled.

For thermographic testing, the control of humidity levels is particularly important as any condensation or misting on the glass can effect the temperature readings. For the test facility to achieve the necessary humidity control, an off-the-shelf dehumidifier as well as a conventional air conditioner were used for temperature and humidity preconditioning. However it should be noted that because the main laboratory function is to carry out accelerated durability testing of insulating glass units, background humidity levels are very high and as a result of these high humidity levels, it is not feasible at present to carry out controlled thermographic testing during the summer months.

A constant temperature cold-liquid source is used to cool the chamber and as a result, there are no on/off surges normally associated with mechanical air cooling. The liquid cooling source is dry ice and compared to conventional mechanical chillers, one key advantage of this low cost approach is that it allows for rapid cooling of the test facility. Again for the cold-side film coefficients, there is no need to use sophisticated equipment and two off-the-shelf air fans provide the required constant conditions.

In addition to environmental control, the other key factor to ensuring accurate thermographic images is the elimination of all warm-side, infra-red reflections. Various experiments were carried out to determine the best method for screening out warm-side heat sources and the low-cost solution that was determined to work effectively was to use a large rectangular tube fabricated from large-sheets of polystyrene. This tube was suspended in front of the window samples and the back face was also blocked off by a large polystyrene sheet. By screening all surfaces that reflect off the test samples high quality thermographic images can be obtained.

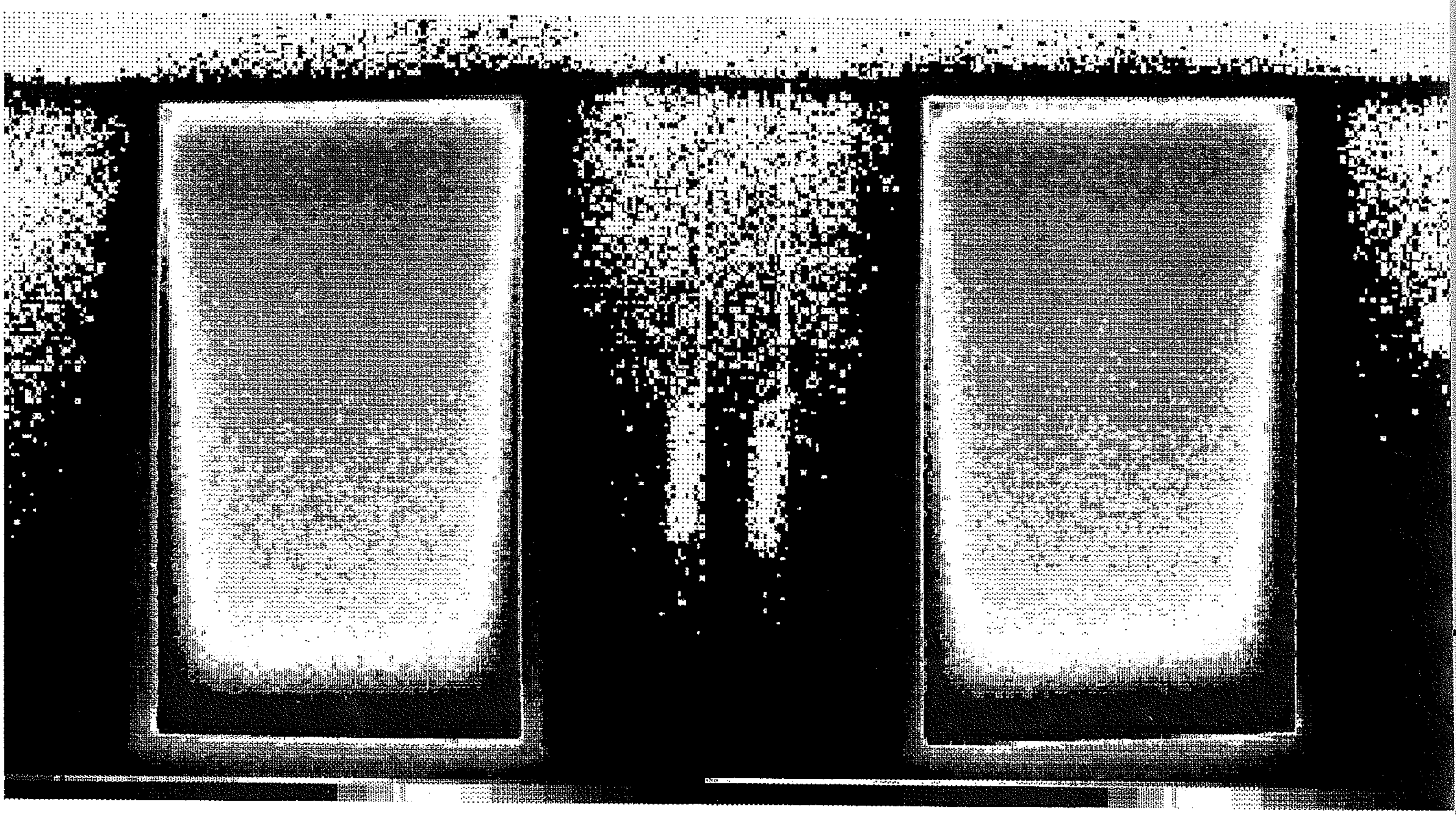
Recent upgrades to the cold chamber facility include adding a data acquisition system and also enlarging the chamber to accept full-size casement windows. However it should be noted that at present, the full-scale chamber is limited to testing at temperatures down to -25°C while the smaller facility can test down to -50°C.

(iii) Side-by-Side Testing of Identical Units

After the cold-chamber facility had been constructed and commissioned, the next step was to demonstrate that the required control of the environmental test-chamber conditions had been realized in the final completed design. To do this, side-by-side testing of identical insulating-glass units was carried out and as shown in Figure 5, essentially identical thermographic images of the two test units were obtained. Through visual inspections it was determined that the very minute differences between the two images were due to very minor variations in the construction and installation of the sealed units.

(iv) Repeatable Thermographic Images from Test to Test

The fourth step in developing the thermographic test procedure was to demonstrate that repeatable thermographic images could be obtained from test to test. After unsuccessfully carrying out a series of tests, hardware/software glitches were discovered in the IR camera. These glitches, while not affecting relative temperature differences or the shapes of the temperature profiles, were interfering with test to test comparisons. Additional work is underway to correct this problem.



Double-Glazed
Low-e / Argon
Super Spacer® Units

Figure 5 Side-by-Side Thermographic Test of Identical Units

However as a first step to solving this problem, by rigorously controlling the IR camera functions, data was obtained that could be compared from test to test. As part of the In-house Thermographic Testing of Narrow-Width Triples contained in Section 3.6 of this report, comparative testing of four sealed units was undertaken with one unit held constant as a reference for all three tests. The surface profiles obtained of the reference unit from the three different tests are shown in Figure 6.

The agreement shown in these results can be seen as proof that IR imaging is capable of obtaining repeatable results from test to test. The misalignment of the profiles at the top sightline can be explained by slight variations in the distance of the camera from the test specimen in the different tests. Each division on the X-scale is a temperature data point and will not be exactly the same distance apart if the distance from camera to test specimen varies. To obtain greater agreement at the sightlines, the camera should be much closer to the test sample than it was in these full specimen shots. This will increase the number of temperature data points in the critical area of interest.

(v) Absolute Temperature Measurements

Given the problems experienced in obtaining repeatable thermographic images from test to test, the final task of obtaining absolute test temperature measurements was not completed. However, a draft test procedure for IR thermography of windows was prepared (See Appendix B) and further development of the IR test method awaits the development of an accurate reference surface-temperature measurement techniques. Work is ongoing both in-house and at a number of other research laboratories in North America on this task.

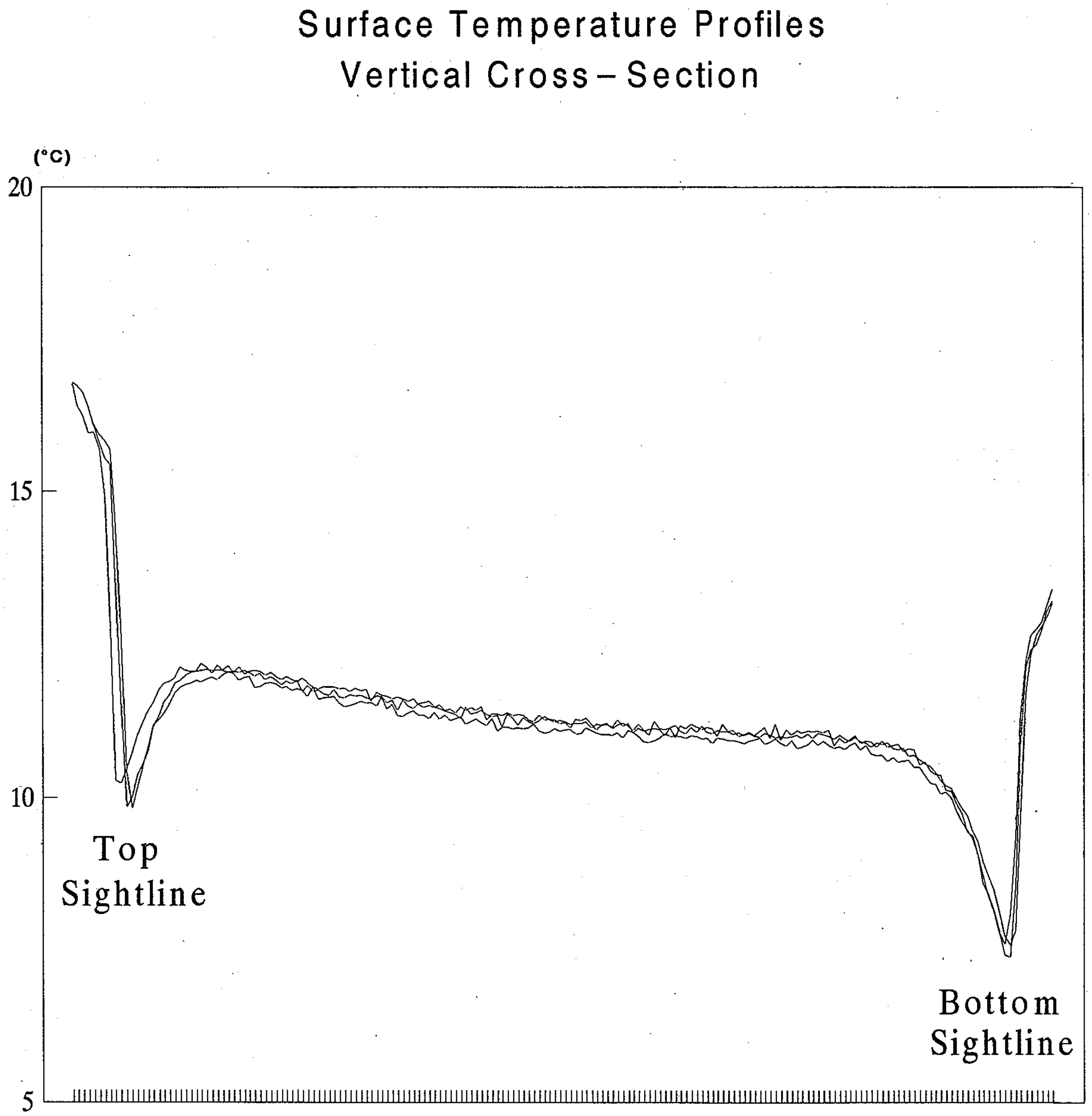
2.6 Testing Program for Condensation Resistance

(i) Preliminary Testing at Ortech International

During Phase One an initial round of thermographic testing was attempted at Ortech International and although no meaningful data was obtained, it was a good learning exercise that helped in the development of an improved thermographic test procedure. To try and correct the initial errors, a second round of thermographic testing was performed at Ortech International during Phase Two and although improved thermographic images were obtained, the data quality was still not satisfactory.

(ii) Simulation of Edge Temperatures

The first stage of the in-house condensation resistance testing was the simulation of modified spacer designs using FRAME. Though the existing FRAME program cannot model bottom edge temperatures, in theory the program should model horizontal surface temperature profiles through the mid-height of a sealed unit. These horizontal profiles are extremely useful in understanding conduction effects of the various components of the window including the spacer assembly.



Clear Slimline Triple with Argon and Super Spacer®

Figure 6 Thermographic Test Repeatability

The first step in the simulation process was to insure FRAME gives accurate horizontal surface temperature profiles through the mid-height of a sealed unit. To achieve this end, FRAME was validated against the data and simulation results contained in the NRC study, "Heat Transfer at the Edge of Sealed Insulating Glass Units: Comparison of Hot Box Measurements with Finite-Difference Modelling". The agreement between FRAME data simulated in-house and the KOBRU 86 data from the NRC study, as shown in Figure 7, was extremely close as was expected. Since KOBRU 86 was shown in the original research to accurately predict the mid-height horizontal surface temperature profiles, it can be inferred that FRAME will also be able to predict mid-height horizontal surface temperature profiles.

After the validation of FRAME for use in predicting mid-height horizontal surface temperature profiles, a wide range of glazing and frame options were run. The first task performed was to determine the impact of the various metal inserts proposed for Super U™ on the conduction performance of the spacer. Runs performed inhouse on a generic PVC casement window, see Figure 8, show the impact of a 3/16" square steel insert on the horizontal temperature profiles compared to pure foam and pure metal spacers. By using this FRAME in this method a hybrid foam/metal spacer has been designed that has essentially the performance of a foam spacer.

In conjunction with the analysis of spacer design, the affects of various frame designs were also investigated. One interesting result of this investigation is highlighted in Figure 9. In thermally-broken aluminum frames with large thermal breaks and insulating spacers, it was determined that the edge-of-glass of specific types of units could actually be warmer than the center-of-glass. This finding can be explained due to the thermal fin effect where the inner aluminum frame member heats the inside surface of the glass because the thermal break and insulating spacer prevent the heat from escaping through to the exterior.

(iii) Preliminary In-House Thermographic Testing of Barrier Designs

Preliminary qualitative thermographic analysis of the different glazing barrier was carried out in-house with the assistance of the Center of Building Diagnostics, Cantech (Ottawa). This qualitative thermographic testing was backed-up by thermocouple measurements of a number of sealed-unit, base-case designs including doubles and triples with low-e, argon gas fill and insulating spacers. Figure 10 shows a typical thermographic output of this side-by-side testing. In this example, a Southwall quad-glazed, krypton-filled Super Glass unit is compared with a plain triple-glazed Super Spacer® unit. In comparing the thermographic images, it should be noted that although the Super-Glass unit has a much higher center-glass temperature and despite the fact that the Super Glass edge seal incorporates a rigid foam-spacer thermal break, the bottom-edge temperatures of the plain Super Spacer® triple-glazed unit are the same if not higher than the Super Glass unit.

One key issue that emerged during condensation-resistance testing was that for window thermographic testing, the CSA A440-specified, cold-side test temperature of -30°C is excessive and impractical if air infiltration effects are eliminated during the test. Given that with most standard double-glazed units, there is significant condensation at test conditions of -10°C and relative humidities above 30%, this means that at the specified test temperature of -30°C, the humidity levels in the test chamber must be kept at extremely low and impractical levels to prevent condensation and misting on the test sample.

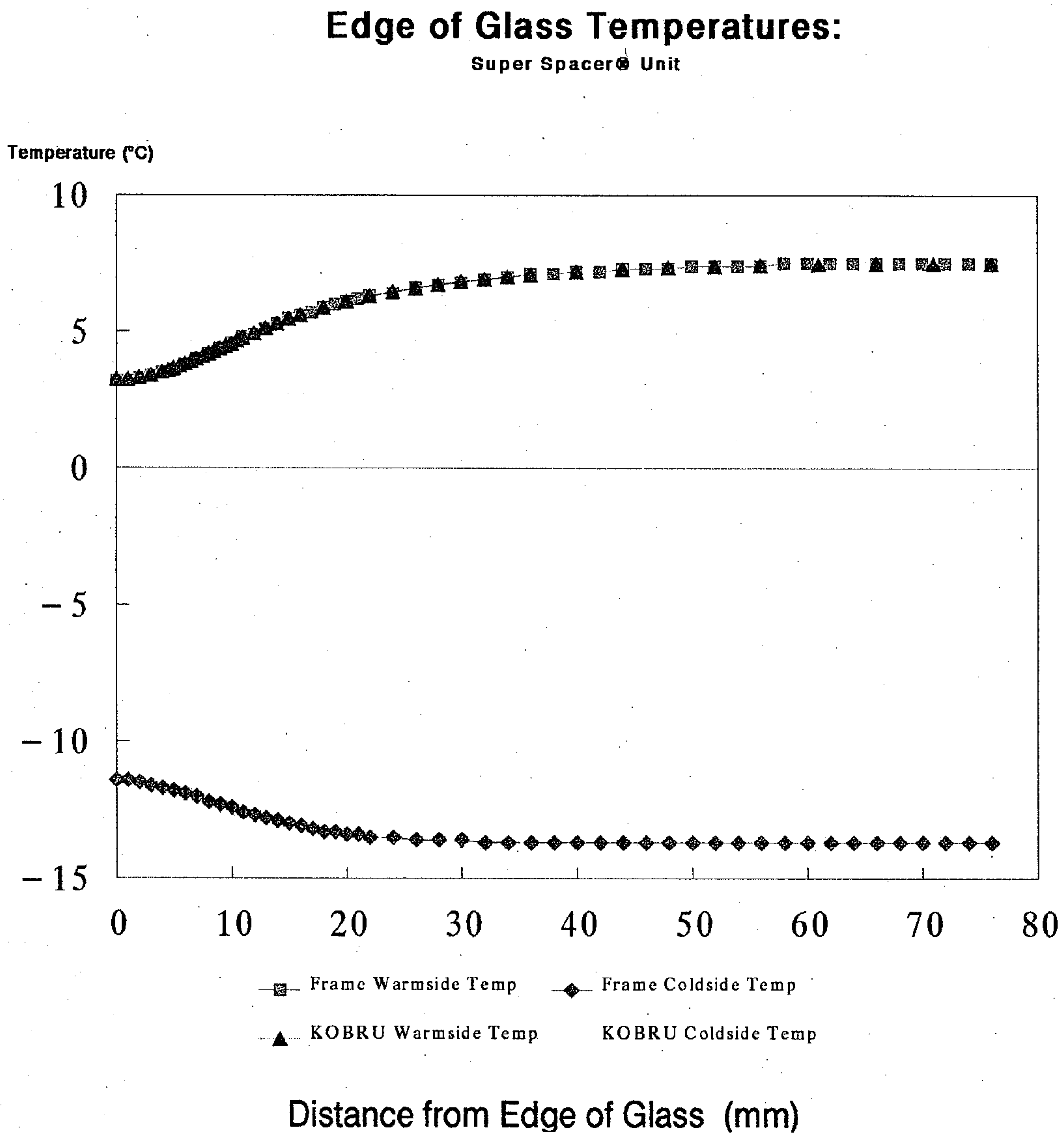


Figure 7 KOBRU 86 and FRAME Comparison

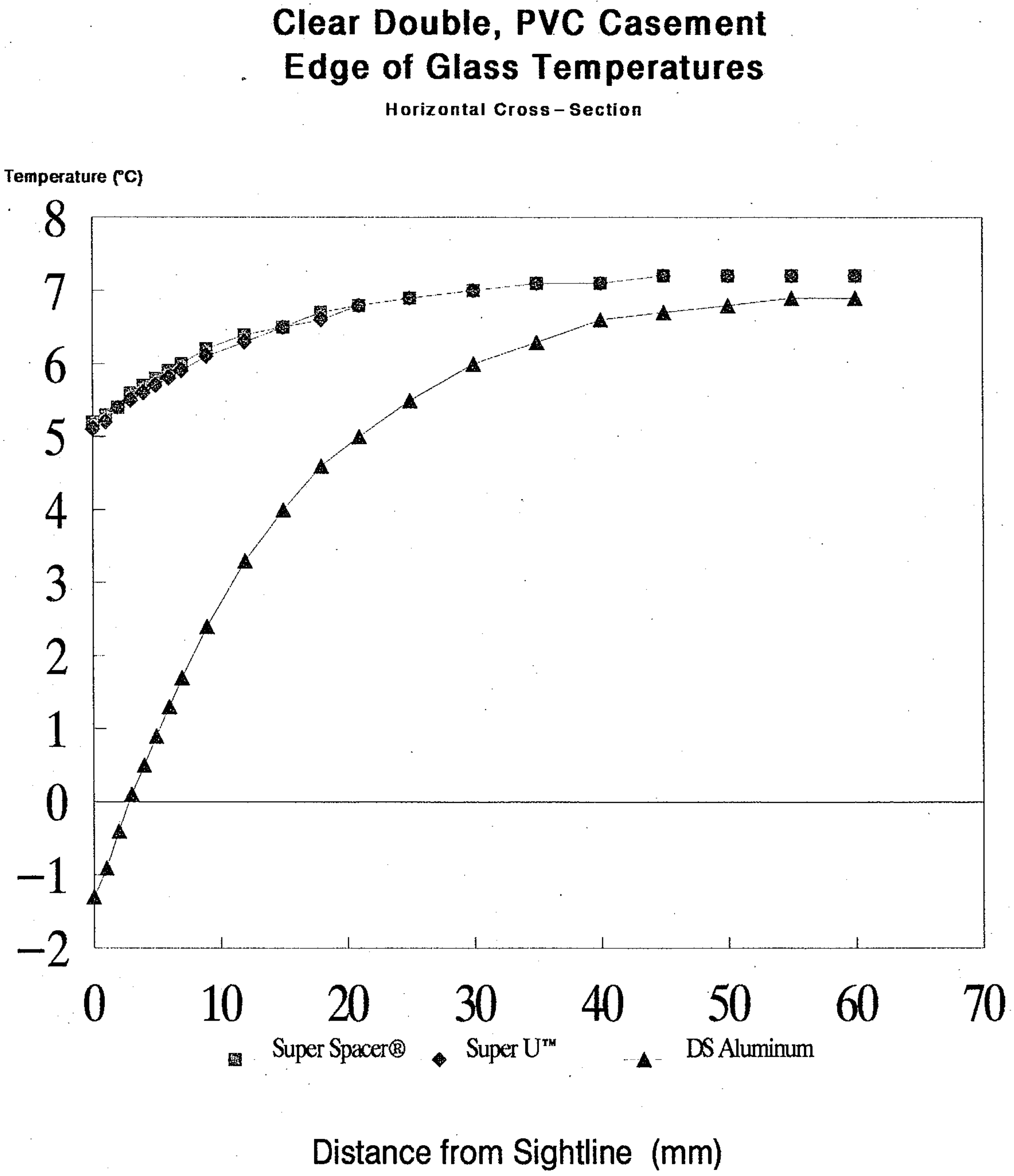


Figure 8 Horizontal Temperature Profiles: Super U^{TM} Spacer

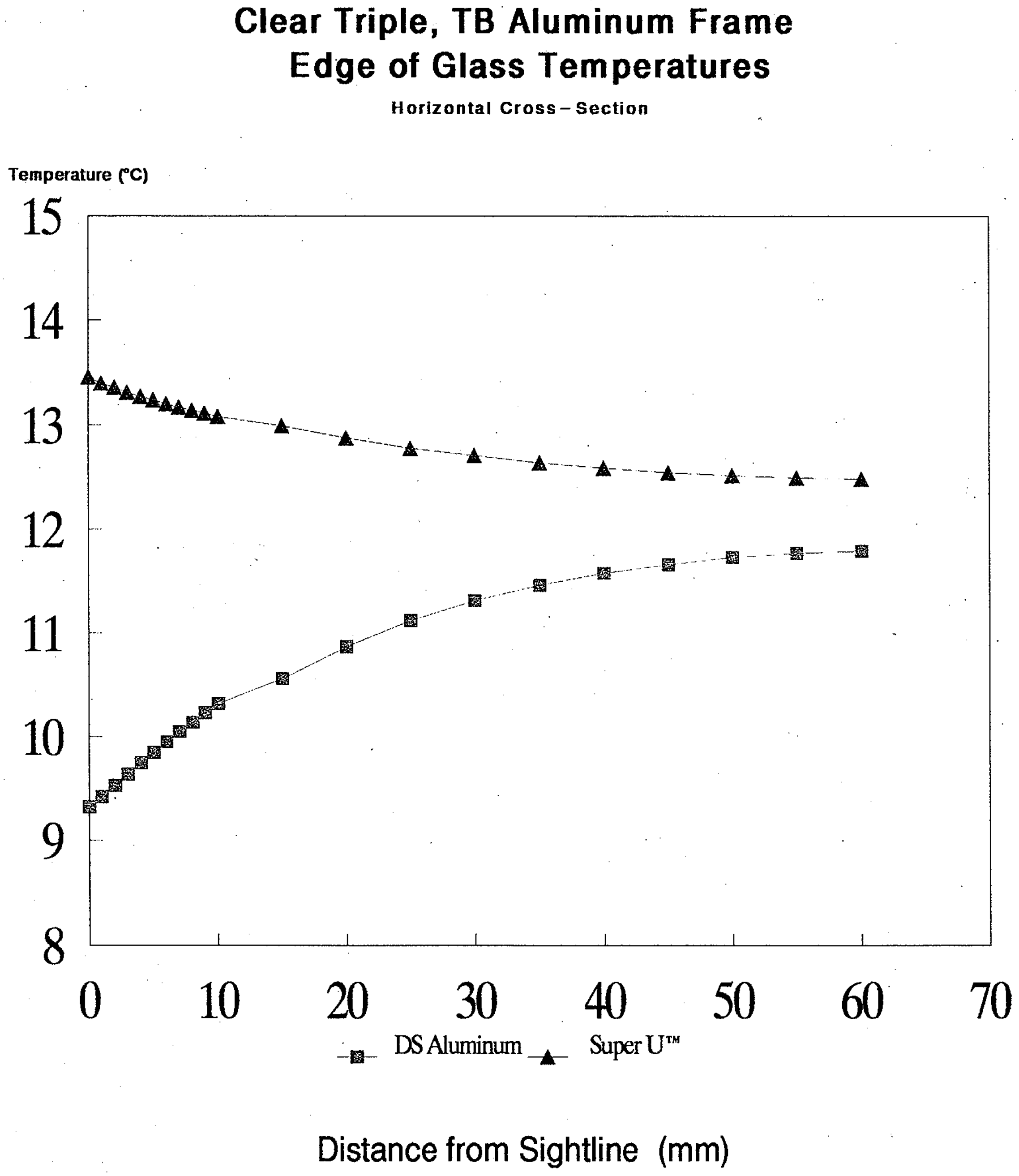
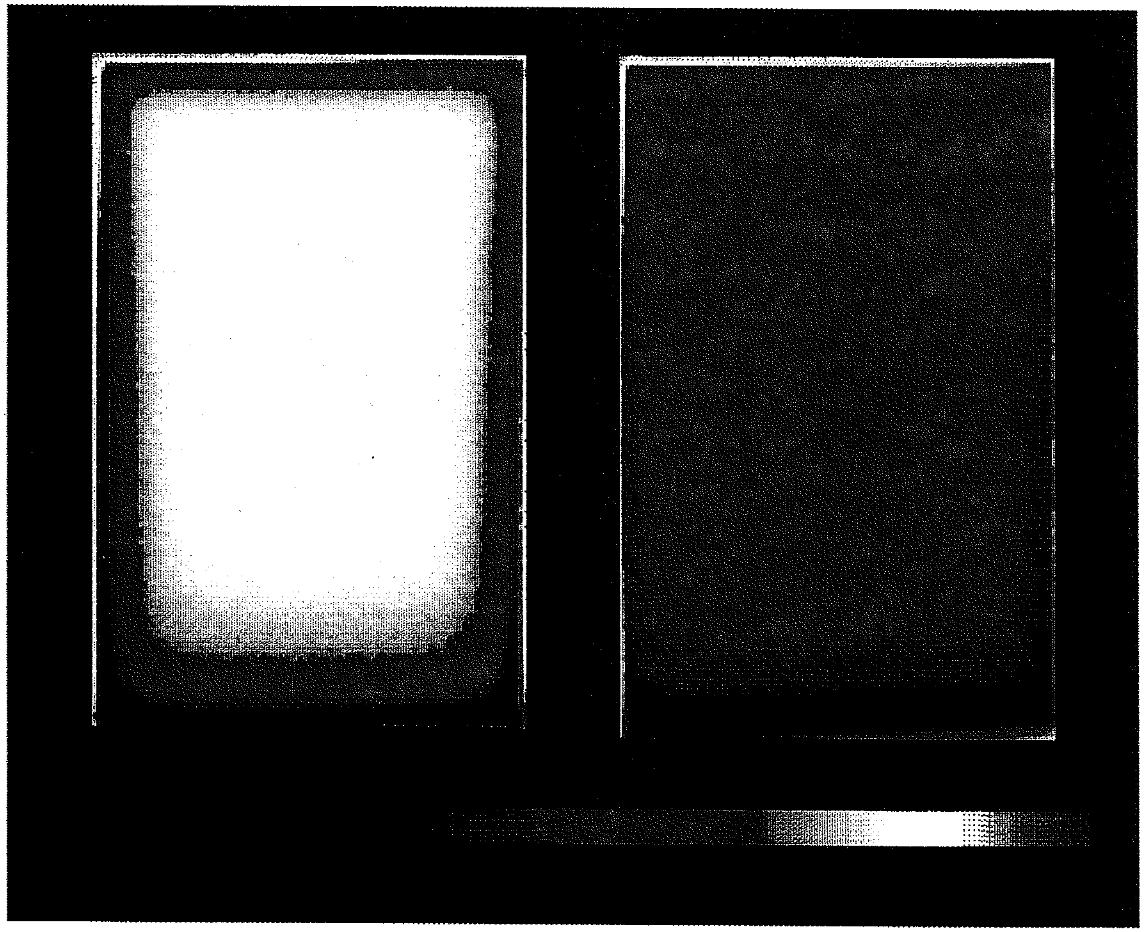


Figure 9 Horizontal Temperature Profiles: TB Aluminum Frame



Quad
Super Glass

Triple
Clear with Super Spacer®

Figure 10 Comparative Thermographic Image: SuperGlass vs. Super Spacer® Triple

Given previous NRC research on temperature index, it is known that condensation resistance data can be linearly interpolated from one test condition to another and so it is therefore recommended that for thermographic testing, the required test temperature condition should be less severe and a temperature of -10°C is recommended.

(iv) In-house Thermographic Testing of Narrow-Width Triples

Although the thermographic test program was not fully complete, a limited test program was carried out to evaluate the condensation resistance of the narrow-width triple-glazed units. The following four IG units were evaluated:

1. A low-e, argon-gas filled double-glazed unit with a 3/4" cavity space
2. A plain narrow width, argon-filled triple-glazed unit with 3/8" cavity spaces.
3. A plain narrow width, krypton-filled triple-glazed unit with 3/16" cavity spaces.
4. A plain regular triple-glazed unit with two 5/8" cavity spaces.

All four Super Spacer® units measured 14" x 20" and had approximately the same center-of-glass U-value. Three cross comparative tests were carried out at a test temperature of -10°C. The narrow-width argon-filled triple remained in the mask wall as a reference and was compared to the other three units. Various thermographic outputs were generated including vertical cross-section temperature profiles through the sealed units. The data was analyzed with the assistance of the Center of Building Diagnostics, Cantech (Ottawa) using the TPI Image software program. The reference unit test results were cross compared and good agreement was achieved between the three data sets indicating that comparison between different tests is valid.

The vertical surface temperature profiles of all four units are shown in Figure 11 and many observations can be made from these profiles. Because of convective-flow within the double-glazed unit, there is a large temperature difference between the top and bottom sightline temperature measurements. The double-glazed unit also exhibits the greatest temperature change over the center-of-glass region due the wide pane spacing and large temperature difference between the two glass lites which allows a great deal of convection to occur. For the regular triple-glazed unit, the top to bottom center-of-glass temperature difference is reduced because there are two cavities each with a smaller temperature difference between the glass lites. The two cavities with their smaller convection driving forces act to dampen convection.

Also, despite the fact that for the regular triple unit, the conductive path through the spacer is longer, the bottom edge temperatures for the regular triple and narrow-width triples are approximately the same indicating that the narrow cavity spaces must be effective in suppressing convection-flow. These results are discussed in more detail in a recent Edgetech Newsletter (Vol. 4, No. 2) article "Thermographic Testing Heralds Advent of Narrow-Gauge Triples" (See Appendix F).

(v) Thermographic Testing of Full Scale Windows

Two full scale windows were tested in the enlarged cold chamber both to test the enlarged cold chamber setup and to investigate the issues involved in testing full scale windows. However,

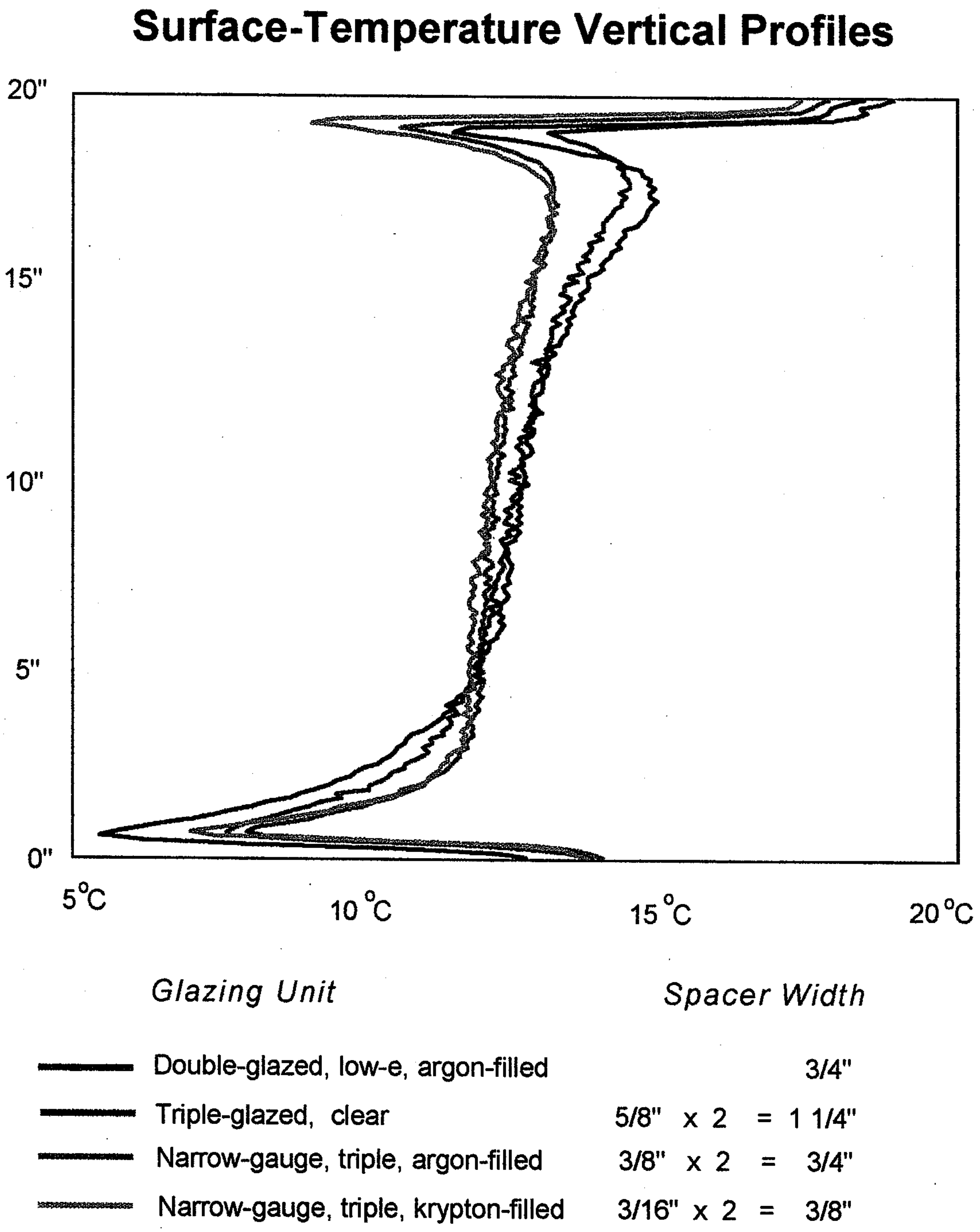


Figure 11 Vertical Temperature Profiles: Narrow-Width Triples

frame and hardware issues were still deferred until all issues involved in obtained glass surface temperature profiles were solved. The full scale testing was carried out at -5°C due to humidity concerns with the metal spacer. Due to camera limitations full scale windows must be imaged in sections and subsequently pasted together with a program such as TPI Image. A processed image of the a high performance casement is contained in Figure 12. The camera lens reflection has been processed out of the image. Figure 13 contains the full height vertical temperature profiles of a plain double-glazed aluminum spacer wood casement and a 2 low-e, gas filled, Super Spacer® triple-glazed fiberglass casement. Discontinuities in the other wise smooth center-of-glass profiles occur where the separate thermographic images are pasted together. These discontinuities are probably due to camera angle effects and further research is underway in this area.

2.7 Durability Testing

A major component of the research project involved carrying out comprehensive IG unit durability testing of the new Super U™ edge-seal design. Various durability tests were carried out including seal integrity, volatile fogging and gas retention.

(i) Edge Seal Integrity

For edge-seal integrity, various Super U™ edge-seal combinations were tested including different sealant options. For example, dual-seal Super U™/silicone sealant units were tested at Ortech International according to CGSB 12.8 test procedures. Dual-seal Super U™/polyurethane units were tested to ASTM E-774/E-773 procedures at Jim Spetz's Testing Laboratory in Wickcliffe, Ohio.

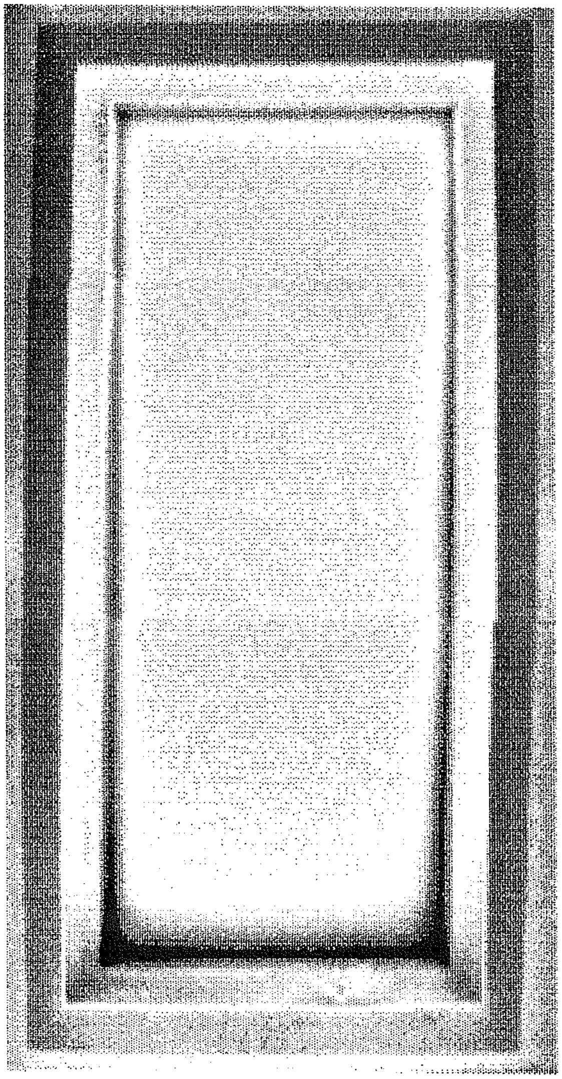
Various other Super U™/sealant combinations were tested by different sealant manufacturers including PRC and Morten International. In terms of Edgetech's in-house testing, various Super U™ edge-seal combinations have been evaluated including Super U™ backed by silicone sealant and by PRC's Permapol sealant. For edge-seal integrity, our key in-house test procedure involves high humidity testing with no temperature cycling but a constant high temperature of 60°C and a relative humidity of between 95 and 100 percent. Under these test conditions, Super U™ units consistently achieved at least six weeks exposure.

(ii) Volatile Fogging

A series of Super U™ units were tested in-house according to CGSB Volatile Fogging test procedures and no visual staining was observed.

(iii) Gas Loss Testing

At present, the only formally recognized gas loss test procedure is the DIN 1286. This test procedure is somewhat controversial in that the test procedure excessively stresses the sample unit so that even high-quality, dual-seal silicone units consistently fail the test. Super U™ /Permapol polysulphide sealant test units were sent to the Institut fur Fenstertechnik e.V. in Germany to



Fibreglass Casement Window
Triple Glazed
2 LOF low-e coatings
2 argon filled cavities
2 Super Spacer®

Figure 12 Thermographic Image of Full Scale High Performance Window

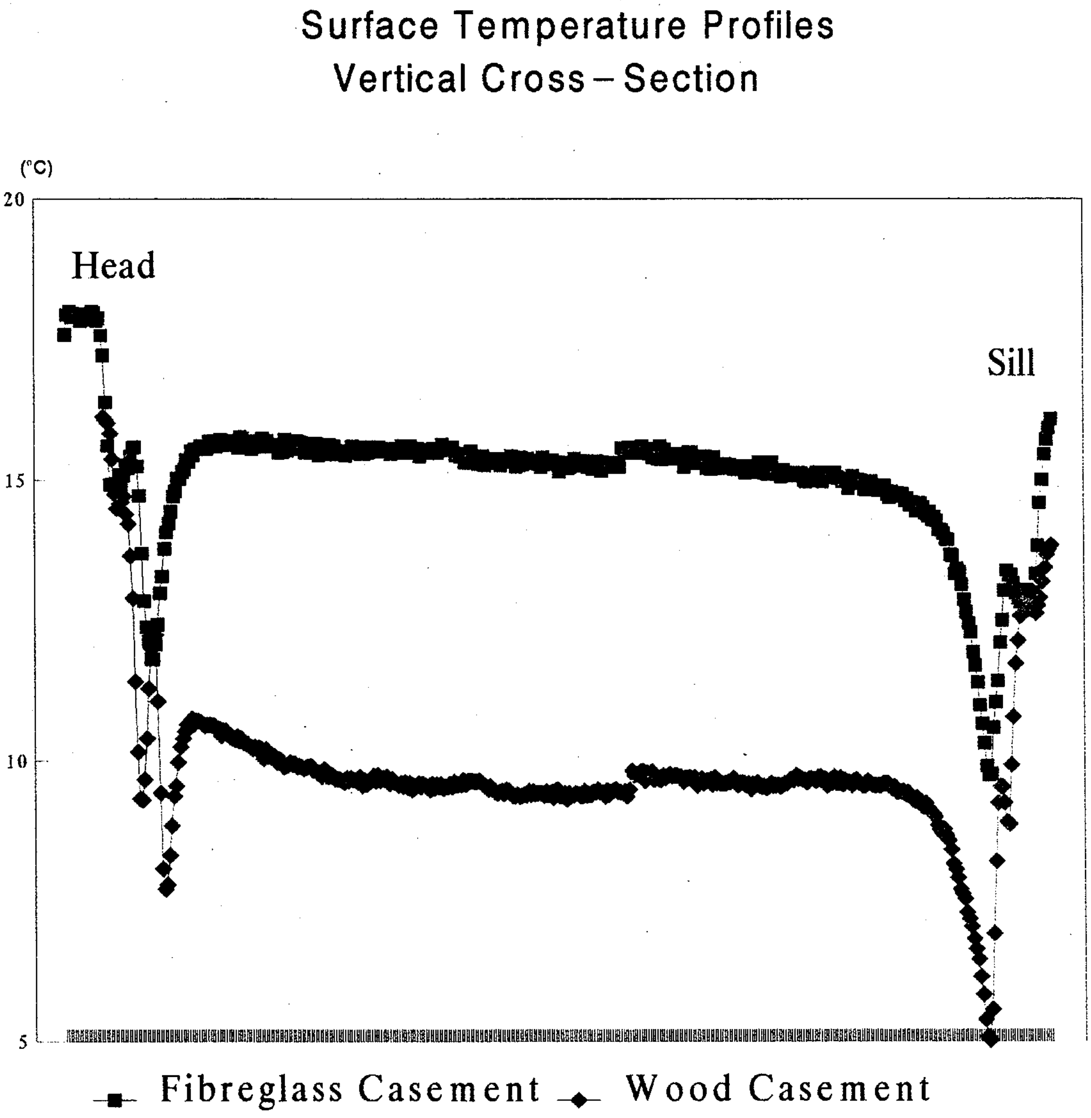


Figure 13 Vertical Temperature Profiles: Full Scale Windows

determine if unweathered units passed the gas-loss component test and these test units successfully passed the DIN gas-loss test. Additional Super U™ test units were sent to Germany to undergo the full-scale DIN weathering test procedures and again these test units successfully passed the DIN tests.

2.8 Field Trials

To test the effectiveness of convective-flow barriers in preventing edge-of-glass condensation, prototype units were installed in various high humidity buildings. Double glazed/convective-flow barrier units were installed in an Ottawa residence. Because of health reasons, the home owner maintained the residence at high humidity levels.

In terms of field performance, there were no surprises and the bottom-edge barrier units performed as predicted by our laboratory testing program. As shown in the photographs in Figure 14 under extreme high indoor temperature humidity levels and cold outdoor temperatures, there was condensation both at the bottom unit edge and also just above the barrier fence. However even though window condensation was not completely eliminated, there was a perhaps surprisingly positive response from the occupants of the field-trial house. Our assumption is that because they could clearly see the unique double-band condensation pattern, they could appreciate that even though the barrier-strip fence might not be the complete answer, it was obviously effective in reducing window condensation.

To demonstrate the thermal performance benefits of high performance triple-glazed warm-edge windows, Edgetech carried out a super-window retrofit project (See Edgetech Newsletter Volume 3, Number 4, Summer 93, "Edgetech's super-window retrofit throttles Victorian energy guzzler"). The project involved replacing existing double-glazed units with high-performance triples. A variety of different glazing designs were incorporated in the project including:

- regular width (1/2" cavity) low-e, argon gas-filled, double-glazed units
- regular width (1/2" cavities) low-e, argon gas-filled, triple-glazed units
- narrow-gauge (1/4" cavities) low-e, krypton gas-filled, triple-glazed units.

During the 1993/94 winter which is one of the coldest on record, daily observations were made of the glazing condensation patterns under varying indoor humidity conditions. These observations showed that triple-glazing outperformed double-glazing and that narrow gauge triples provided at least the same condensation resistance as regular width triples. At least for fixed windows, these high-performance triple-glazed windows essentially eliminated window condensation even with high indoor humidity and extreme exterior cold temperatures. However, particularly for certain types of operable windows (eg. single-hung sash), some bottom-edge condensation which is due in part to air infiltration, was observed.

2.9 Production Equipment and Trials

For the Super U™ edge seal design, three different types of production equipment were developed.

Double-Glazed Units
2" Barrier Fence in Right Unit
No Barrier Fence in Left Unit

Figure 14 Barrier Fence Field Trials

(i) Small-Scale Unit Production

For small-scale production of Super U™ units, a double-head, hand-tool notcher was developed. The new tool design was based on the wood hand-notcher developed for regular Super Spacer® production. Drawings for this tool are contained in Figure 15. The new product has been commercialized and is presently being used for the fabrication of Super U™ Cushion Edge units.

(ii) Residential Unit Production

In cooperation with FDR Design, a prototype semi-automated production machine, seen in Figure 16, was developed for laminating the new Super U™ spacer to rigid metal subframes. Known as the Warm-Wrap Machine, the prototype equipment design utilizes the same basic rotating motion that is used by conventional polyisobutylene application equipment. The new equipment design automatically senses the metal sub-frame corners and pre-notches the Super U™ foam spacer creating sharp and well-defined corners after spacer lamination.

This prototype equipment is currently undergoing full-scale plant trials at the AFG Plant in Winnipeg. A present design limitation of the prototype equipment is that it cannot conveniently be used to fabricate large-scale architectural units and its main future application will be for the fabrication of Super U™ stained-glass units.

(iii) Commercial Unit Production

For commercial-size units, Edgetech is working with Tools-for-Bending Inc. in developing Super U™ laminating equipment which can operate in conjunction with their existing metal-spacer bending equipment. Some initial equipment designs have been evaluated and full-scale prototype equipment is under development.

2.10 Thermal Performance Evaluation

The thermal performance of the two alternative convective-flow barrier designs was evaluated using both FRAME computer analysis and cold-chamber testing.

(i) Super U™ Edge Seal

Initially, the thermal performance of the Super U™ edge-seal design was optimized based on a series of FRAME computer analysis runs and this analysis study showed that the metal insert did not significantly downgrade the thermal performance of the edge-seal design. The accuracy of the Super U™ FRAME computer simulations was confirmed based on testing carried out by AFG at the National Research Council of Canada and also by the Kawneer Company at Architectural Testing in the United States.

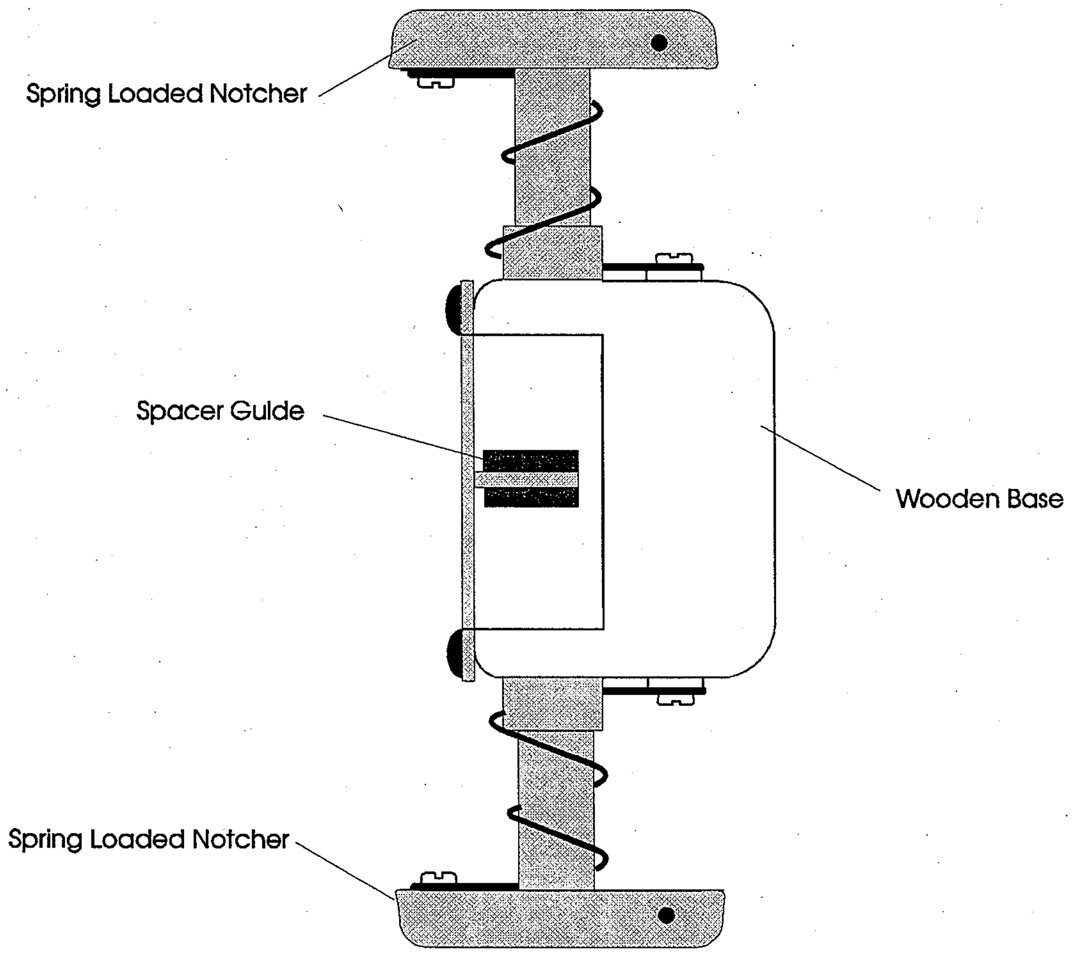
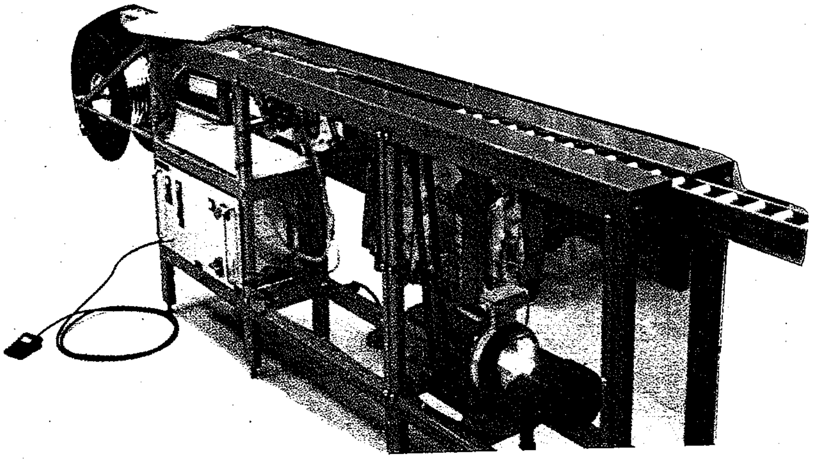


Figure 15 Production Equipment: Double Notcher



Warm Wrap :

- Applies Edgetech's Super-U spacing-and-desiccant system to rigid metal frame
- Includes foot-switch, Start, Stop, Pause Control Pushbuttons, Manual Feed, Notch & Cut
- Automatically adjusts to any size rectangle
- Accurately notches corners and cuts to length
- Convertible right-hand or left-hand design
- Rigid spacer flows normally through production, PIB application, Gas fill, Dual seal
- Vapor barrier is left intact around corner. Application motion is similar to PIB application
- Designed, serviced and manufactured in North America

Figure 16 Production Equipment: Warm-Wrap Machine

Our intention was to also submit Super U^{TM} test samples to the National Research Council for evaluation according to the NRC/EMPA edge-seal methodology. However as explained in a recent Edgetech Newsletter article (See Volume 4 No.1), some form of mix-up occurred and conventional metal-spacer units were evaluated instead. Consequently, the initial reported Super U^{TM} test results were incorrect and as a result, the testing program is being repeated.

(ii) Narrow-Width Triple-Glazed Units

Thermal performance advantages of narrow-width triples was established based on a series of computer analysis runs using both the FRAME and Window programs. The results of these studies are reported in part in a conference paper entitled "Triple Glazing: A Power Play for the 90's" that was presented at a recent World Conference on Advanced Housing for Energy Efficiency and Environmental Responsibility (See Appendix D). These analysis were also reviewed in a recently published technical article in Glass magazine, January 1994 titled "Warm-Edge Technology and the Triple-Glazing Revival: A Cold Climate Perspective On Super Window Commercialization" (See Appendix C).

One key conclusion of both these papers is that if the triple-glazed, narrow-cavity spaces required for convection-flow suppression are filled with argon or krypton gas, the overall window thermal performance is not significantly downgraded from regular width plain triple glazing. Moreover, the addition of a third glazing lite provides the same thermal benefits of incorporating a low-e coating within a double-glazed unit and assuming automated production equipment is used, there is no significant cost difference between the two glazing options.

3.0 CONCLUSIONS

As a result of the Phase Two research program, the following main conclusions were reached:

(i) Although the convective-flow barrier design is effective in reducing condensation, some bottom-edge condensation with double-glazed units can still occur under extreme exterior cold conditions and high interior humidity levels.

(ii) Double-glazed units incorporating bottom-edge barriers can be efficiently manufactured using the combination of a metal insert channel and a U-shaped silicone foam spacer.

(iii) The hybrid metal insert/U-shaped silicone foam design offers the option of conventional dual-seal durability while providing a high performance insulating edge seal.

(iv) Assuming the same warm-edge cavity width, slim-line argon or krypton-filled, triple-glazed units provide at least the same condensation resistance and can be manufactured at lower cost than low-e, argon gas-filled double-glazed units incorporating bottom-edge barriers.

(v) Narrow-width argon or krypton-filled, warm-edge triples provide the same condensation resistance as regular-width, warm-edge triples.

(vi) Specifically with plastic-frame windows, narrow-width argon or krypton-filled, quad-glazed units can provide further improved condensation resistance for extreme cold-climate locations.

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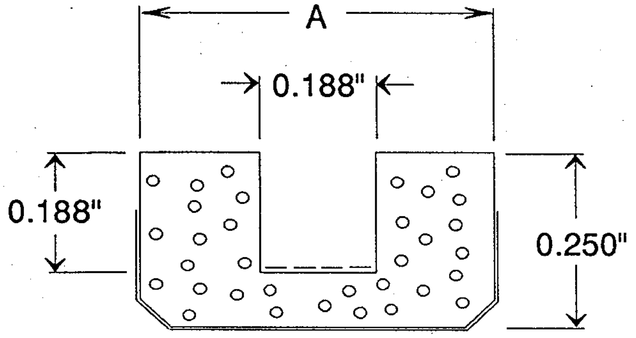
Appendix A: Product Information Sheets

Super U™ (3/16" Slot)

Product Information Sheet



Legend:

——— metallized mylar vapor barrier
— — — pressure sensitive acrylic adhesive

Spacer Widths (A)

Size	Imperial	Metric*
3/8" †	0.375	9.5
7/16"	0.438	11.0
1/2"	0.500	12.5
9/16" †	0.563	14.5
5/8"	0.625	16.0
11/16" †	0.688	17.5
3/4"	0.750	19.0
13/16" †	0.813	20.5

* Metric spacer widths are conversions to the nearest half millimeter from the imperial sizes.

† Sizes indicated require a 5,000 ft. minimum and an additional four week lead time on initial order.

The dimensions specified above are Edgetech's standard sizes. Other standard sizes and shapes are available in the following options:

Super Spacer®
Super U™ Cushion Edge

The spacer is made from a UV resistant, flexible silicone foam which incorporates approximately 40 percent, by weight, of desiccant fill material. The low-deflection desiccant system is comprised of 3A molecular-sieve material with a small percentage of silica gel for limited solvent adsorption. Super U™ is produced with less than 1.5% moisture content by weight.

The silicone foam has a thermal conductivity of 0.83 BTU*in/hr/ft^2/F or 0.12 W/mC.

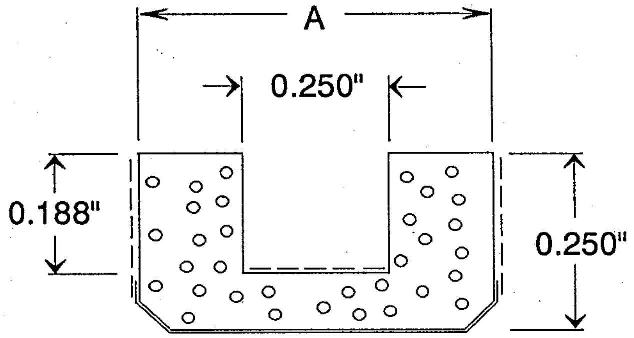
Neutral grey is the standard color. Super U™ is also available in four additional custom colors. For orders of 5,000 ft. or more, dark bronze, black, almond and white are available, however, these colors require an additional two week lead time.

For orders of more than 50,000 ft., Edgetech IG Ltd. can provide a custom color and/or size to your specifications. For custom colors and/or sizes, please contact Edgetech IG Ltd. for lead times and further details.

Super U™ is a custom option of Edgetech's standard Super Spacer® product and as such, some restrictions may apply.

Super U™ Cushion Edge (1/4" Slot)

Product Information Sheet



Legend:

——— metallized mylar vapor barrier
— — — pressure sensitive acrylic adhesive

Spacer Widths (A)

Size	Imperial	Metric*
3/8"	0.375	9.5
7/16" †	0.438	11.0
1/2"	0.500	12.5
9/16" †	0.563	14.5
5/8"	0.625	16.0
11/16" †	0.688	17.5
3/4"	0.750	19.0
13/16" †	0.813	20.5

* Metric spacer widths are conversions to the nearest half millimeter from the imperial sizes.
† Sizes indicated require a 5,000 ft. minimum and an additional four week lead time on initial order.

The dimensions specified above are Edgetech's standard sizes. Other standard sizes and shapes are available in the following options:

Super Spacer®
Super U™

The spacer is made from a UV resistant, flexible silicone foam which incorporates approximately 40 percent, by weight, of desiccant fill material. The low–deflection desiccant system is comprised of 3A molecular–sieve material with a small percentage of silica gel for limited solvent adsorption. Cushion Edge is produced with less than 1.5% moisture content by weight.

The silicone foam has a thermal conductivity of 0.83 BTU*in/hr/ft^2/F or 0.12 W/mC.

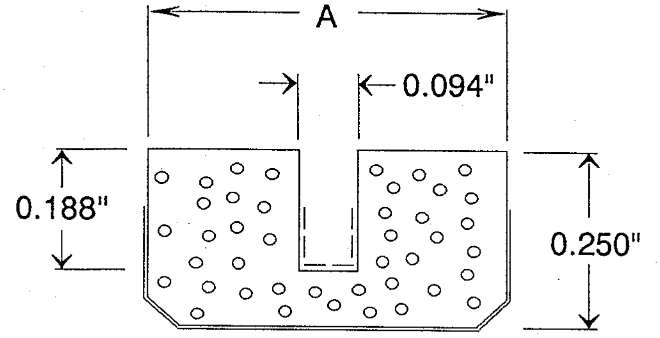
Neutral grey is the standard color. Cushion Edge is also available in four additional custom colors. For orders of 5,000 ft. or more, dark bronze, black, almond, and white are available, however, these colors require an additional two week lead time.

For orders of more than 50,000 ft., Edgetech IG Ltd. can provide a custom color and/or size to your specifications. For custom colors and/or sizes, please contact Edgetech IG Ltd. for lead times and further details.

Super U™ Cushion Edge is a custom option of Edgetech's standard Super Spacer® product and as such, some restrictions may apply.

Super U™ Triple (3/32" Slot)

Product Information Sheet



Legend:

——— metallized mylar vapor barrier

— — — pressure sensitive acrylic adhesive

Spacer Widths (A)

Size	Imperial	Metric*
3/8" †	0.375	9.5
7/16" †	0.438	11.0
1/2" †	0.500	12.5
9/16" †	0.563	14.5
5/8" †	0.625	16.0
11/16" †	0.688	17.5
3/4"	0.750	19.0
13/16" †	0.813	20.5

* Metric spacer widths are conversions to the nearest half millimeter from the imperial sizes.

† Sizes indicated require a 5,000 ft. minimum and an additional four week delivery on initial order.

The dimensions specified above are Edgetech's standard sizes. Other standard sizes and shapes are available in the following options:

- Super Spacer®
- Super U™
- Super U™ Cushion Edge

The spacer is made from a UV resistant, flexible silicone foam which incorporates approximately 40 percent, by weight, of desiccant fill material. The low–deflection desiccant system is comprised of 3A molecular–sieve material with a small percentage of silica gel for limited solvent adsorption. Super U™ Triple is produced with less than 1.5% moisture content by weight.

The silicone foam has a thermal conductivity of 0.83 BTU*in/hr/ft^2/F or 0.12 W/mC.

Neutral grey is the standard color. Super U™ Triple is also available in four additional custom colors. For orders of 5,000 ft. or more, dark bronze, black, almond and white are available, however, these colors require an additional two week lead time.

For orders of more than 50,000 ft., Edgetech IG Ltd. can provide a custom color and/or size to your specifications. For custom colors and/or sizes, please contact Edgetech IG Ltd. for lead times and further details.

Super U™ Triple is a custom option of Edgetech's standard Super Spacer® product and as such, some restrictions may apply.

Appendix B: Draft IR Test Method

Preliminary Test Method for Measuring Fenestration Surface Temperatures Using Infrared Techniques

Draft 2 **August 1992**

Prepared by: David Sargent, Edgetech I.G. Ltd. and
Dag Holmsten, Total Vision

1.0 Purpose

To specify a procedure for measuring fenestration surface temperatures using infrared techniques.

2.0 Scope

This standard test method provides requirements and guidelines and specifies calibration procedures required for the measurement of surface temperatures of fenestration systems using infrared techniques.

3.0 Definitions

Background Reflection is infrared ambient radiation being reflected from the surface of the measured object. Most cameras have a function that compensates for diffuse background reflection.

Long Wave, in general, refers to the 8-12 (or 8-14) um wavebands in the electro-magnetic spectrum.

Short Wave, in general, refers to the 3-5 um wavebands in the electo-magnetic spectrum.

Specular Reflection is the reflection from a specific source such as the camera operator or lights. The actual shape of the reflected object can usually be seen in the surface temperature map.

Surface Emissivity is the object's imperfect ability to emit thermal radiation as compared to a perfect emitter or a black-body radiator. This value must be used as a correction factor since all infrared cameras otherwise assume the window is a blackbody.

Transmittance is the transmission of infrared radiation through the object of thermographic interest at a given wavelength.

4.0 Equipment

4.1 Thermographic Camera

Comment: *Work is ongoing with both long wave and short wave systems to determine their suitability for this test. At this time, both long wave and short wave systems appear to be able to perform this test. Resolution and other features of individual models appears to be a much more important criteria than wave length. Once validation is completed acceptable IR cameras should be specified here.*

4.2 Environmental Chamber

Comment: *The environmental chamber is a very critical piece of equipment for infrared data acquistion. Rigorous temperature and humidity control are needed as well as extensive shielding of any heat sources. Requirements for the environmental chamber must be specified here.*

5.0 Method

5.1 Thermographic Camera Calibration

During the test, verify that the camera is calibrated correctly by the use of an opaque test object mounted in the test mask of a known and highest possible emissivity. The temperature (obtained by thermocouple measurement) should be set at a value at least 2 degree C colder than ambient. Close to it, but surrounded by air, should be mounted a diffuse reflector providing ambient air temperature radiation to the IR-scanner.

5.2 Specimen Preparation

The fenestration product's warm side surface must be clean and dry. The dryness must be obtained by lowering the humidity of the warm side chamber, not by wiping the surface dry at the time of data acquisition.

5.3 Chamber Conditions

The temperatures of the warm and cold side must be maintained to within 0.2 degrees C at all times during the test. Film coefficients must also remain constant during the test. The specimen must be maintained at the desired temperatures and with the desired film coefficients for 3 hours for equilibrium to be reached.

5.4 Eliminating Reflections

The warm side surface of the fenestration product to be tested must receive uniform diffuse radiation from the warm side chamber. In order to achieve this uniform diffuse radiation, it is necessary to shield the test fenestration product from any walls (including the ceiling and floor), lights, equipment, etc. that are not at a uniform temperature. Warm side heating, cooling and dehumidification equipment must not introduce air directly onto the surfaces that emit radiation to the test fenestration product.

Initial calibration experiments should be undertaken at the construction stage of the mask wall and periodically thereafter to insure that there are no reflections and that the film coefficients are uniform. These calibration experiments consist of testing two identical units side by side. The units should be simple double glazed or single glazed units that will give simple temperature profiles. Comparison of these profiles will enable the determination of any flaws in screening or film coefficients.

5.5 Data Acquisition

A preliminary temperature profile of the window should be acquired to insure that the test conditions have been met. Any deviation from a symmetric profile (see Figure 1) must be due to the fenestration product itself, not due to reflections, air infiltration or non-uniformity of test conditions (chamber temperatures or film coefficients).

5.6 Surface Emissivities

The emissivities and transmission characteristics of all materials in the tested fenestration product must be known in order to calculate the surface temperatures of the fenestration product.

5.6.1 Transmission Verification

When the exact spectral range of the IR-scanner is unknown or known to include response below (at shorter wavelengths than) 5 microns, the following verification is required. The verification must be repeated for each new window-type/assembly to be tested.

1. Before installing product in cold chamber, position an object at least 10 degree C warmer than ambient 1 meter in front of the infrared scanner and note its average temperature. Detailed measurements are not necessary. Make sure the thermal image of the object is well focused.

2. Position window to be tested between object (no contact!) and scanner. If thermal image of object remains on screen after scanner has been set to window average temperature, scanner is unsuitable to test this product. (Temperature variation of less than 0.1 degree C could be accepted)

5.6.2 Emissivity Verification

Comment: *Three possible methods exist to determine the individual material surface emissivities and are listed in the options below. One of the options must be chosen for the final test method.*

Option A: Blackbody (Preferred Method)

The following method is recommended due to the potential errors that often will be introduced using the thermocouple procedure (Option B).

1. Only Infrared Cameras with a field-verified emissivity measurement inaccuracy of less than 1% can be used. (If the stated accuracy of the system is 2 degree C at an emissivity of 1 and ambient temperature, this means roughly 2% temperature measurement accuracy. Divide by the ratio of isotherm units per degree C change in temperature to get measurement inaccuracy). Note that the sought inaccuracy value refers to surface temperatures ranging from 20 degrees C to -10 degrees C.

2. Perform camera calibration test (5.1).

3. Select an area in the middle of the window and make an area temperature average measurement (2"x2" area min.).

4. Apply high emissivity paint to a small surface in the middle of the same area (min. 1"x1" surface area). Emissivity must be greater than 0.95 and so verified with the scanner used. Wait for a minimum of 5 minutes.

5. Repeat the measurement but this time in three areas:
   a. only the painted surface, with the emissivity correction (emissivity of paint).
   b. only the unpainted 1"x1" surface in proximity to the paint.
   c. of exactly the same area as in 3.

6. Change the emissivity setting to get exactly the same temperature read out in 5c as in 3. Wait 5 minutes and repeat the measurement to make sure the value has not changed.

7. Now only measure the area in 5b. Adjust the emissivity setting until the output exactly matches the value in 5a. Make sure the emissivity value obtained is lower than the value obtained in 6 and lower than the value of the paint. If not, the paint is inappropriate or there is reflection interference. Make adjustments and repeat the procedure.

8. The emissivity value obtained in 8 can now be used for all glasses of exactly matching surface composition.

Option B: Thermocouples (General Method)

1. Use thermocouples of equal and very high quality to measure temperature of two arbitrary points on glass (once cooled and at stable temperature).

2. Perform camera calibration test (5.1).

3. Identify first glass measurement point in thermal image and measure with spot cursor or isotherm.

4. Adjust emissivity value until scanner measurement coincides with thermocouple reading.

5. Move cursor (isotherm) to second point. Read-out should now correspond to thermocouple measurement without additional emissivity adjustment.

6. Use obtained emissivity value in all further measurements.

Option C: Default Emissivities/Separate Test (Easy Alternative)

When the test object contains standard materials known to match the below list, the following default emissivities may be used:

Uncoated (interior surface) glass	eg. 0.90

5.7 Temperature Map

The scanner is now ready to make measurements. A minimum of 10 complete images taken at 5 minute intervals should now be stored digitally or on a calibrated analog video.

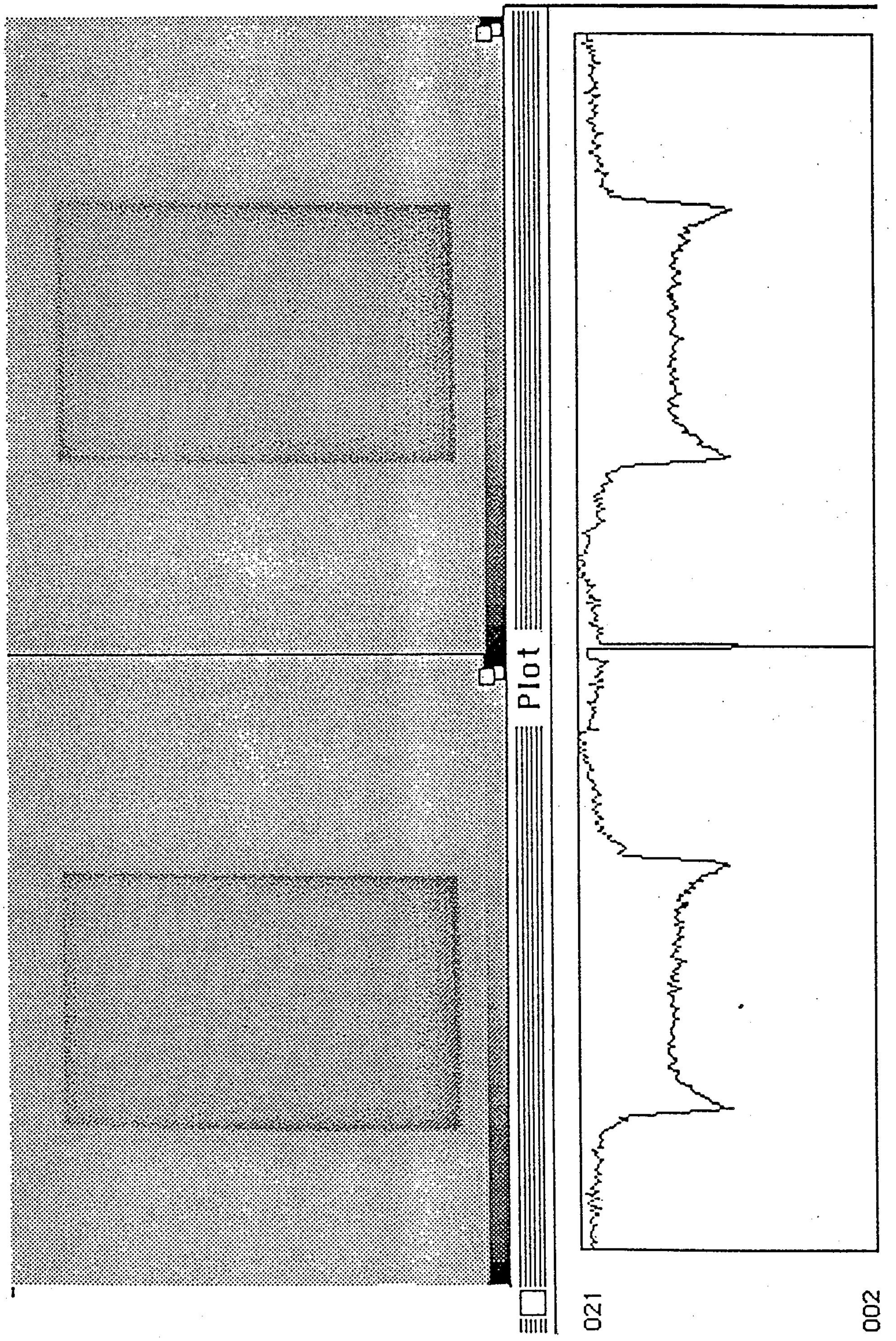
6.0 Reporting of Results

Temperature maps can be presented in many ways, but should as a minimum contain:

1. Stepped gray or color image indicating clearly in attached scale lowest and highest temp in image.
2. Histogram indicating % of total surface glass area below a given critical temperature.
3. Specific cursors or isotherms indicating location and temperatures of five lowest temperatures.
4. Format: Any hardcopy format such as computer or video print, provided each step of color or gray scale is clearly discernible.
5. Log-Print-Out or Video recording of camera reading of references (5.1) at the time of each glass temperature measurement. Deviations of more than 0.5 degree C are unacceptable, whatever the cause.

7.0 Reference Publications

Figure 1:



Appendix C: Warm-Edge Technology and the Triple Glazing Revival: A Cold Climate Perspective on Super Window Commercialization

Warm-Edge Technology and the Triple-Glazing Revival

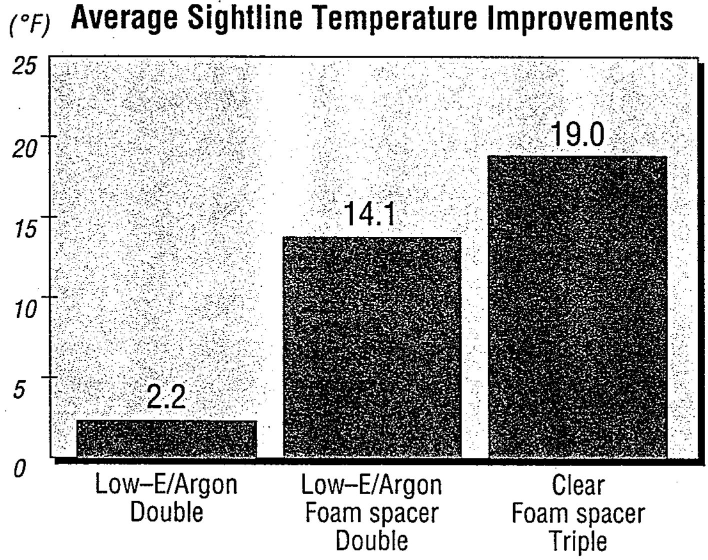
A cold-climate perspective on super-window commercialization

By Michael Glover

An important market trend for the window industry in the 1990s has been the commercialization of warm-edge technology. Especially in the past year, market acceptance of this new technology has been quite dramatic, and Edgetech estimates that by 1995 at least 30 percent of all windows manufactured in North America will incorporate some form of warm-edge product.

Figure 1

Average Sightline Temperature Improvements



Sealed units incorporated in PVC foam-filled frame. See "Analysis Study" p. 34.

Given its rapid market acceptance, warm-edge technology must have some strong consumer appeal, and the main inducement appears to be the expectation of condensation-free windows. For a high-performance warm-edge product, Figure 1, "Average Sightline Temperature Improvements," (see above) shows that the substitution of an insulating-foam spacer results in a 12-degree F average sightline improvement for a low-E, argon-filled, double-glazed unit. Although an impressive edge-temperature increase, it is important to note that this average sightline condition represents the window mid-point (halfway up the window) temperature and that, in reality, perimeter temperatures at the top and bottom are higher and lower respectively. As a result, some limited bottom-edge condensation may still occur if there are both high indoor humidity and cold outside temperatures.

The problem of bottom-edge condensation is primarily caused by cavity convection flow. Based on direct measurements using laser technology, it can be demonstrated that under cold outside conditions cavity gas in a double-glazed unit flows downwards near the cold exterior-glazing lite and upwards near the warm interior-glazing lite. As the gas adjacent to the cold exterior glazing descends, it becomes progressively colder and then at the cavity bottom it turns and comes into contact with the bottom edge of the interior glazing. Consequently, the interior lite's bottom edge is cooled by the coldest fill-gas within the double-glazed unit, and this is the reason why even with today's warm-edge products there may be still some bottom-edge condensation problems.

To prevent cold descending gas from directly contacting the interior glazing, some sort of convection-flow barrier is needed. Although Edgetech has investigated a number of alternative barrier designs, we have concluded that triple glazing is the simplest and most cost-effective solution. The reasoning is that the extra center glass lite, in addition to being a convection-flow barrier, helps to significantly improve thermal performance. As a convection-flow barrier, the triple-glazed center lite is extremely effective because it totally blocks the cold outer-cavity down flows and so prevents this very cold cavity gas from directly contacting the interior glazing bottom edge.

In Figure 2, "Bottom Corner Surface Temperatures," (see p. 34), these triple-glazing performance advantages are graphically documented by the four colored IR thermographic images. Comparing the thermographic images of the two double-glazed units, the dark blue color shows that the metal-spacer bottom edge is colder than the light blue of the foam spacer. In the case of the triple-glazed units, the light blue color shows that the metal-spacer bottom edge remains comparatively cold but that the foam-spacer unit is almost uniformly warm, indicating that there would be essentially no condensation.

Window frame developments

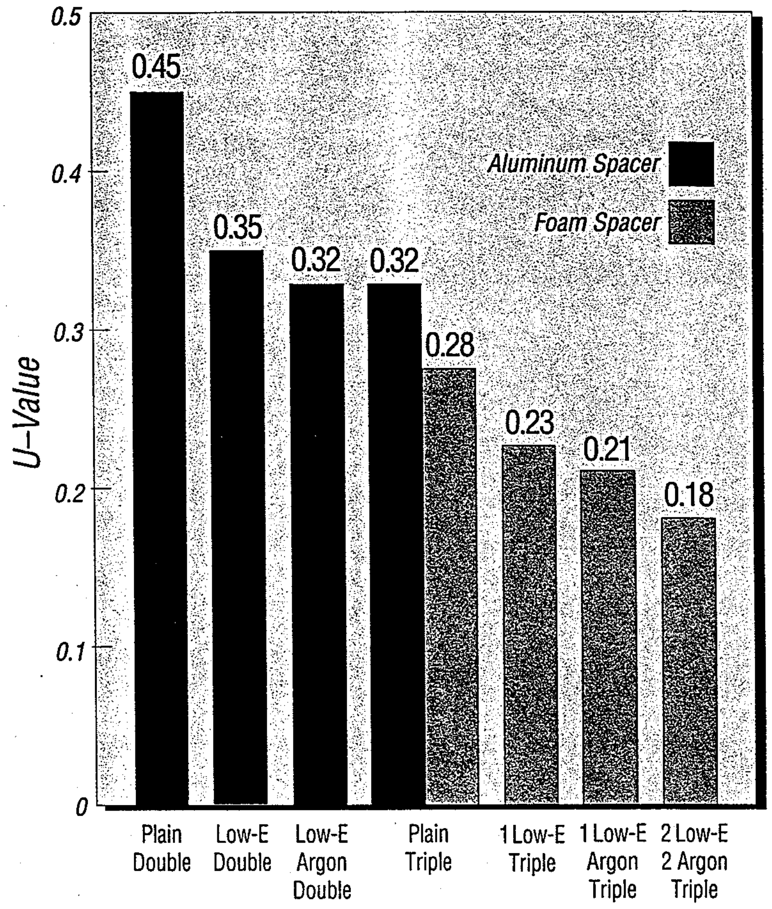
Because of their extra weight, triple units have traditionally been unpopular with window manufacturers. Although the weight issue remains a concern for the wood-window industry, it is much less important for the fast growing PVC window industry. This is because in fabricating the more robust profiles needed for the heavier triple units, a limited amount of additional plastic material is required and so extra material costs can be quite minimal.

In addition to rapidly increasing PVC window sales, the triple-glazing revival is also being helped by the emerging popularity of pultruded-fiberglass frames. Although somewhat more expensive than PVC extrusions, pultruded-fiberglass profiles offer enhanced structural strength and rigidity and are particularly suitable for supporting the heavier weight of triple-glazed windows.

To remain competitive with plastic-frame technology, the traditional wood window industry is looking for innovations in insulating glass technology. For example, one key development is krypton gas filling that provides for reduced 1/4-inch cavity widths (double- or triple-glazed) with no loss in thermal performance. When combined with the introduction of ultra-thin, chemically-tempered glass, which can be clearer and thinner than other glass, these two innovations together create lightweight, slim-line triples that can be installed in existing wood windows without any modifications to hardware or framing design.

Chart 1

Overall U-values: Double versus Triple Glazing



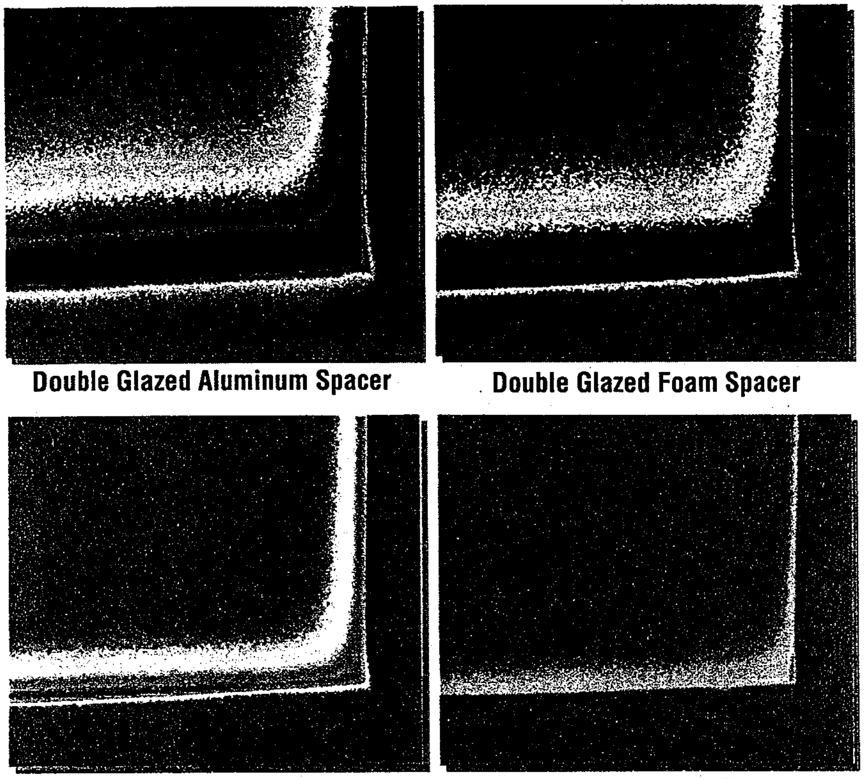
- Low-E, argon gas-filled, metal-spacer, double-glazed units have the same overall U-value as clear, metal-spacer, triple-glazed units.
- For double-glazed units, a low-E coating and argon gas-fill achieves a 0.13 U-value improvement, but, in addition, a further 0.14 U-value improvement can be obtained by upgrading to a high-performance warm-edge, triple-glazed unit.
- For triple-glazed units, the substitution of foam spacers provides a 0.04 warm-edge U-value improvement, a significant benefit when compared to other triple-glazing upgrades. For example, adding one low-E coating results in a 0.05 U-value improvement, upgrading with argon gas produces a 0.02 U-value improvement, while adding a second low-E coating only provides an additional 0.03 U-value improvement.

Double–glazed unit: 7/8" overall width dimension
Triple–glazed unit: 1 5/8" overall width dimension
Pyrolitic low-E E= 0.20

For North America's coldest regions, the performance benefits of triple glazing are very apparent and triple glazing has never lost its popularity. For example, in the Canadian province of Manitoba approximately 95 percent of all windows sold are triple-glazed. Given this dominant market share, suitable window frame technology has to be

Figure 2

Bottom Corner Surface Temperatures



Double Glazed Aluminum Spacer

Double Glazed Foam Spacer

Triple Glazed Aluminum Spacer

Triple Glazed Foam Spacer

These thermographic images were provided by CBD Ottawa.

readily available and it follows that there are no technical restraints preventing large scale triple-glazing commercialization in other North American markets.

Market factors

Because triple glazing is generally perceived to be more expensive, its widespread adoption may seem unlikely. However, a number of factors are driving the future market acceptance of this higher performance technology.

First, the addition of low-E and argon gas filling has very limited impact on edge-of-glass temperatures and, compared to high-performance doubles, clear (no coating) warm-edge triples offer superior condensation resistance.

Second, clear triples provide equivalent energy savings and can be produced for about the same price as high-performance doubles. Also, in

Triple Glazing: Thermal Performance Analysis

Study Methodology

To document the thermal performance improvements achieved with different triple-glazing upgrades, Edgetech recently completed a detailed computer analysis study. Starting from the base case of clear double- or triple-glazing, various options were evaluated, including different low-E coatings, gas-fill additions and warm-edge upgrades. Different overall unit-width sizes were also analyzed: $^{7}/_{8}$-inch for double-glazing; 1 $^{5}/_{8}$-inch for regular triple-glazing and 1-inch for slim-line units. For all units, $^{1}/_{8}$-inch thick glass was assumed. All the different unit designs were also incorporated into the same window-frame design consisting of a PVC foam-filled, residential casement window, NFRC standard size (2 ft. x 4 ft.).

For each glazing option, both overall window U-values and Canadian ER energy ratings were determined. Overall U-values for the different glazing options were calculated according to the NFRC 100-91 procedure, using Window 3.1 and Frame 2.2 computer programs. The Canadian Energy Ratings (ER) were calculated according to the CSA A440.2 standard, although center-of-glass U-values were calculated using the Window 3.1 program, as opposed to the Vision program specified by the Canadian standard. For air infiltration, a CSA A3 rating was assumed (0.55 m3/hr per m of crack length).

As background information, note that the Canadian ER rating is calculated by subtracting transmission and air-infiltration heat losses from overall solar gains. The single-number rating is calculated over the heating season and can be either positive or negative depending on whether the window provides a net heat gain or loss. For the ER rating system, key assumptions include: standard sizes for different window types; averaged Canadian weather data; averaged incident-solar radiation; and typical wood-frame house construction.

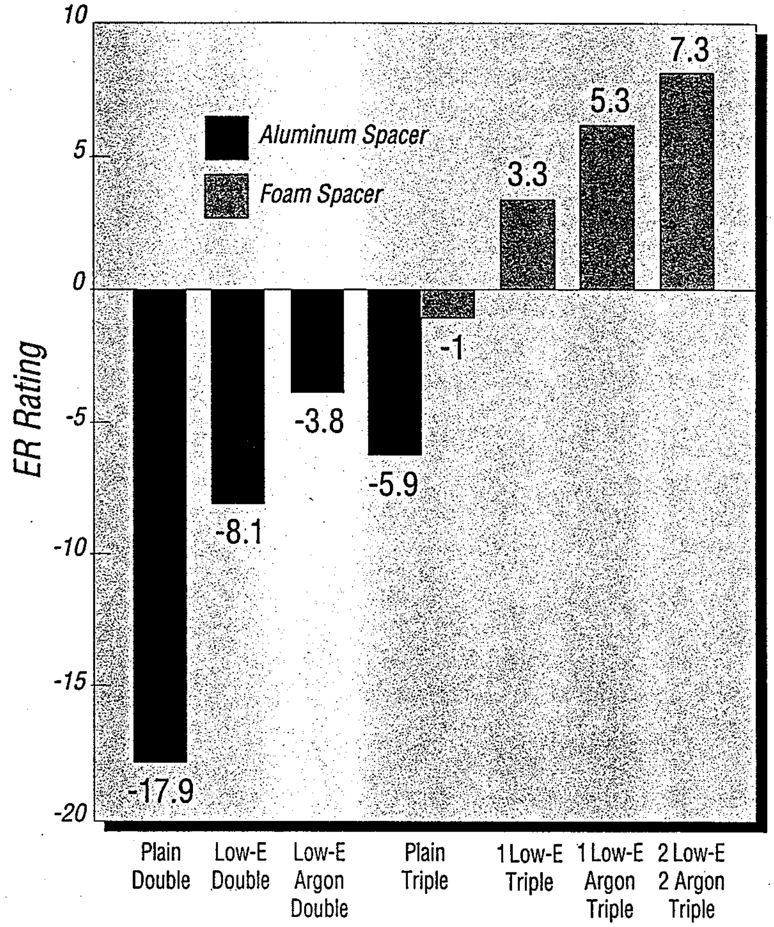
Because the Canadian rating system recognizes the importance of passive solar gains, the results can be somewhat controversial in that windows with the lowest U-value do not necessarily have the highest overall performance. Also, ER ratings only apply to the heating season and do not take into account air conditioning loads.

Performance results

For the different triple-glazing upgrades, the analysis results are summarized in Charts 1-5, with detailed conclusions listed.—*MG*

Chart 2

ER Ratings: Double versus Triple Glazing



- Upgrading from a plain metal-spacer, triple-glazed unit to a warm-edge, Super Spacer unit achieves a 4.9 W/m^2 ER improvement. In comparison, adding a low-E coating only produces a 4.3 W/m^2 ER improvement. Consequently, substituting a foam spacer provides greater overall energy savings than adding a low-E coating to triple-glazed units.
- Adding argon gas-fill provides a further 2.0 W/m^2 ER improvement, which is significantly less than the foam-spacer improvement but is the same as adding a second low-E coating to triple-glazed units.
- In terms of overall energy performance, adding a low-E coating to double-glazed units provides a 9.8 W/m^2 ER improvement. In comparison, adding a second low-E coating to triple-glazed units only provides a 2.0 W/m^2 ER improvement, or approximately 80 percent less energy savings.

Double–glazed unit: $^7/_8$" overall width dimension
Triple–glazed unit: $1^5/_8$" overall width dimension

the special case of clear slim-line, argon gas-filled triples (see the "Thermal Performance Analysis ," p. 34), there may even be some cost savings. In arriving at this somewhat surprising conclusion, the following assumptions are made: the extra thin-glass center lite is less expensive than a low-E coating; both units are argon gas-filled; edge-seal material costs are equivalent because cavity widths are the same; and the use of automated production equipment results in minimum additional labor costs for the triple-glazed units.

Third, the incremental cost of further upgrading to high-performance triples can be justified when cost-compared to other building energy conservation measures.

For example, in the case of new construction, upgrading wall insulation from R-20 to R-40 only achieves a 0.025 U-value improvement, or about 15 percent of the 0.14 U-value improvement provided by a triple-glazing upgrade (from 0.32 to 0.18; see Chart 1, "Overall U-Values," p. 33). Assuming a 15 percent window area, this means that both of these conservation measures reduce residential heat loss by about the same amount. However, taking into account solar gains and overall energy efficiency, high-performance triples provide a positive net energy contribution (ER 7 W/m^2), and with R-40 insulated walls, there is a negative heat loss (ER-3 W/m^2).

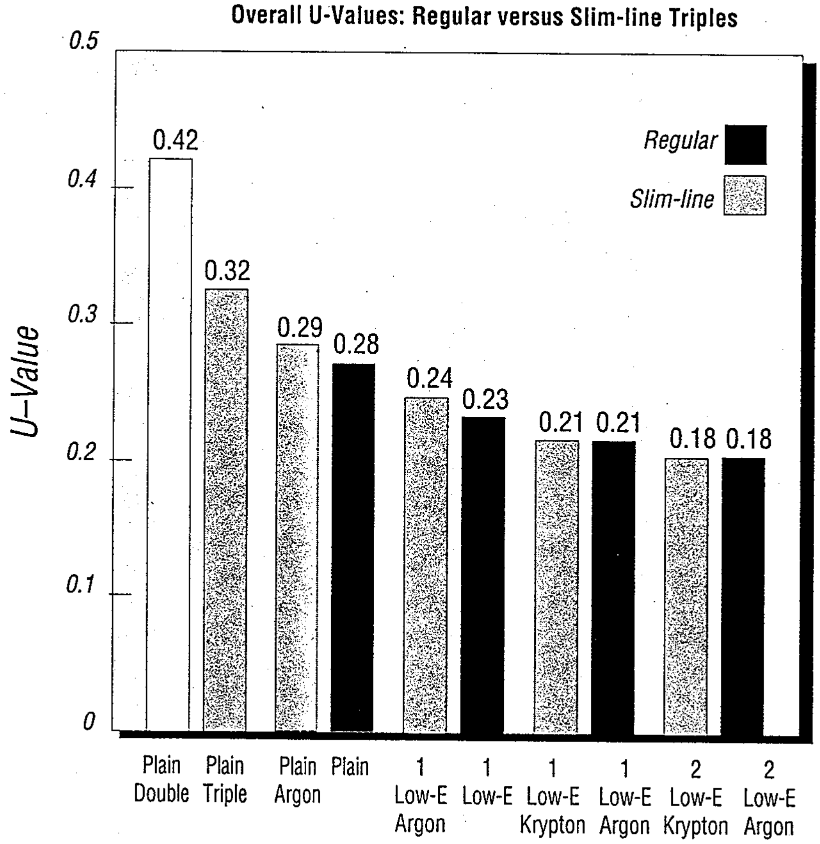
In addition to providing higher overall energy savings, triple-glazing upgrades are typically less expensive than the extra construction costs of R-40 walls. For energy-retrofit applications, these comparative cost advantages are even more apparent, because existing wall cavities are usually already filled and adding extra wall insulation is a very expensive proposition. In contrast, since existing windows are commonly replaced by consumers in the course of ongoing home maintenance, only the incremental costs have to be justified, making the triple-glazing retrofit a much more affordable option.

Fourth, if full advantage is taken of their high-performance potential, triples are also cost-effective for the new house construction market. As demonstrated by the Canadian Advanced House program, high-performance triples are a key component of a new generation of energy-efficient designs that consume 75 percent less energy than conventional houses. High-performance triples are also an important part of the new healthy-house design strategy.

Although still in the demonstration stage, these new healthy houses typically feature special types of year-round displacement ventilation systems that offer superior indoor air quality. The connection with window technology is that for these new displacement systems to operate satisfactorily, it is essential that the glazing provides high radiant-comfort surface temperatures, minimum heat loss and no window down-drafting. Only high-performance triple-glazing units meet these demanding criteria, and, if the healthy-house market takes off as anticipated, high-performance triples could find a strong niche market in new house construction.

Chart 3

Overall U-Values: Regular versus Slim-line Triples



- For window manufacturers, the key slim-line advantage is that both double-glazed units and triple-glazed units can be incorporated within the same window-frame profile.
- With plain slim-line units, the addition of argon gas improves unit performance so there is only a 0.01 U-value difference between slim-line and regular-width units.
- With high performance low-E glazing, the substitution of krypton gas further enhances slim-line performance to the same level as argon gas-filled, regular width units.
- For plain, slim-line, triple-glazed units (1-inch wide cavity, outside diameter) the addition of argon gas filling results in a significant 0.03 U-value improvement, which means that this upgrade is an exception to the general rule that gas filling is only worthwhile for units incorporating low-E coatings.

Slim-line Triple Units—1" overall
Regular Triple Units— $1^5/_8$" overall
Foam spacer edge seal

Edge-seal integrity

For this new high-performance triple market, the addition of low-E coatings and argon gas fills can accentuate edge-seal durability problems. There are three main concerns.

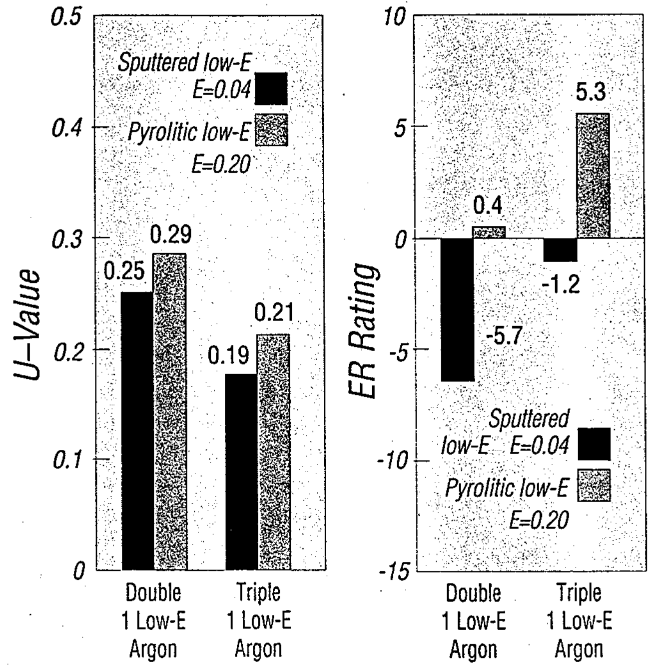
First, there are higher temperatures and pressures within the unit cavity that can result in increased sealant and glass stress. Second, these higher temperatures can cause thermal degradation and volatile outgassing from any organic plastic materials contained within the sealed unit. Third, long-term gas retention becomes more critical, especially for slim-line units where any gas loss can result in reduced thermal performance.

Typically, conventional edge-seal systems have not been designed for these more extreme conditions and so these products are not appropriate for this high-performance triple market. Consequently, in response to this emerging market need, various companies are developing new systems or significantly modifying existing edge-seal products.

Currently, many North American insulating glass manufacturers are

Charts 4 & 5

Sputtered versus Pyrolitic Low-E Coatings



- Compared to second-generation pyrolitic coatings (E = 0.20), the substitution of a solar-control sputtered low-E coating (E = 0.04) provides a 0.04 U-value improvement. However, for triple-glazed units with one low-E coating, the comparative sputtered-coating advantage is reduced to a 0.02 U-value improvement.
- Not surprisingly, with the Canadian ER rating system, pyrolitic coatings outperform solar control sputtered coatings with a 6.1 W/m² performance advantage for double-glazed units and a 6.5 W/m² performance advantage for triple-glazed units.

Double–glazed unit: 7/8" overall width dimension
Triple–glazed unit: 1 5/8" overall width dimension
Foam spacer edge seal

faced with making important investment decisions on what type of warm-edge production equipment they should purchase. Before making any long-term investments, the implications of the triple-glazing revival should be assessed. Specifically, IG manufacturers should keep in mind that warm-edge technology is more than just substituting a low-conductive product and that for high-performance triples, the spacer system must be deliberately designed to meet the more severe edge-seal conditions.

Super window commercialization

The widespread introduction of high-performance triples is the next logical step in the commercialization of super-window technology. (The term "super window" refers to any high-performance triple-glazed window featuring a well-insulated frame.) In addition to improved energy efficiency, this new super-window market is being driven by consumer demand for totally condensation-free windows.

For double-glazed windows, although low-E and argon gas fill improve center-of-glass performance, these upgrades do little to prevent perimeter-edge condensation. The further addition of low-conductive spacers significantly helps increase average edge-of-glass temperatures, but because of cavity convection flow, bottom-edge condensation problems may still persist under certain extreme conditions. As a countermeasure, the addition of a third center-glass lite blocks the cold outer-cavity down flows and, when combined with high-performance insulating spacers, the end result is significantly increased bottom-edge temperatures. The insertion of the extra center-glass lite also helps improve thermal performance and this improvement can be further upgraded by the addition of low-E coatings and argon gas fills. Although as the analysis study (see the "Thermal Performance Analysis," p. 34) documents, these center-of-glass upgrades do not provide the same substantial triple-glazing performance improvements that these features achieve with double-glazed units. In comparison, the substitution of insulating foam spacers results in quite substantial energy savings and so warm-edge technology is the most important triple upgrade.

In the '90s, consumers—emerging from the recession—are cautious about investing in energy efficiency and so it is easy to underestimate the pace of technological change in the window industry. However, some dramatic developments are occuring, with plastic-frame windows poised to gain a dominant market share. When combined with other strong market factors, super window commercialization is being accelerated, and I think high-performance, warm-edge triples will soon gain a significant cold-climate market share. ■

Michael Glover is technical director of Edgetech IG Ltd., a subsidiary company of Lauren International, New Philadelphia, OH, which manufactures Super Spacer, a leading warm-edge product. Formerly, Glover was head of the Super Window Program at the National Research Council in Canada. He has a degree in architecture from Liverpool University and for the past 20 years has worked in various technical fields related to building science.

Appendix D: Triple Glazing: A Power Play for the 90's

Technical Paper

Innovative Housing: A World Conference on Advanced Housing for Energy Efficiency and Environmental Responsibility

Vancouver, British Columbia, Canada

June 21-25, 1993

Triple Glazing: A Power Play for the 90's

Michael Glover, Edgetech IG Ltd.

Abstract

When low-e coatings and argon-gas fill were first commercialized in the early 1980's, part of their appeal was that the need for triple glazing was eliminated. A decade later "triples" are poised to make a significant comeback. This paper explains the changing market conditions that have led to this renewed interest in triple-glazing technology with specific emphasis on the new window labelling programs in North America. The performance improvement achieved with alternative double and triple-glazing options are documented and this analysis shows that a slim-line, argon-filled, triple-glazed, warm-edge unit out performs a conventional double-glazed unit with a low-e coating and argon gas fill. These slim-line units can be very cost effectively manufactured using a new edge-seal system developed specifically for triple glazing. Finally, the impact of this new high performance, triple-glazed technology on residential building design is briefly reviewed.

Triple Glazing: A Power Play for the 90's

Michael Glover, Edgetech IG Ltd.

1. Triple-Glazing Revival: Market Factors

When low-e coatings and argon gas fill were first commercialized in the early 1980's part of their appeal was that the need for triple glazing was eliminated. A decade later, "triples" are poised to make a significant comeback. There are six key market factors that have led to the renewed interest in triple glazing. These are:

(i) introduction of more comprehensive window rating systems;

(ii) growing popularity of PVC and pultruded fiberglass frame profiles;

(iii) development of new warm-edge technologies specifically for triple glazing;

(iv) lower cost solution than high performance double-glazing

(v) option for high performance glazing upgrade

(vi) warm-edge expectation of no condensation

(i) More Comprehensive Window Rating Systems

At outlined in detail in Section 2, one key market factor that is influencing the triple-glazing revival is the development of more comprehensive window rating systems in North America. By providing the consumer with detailed comparative information on window energy efficiency, the performance advantages of triple-glazed units are clearly highlighted.

(ii) Growing Popularity of Plastic Hollow-Profile Window Frames

A second market factor is the growing popularity of PVC and fiberglass windows in North America. Given the projected future shortage of timber, this trend towards plastic hollow-profile windows will likely accelerate in the next year or two. One key advantage of plastic-profile frames is that compared to wood, very limited additional material, and therefore costs, are involved in fabricating the wider frame profiles needed for triple glazing.

(iii) Development of New Warm-Edge Technologies for Triple Glazing

Traditionally using conventional metal spacer technology, triple glazed units were more expensive to manufacture than double-glazed units. Also with conventional metal spacer technology, there were higher rates of unit failure due to increased edge-seal stresses and the inability to visually check the integrity of the inner-lite seals. As outlined in more detail in Section 4, our company is developing a new edge-seal technology known as the Super U Triple which overcomes these traditional drawbacks and allows triple-glazing to be manufactured just as efficiently as double-glazed units.

(iv) Lower Cost Solution than High Performance Double Glazing

High performance double glazed units incorporating argon gas fill and low-e coatings are increasingly becoming the norm for the North American market place. For example, Andersen Windows who are the largest window manufacturer in the world, only produces windows incorporating high performance double glazed units. As documented in detail in Section 3, a plain triple-glazed Super U unit provides at least the same overall U-value improvement as a low-e, gas-filled, double-glazed unit. Given this starting base case and the costs involved in adding a low-e coating and argon gas fill, it can be more cost effective, particularly for PVC window manufacturers, to fabricate Super U Triples than high performance double-glazed units.

(v) Option for High Performance Glazing Upgrade

Given plain triple glazing as the base-case unit, the window manufacturer can offer a high performance upgrade using the same window profile. As detailed in Section 3, an overall R-7 window can be achieved with the addition of two low-e coatings and argon or krypton gas fill. These high performance triples have the potential for radically transforming cold-climate building design and the long-term market potential of these high triples should not be underestimated.

(vi) Warm-Edge Expectation of No Condensation

Recently, the benefits of warm-edge technology have been brought into focus through aggressive marketing programs by window manufacturers. As a result when consumers purchase high performance glazing units, they expect no perimeter edge condensation. However with double-glazed units under extreme winter conditions, some bottom-edge condensation may occur even with a high performance, warm-edge technology. This bottom-edge condensation is primarily due to convection flow within the cavity space where cold air descends down the inner face of the exterior lite creating a cold-air vortex at the unit-cavity bottom. The key advantage of triple glazing is that the center-glass lite prevents this outside cold-air vortex from reaching the interior glass lite and consequently even under high interior humidity conditions and severe cold temperature conditions, bottom-edge condensation is essentially eliminated.

2. New Window Labelling Programs in North America

In North America, various initiatives are underway to develop new window rating standards and labelling programs.

(i) Canadian ER Rating

In Canada, a single-number, window-energy rating system has recently been introduced. This ER rating is measured in W/m² and is calculated by subtracting transmission heat losses and air infiltration losses from overall solar gains. The ER rating can be positive or negative indicating whether the window provides a net heat gain or loss to the house. Key assumptions made in calculating the Canadian ER rating include: standard sizes for different window types; averaged Canadian weather data; averaged incident solar radiation, and typical wood-frame house.

For a more specific determination of a window's energy performance, the Canadian rating system also includes a procedure for calculating window energy performance for a particular project. This procedure known as the ERS rating takes into account such factors as building geographic location, window orientation, house construction type and window size. Just like light bulbs, ERS performance for a given window size can be measured in watts and for a specific house design, the "window power" provided can be easily calculated using simple spread-sheet computer programs.

(ii) NFRC Window Labelling

In the United States, a separate organization known as the National Fenestration Rating Council has been set up to develop a new window rating system and they have adopted a somewhat different approach to the Canadian strategy. Instead of a single number, the NFRC rating system provides performance data on key window parameters, including: overall U-value, solar heat gain coefficient (SHGC), air infiltration and condensation resistance. To provide an overall performance rating, it is planned that these individual parameter values will be plugged into a special "kiosk" computer program which will calculate overall energy performance for a specific location and house design. Although the NFRC approach may be more complex, this complexity is necessary because of the wide variations in the US climate. For locations as geographically varied as Florida and Alaska, it is simply not possible to develop a technically-valid, single-number rating system.

At present, only the NFRC test procedure for U-value has been formally implemented and based on the ASHRAE methodology, this new test procedure calculates overall U-value performance, including: center-of-glass, edge-of-glass and window-frame performance. The additional component performance standards will be implemented in the next few months, including a significantly upgraded condensation resistance test.

(iii) Upgraded Durability Standards

To help address consumer concerns regarding the long-term durability of these new high efficiency windows, initiatives are also underway to upgrade the existing durability standards. For example in Canada, the focus is on upgrading the existing insulating-glass durability standard CGSB 12.8. Three key concerns are long-term gas retention, volatile fogging from organic materials and possible long-term performance degradation of the low-e coating.

3. Performance Improvement with Triple Glazing

To document the performance improvement achieved with triple glazing, a detailed computer analysis study was carried out. Figure 1 summarizes the thermal performance improvements achieved with alternative double and triple-glazing design options including different low-e coatings, edge-seal designs and argon or krypton gas fill additions. All glazing options were incorporated in the same window frame design consisting of a PVC foam-filled casement window, NFRC standard size AA (2' x 4') with an 7/8" overall width for double glazing and 1 5/8" for triple-glazing.

Window performance data is given for four key component criteria: overall U-value, solar heat gain coefficient, Canadian ER energy rating, and coldest average edge temperatures.

Overall U-values for the different glazing options are calculated according to the US National Fenestration Rating Council NFRC 100-91 procedure using Window 3.1 and Frame 2.2 computer programs.

Solar heat gain coefficients (SHGC's) are calculated using the Window 3.1 computer program and Enermodal Engineering's Window Energy Rating spreadsheet. It should also be noted that the solar heat gain coefficient is for the overall window and that the glazing area is limited to 70 percent of the total window area.

The Canadian Energy Ratings are calculated according to the CSA A440.2 preliminary standard. Although it should be noted that overall window U-values are calculated using the Window 3.1 program as oppose to the Vision program as required by the Canadian standard. For air infiltration, a CSA A440.2 A3 rating is assumed (0.55 m^3/hr per m of crack length).

The coldest average edge temperature is the average edge temperature as calculated by the FRAME computer program. This average temperature does not take into account convection flow effects within the sealed-unit and so in practice, particularly for double-glazed units, bottom-edge glass temperatures will be lower.

In evaluating the results of the analysis study, the following five points should be noted.

(i) For a triple-glazed unit in foam-filled PVC frame, the substitution of an insulating foam Super Spacer® edge seal provides an overall O.04 U-value improvement.

(ii) In terms of overall U-value, a plain Super Spacer® triple-glazed unit has the same overall 0.28 U-value as a double-glazed, metal-spacer unit with a high performance, solar-control, low-e coating (e=0.04).

(iii) Although high performance, solar-control low-e coatings provide significant U-value improvements, these coatings also significantly reduce useful solar winter gains. As shown, the Canadian rating of a solar-control low-e, argon-gas filled, double-glazed, metal-spacer unit is ER -10.2, while the rating for a plain Super Spacer® triple is ER -1.0. This difference represents a significant overall performance improvement of 9 W/m².

(iv) The ER difference between a plain triple-glazed, metal-spacer unit and a Super Spacer® unit is 4.9 W/m². In contrast, the addition of a solar-gain low-e coating only increases the ER rating by ER 4.3, and so for triple-glazed units substituting a high performance foam edge seal can provide greater energy savings than adding a low-e coating.

(v) For very high performance triple glazing, the addition of one solar-gain, low-e coating provides a 0.05 U-value improvement and increases the ER rating from -1.0 to 3.3. The addition of a second low-e coating provides a further 0.03 U-value improvement and further increases the ER rating from 5.3 to 7.3. Given this limited performance improvement, it is questionable whether adding a second low-e coating is a cost-effective option.

To document the energy performance achieved with slim-line, triple-glazed units (1" overall dimension), further detailed FRAME computer runs were carried out for both triple and double-glazed units. In evaluating the slim-line results which are summarized in Figure 2, the following five points should be noted.

(i) Conventional wisdom dictates that argon gas filling is only worthwhile if a low-e coating has first been added. However, for slim-line, triple-glazed units with sub optimum cavity widths, adding argon gas fill can significantly improve thermal performance and is a very cost-effective option.

(ii) For a metal spacer, double-glazed units, the addition of a solar-gain, low-e coating and argon gas filling increases the overall window U-value by 0.12 and the ER rating by 13.9 W/m². In comparison for a slim-line triple, the addition of argon gas fill and a thin glass center lite combined with the substitution of an insulating foam spacer increases the overall U-value by 0.16 and the ER rating by 15.6 W/m².

(iii) As well as providing greater overall energy savings, the slim-line triple is also more economical to manufacture. For example in the case of a small window manufacturer in Canada, the cost of a low-e coating is typically about $0.90 per sq. ft. In comparison, the incremental cost of the thin glass sheet is about $0.30 per sq. ft. and the incremental cost of the warm-edge spacer is about $0.40 per linear ft. Given that labor costs are about the same, this means that compared to a high performance double, a slim-line triple-glazed unit can be produced at an approximate cost saving of $0.20 per sq. ft.

(iv) In the future, it is likely that the low-e coating price, particularly pyrolitic low-e coatings will be reduced due to the economies of large volume production economics. Although this means that a high performance double-glazed unit can be produced more economically, it also means that a high performance triple can also be more economically produced. In the case of an argon-gas filled slimline triple, the addition of a solar-gain low-e coating provides a further 0.05 U-value improvement and increases the ER rating by 4.8 W/m².

(v) With the substitution of the more expensive krypton gas, there is a further 0.06 U-value improvement and the ER rating is increased by an additional 4.1 W/m². It should be noted that the addition of a second low-e coating provides a further 0.03 U-value improvement. However, the Canadian ER rating is only increased by 1.0 W/m² and so, except possibly for north-facing windows, this additional energy-saving measure is hardly worthwhile.

4. A New Warm-Edge Product for Triple Glazing

To address the growing triple glazing market, our company Edgetech IG, is developing a new warm-edge glazing product known as the Super U™ triple. As illustrated in Figure 3, the new edge seal design consists of a flexible foam U-shaped profile with a continuous barrier film laminated to the back face and spacer sides. In one single application, the Super U™ triple spacer is wrapped around a thin center glass lite and is held in position by acrylic pressure sensitive adhesive incorporated within the center groove.

Compared to conventional triple-glazed units, there are three key advantages to this new edge seal design. First, the flexible foam profile cushions the thin inner glass from breakage. Second, the vapor barrier film is continuous between the inner and outer glass lites reducing potential moisture and inert gas transmission. Third, for dual seal units, the inner polyisobutylene seal is only applied on two sides, so quality assurance for edge seal integrity can easily be maintained.

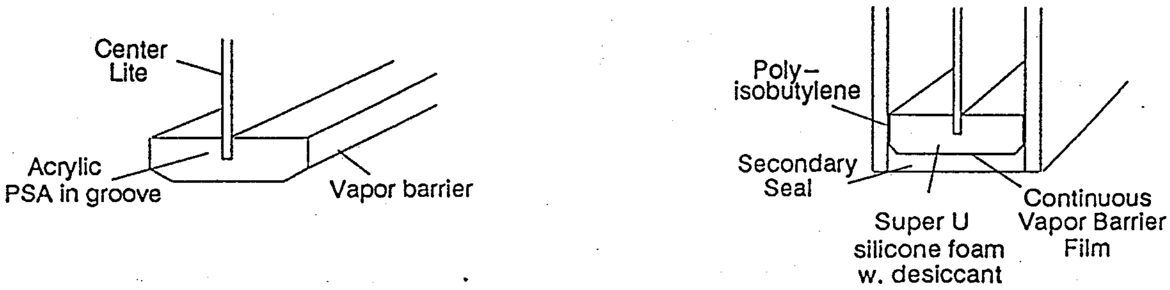


Figure 3 **Cross-section of Super U™ Triple**

5. Impact of High Performance Triple-Glazed "Super-Windows" On Residential Building Design

The development of high performance, triple-glazed "super-windows" can have a significant future impact on North American residential design for both new and retro fit applications.

For new R-2000 house construction, "super windows" can be more cost effective than super-insulated wall construction in upgrading building-envelope performance. For the even more energy efficient Advanced House projects, "super windows" can allow for the introduction of significant cost-saving innovations in integrated mechanical system design and this was demonstrated in the first Advanced House Project in Brampton.

For existing houses, "super windows" can also be a key component of radical retrofit strategies. Recently, our company sponsored a R-2000 Upgrade Demonstration Project where an existing 100 year old heritage house was radically retrofitted with high performance triple-glazed units and an advanced energy-efficient gas boiler for space and water heating. Although detailed monitored results are not available, initial feedback shows that monthly heating bills have been substantially lowered and that the goal of meeting the R-2000 performance standards for new construction has been realized.

	Window U–Value (Imperial)	Window SHGC	Coldest Edge Temperature (°C)	Canadian ER (W/m^2)
Double Glazed Units (O.D. = 7/8")				
Clear / Aluminum Spacer	0.45	0.54	–0.16	–17.9
Clear / Super Spacer®	0.42	0.54	5.36	–14.5
Low–e 0.20 / Argon / Aluminum	0.32	0.52	1.04	–3.8
Low–e 0.09 / Argon / Aluminum	0.30	0.46	1.28	–5.2
Low–e 0.04 / Argon / Aluminum	0.28	0.37	1.39	–10.2
Low–e 0.20 / Argon / Super Spacer®	0.29	0.52	7.67	0.4
Low–e 0.09 / Argon / Super Spacer®	0.26	0.46	8.14	–0.8
Low–e 0.04 / Argon / Super Spacer®	0.25	0.36	8.37	–5.7
Triple Glazed Units (O.D. = 1 5/8")				
Clear / 2 Aluminum Spacer	0.32	0.48	3.52	–5.9
Clear / 2 Super Spacer®	0.28	0.48	10.40	–1.0
1 Low–e 0.20 / 2 Super Spacer®	0.23	0.46	11.12	3.3
1 Low–e 0.09 / 2 Super Spacer®	0.22	0.41	11.34	1.2
1 Low–e 0.04 / 2 Super Spacer®	0.21	0.33	11.42	–3.6
1 Low–e 0.20 / 1 Argon / 2 Super Spacer®	0.21	0.46	11.36	5.3
1 Low–e 0.09 / 1 Argon / 2 Super Spacer®	0.20	0.40	11.53	3.2
1 Low–e 0.04 / 1 Argon / 2 Super Spacer®	0.19	0.33	11.71	–1.2
2 Low–e 0.20 / 2 Argon / 2 Super Spacer®	0.18	0.42	12.33	7.3
2 Low–e 0.09 / 2 Argon / 2 Super Spacer®	0.15	0.35	12.70	4.5
2 Low–e 0.04 / 2 Argon / 2 Super Spacer®	0.15	0.23	12.87	–3.0

Figure 1 Performance Comparison: Double v. Conventional Triple Glazing

	Window U–Value (Imperial)	Window SHGC	Coldest Edge Temperature (°C)	Canadian ER (W/m^2)
Double Glazed Units (O.D. = 1")				
Clear / Aluminum spacer	0.45	0.54	−0.06	−17.9
Low–e 0.20 / Argon / Aluminum	0.33	0.52	1.13	−4.0
Triple Glazed Units (O.D. = 1")				
Clear / Super U™	0.32	0.49	7.62	−5.6
Clear / 2 Argon / Super U™	0.29	0.49	8.08	−2.5
Clear / 2 Krypton / Super U™	0.27	0.49	8.54	0.8
1 Low–e 0.20 / 2 Argon / Super U™	0.24	0.47	8.73	2.3
1 Low–e 0.20 / 2 Krypton / Super U™	0.21	0.47	9.27	6.3
2 Low–e 0.20 / 2 Krypton / 2 Super Spacer®	0.18	0.42	9.72	7.3
Quad Glazed Unit (O.D. = 1")				
Super Glass® (Quad)	0.19	0.35	5.06	0.2

Figure 2 Performance Comparison: Double v. Slim–Line Triple Glazing

Appendix E: Convection-Flow Barriers for High Performance Glazing Units

CONVECTION-FLOW BARRIERS FOR HIGH PERFORMANCE GLAZING UNITS

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ABSTRACT

Condensation on windows has been greatly reduced by the introduction of various high-efficiency window components such as low-e coatings, low-conductive gas fill, insulating-foam spacers and energy-efficient window frames. In particular, the substitution of an insulating-foam spacer, helps reduce the cold-weather problem of bottom edge-of-glass condensation. However, our research has shown that although substitution of an insulating spacer substantially reduces conductive heat loss through the perimeter edge-seal, condensation can still occur particularly if there is extreme cold weather and high interior humidity levels. Further, our research has shown that these cold bottom-edge temperatures are in part caused by surface convective flow of the air or low-conductive gas within the sealed cavity space of the double-glazed unit.

In order to address this problem, our company has developed the new product concept of a convective-flow barrier. This barrier which is typically a transparent vertical fence is placed along the bottom edge of the glazing unit and the barrier prevents the cold-side convective flow from directly reaching the warm-side glazing sheet. Typically, the optimum height of this barrier is about two inches. This paper summarizes the preliminary results of our on-going R&D program and reports the results of our laboratory evaluation of different prototype designs. Our testing program involves cold-chamber testing, IR thermographic analysis and interferometric studies.

INTRODUCTION

Today when consumers purchase high performance glazing units, they expect that there will be no condensation on the window, However particularly in the first few months after the house has been occupied, the relative-humidity levels in the building can be well in excess of 50 percent and as a result of these high humidity levels, edge-of-glass condensation is a very common complaint.

As noted in the attached charts, center-of-glass temperatures are significantly increased with the addition of low-e coatings and argon gas fill. However, bottom-of-glass temperatures are only marginally improved. For example, in Figure 1 and 2, the charts show that in Winnipeg where the outside design temperature is -33°C, the center-of-glass temperature is 10°C while the bottom edge-of-glass temperature is around 0°C[1]. These cold bottom

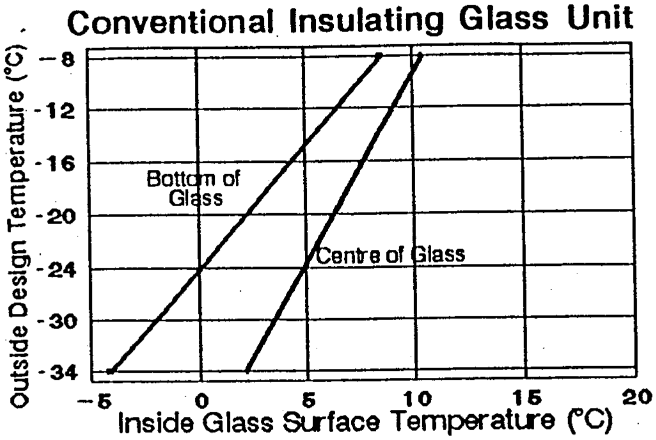


Fig. 1A Cold-weather, glass-surface temperatures

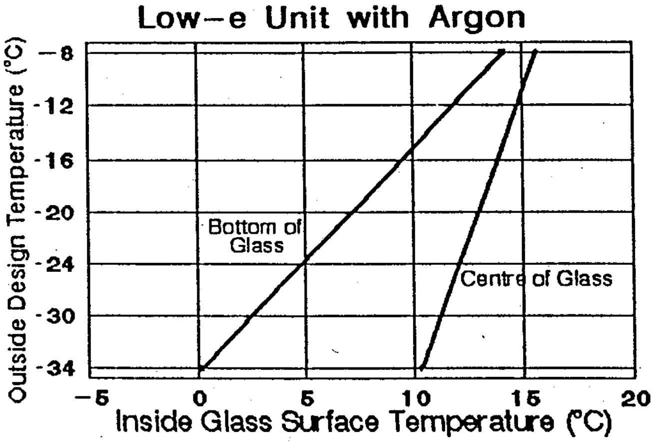
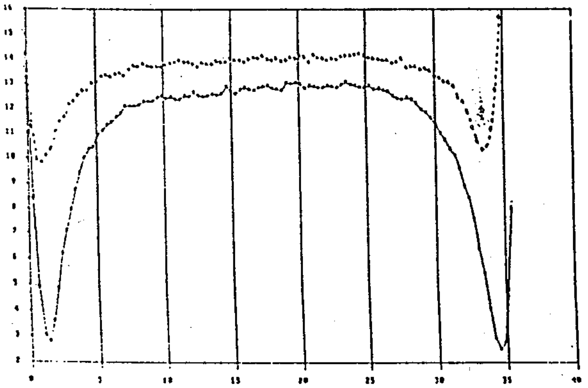


Fig. 1B Cold-weather, glass-surface temperatures



■ Metal spacer + Foam spacer
Warm side: 22.5°C Cold: -15°C

Fig. 2 Comparative Thermographic Analysis of Foam and Metal-spacer Edge Seals

edge-of-glass temperatures are caused by both conductive heat loss through the conventional metal spacer and also by convective flow within the sealed unit.

To reduce conductive heat loss through the edge seal, our company has developed a new type of insulating-foam spacer. As shown by the temperature profile in Figure 2, for a horizontal roof light, the substitution of a foam spacer increased edge-of-glass temperatures of a glazing unit by about 7°C at the test temperature of -15°C. The temperature profile lines were generated by computer software based on thermographic camera analysis carried out by Ortech International.

CONVECTIVE-FLOW BARRIERS

For vertically-installed windows, the warm-edge effect of an insulating spacer may be less apparent because of convective flow within the unit. As shown in Figure 3A under cold-temperature conditions, air or fill gas within the cavity space flows upward near the indoor glazing and downward near the outdoor glazing. As the cold gas descends it becomes progressively colder and at the bottom of the unit, the cold gas turns and flows across the bottom of the unit to the warm side causing a local cold spot at the bottom-edge.

In order to help prevent bottom edge-of-glass condensation, our company has developed the new product-design concept of a convective-flow barrier. As shown in figure 3B, this barrier which is typically a vertical-fence made from transparent sheet material is placed along the bottom edge of the sealed unit and effectively prevents the flow of cold air or gas across the bottom of the sealed unit from reaching the warm-side glazing.

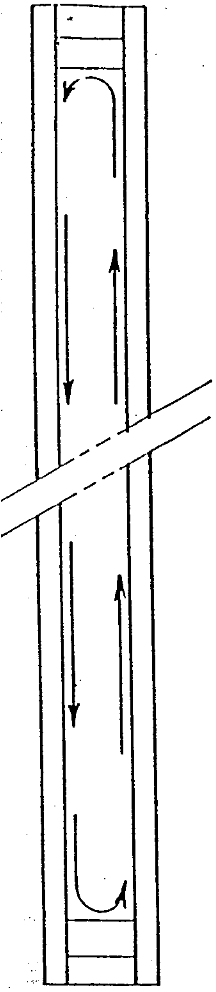


Fig 3A

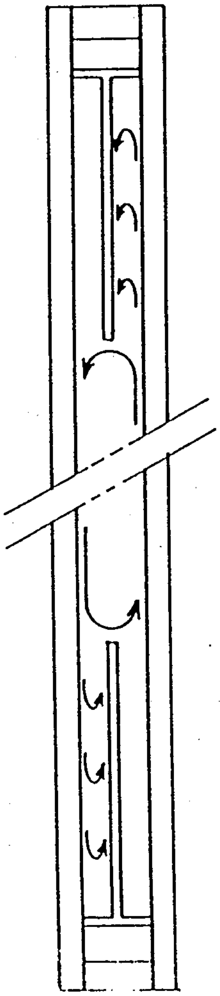


Fig 3B

A. Natural Convection within Double Glazed Unit
B. Double-Glazed Unit with Vertical-Barrier Fence

EXPERIMENTAL RESULTS ON THE EFFECTIVENESS OF CONVECTIVE-FLOW BARRIERS

To demonstrate the effectiveness of the convective-flow barrier, the following four experiments were carried out.

EXPERIMENT ONE: Side-by-Side Comparison of Sealed Unit With and Without a Vertical-Fence Barrier.

To demonstrate the effectiveness of convective-flow barrier designs, a side-by-side comparison test of glazing units with and without a vertical-fence barrier was carried out. The design of the test units was standardized with a ½ inch air-filled cavity between the glazing sheets and a low-emissivity coating on the inner face of the warm-side glazing sheet. The test units also incorporated a perimeter insulating edge-seal consisting of a desiccant-filled, silicone-foam spacer backed up by hot-melt butyl sealant.

The test apparatus consisted of a small cold chamber which was maintained at -17°C ± 2°C while the warm-side temperature was stable at around 20.5°C. The tests were performed with forced convective air-flow on the cold-side and natural convective air flow on the warm side. The warm-side temperatures of the test unit was measured using an Inframetrics thermographic camera and based on the infra-red image, Thermoteknix software was used to calculate and document various factors, including: surface-temperature profiles; minimum/maximum surface temperatures, and average surface temperatures etc. The infra-red thermographic camera also provided a visual multi-colored image of the warm-side surface temperatures of the test units.

To allow direct back-to-back comparison, the units were sized approximately 7" x 20". One test unit incorporated a 2" vertical-fence barrier, top and bottom, while the other test unit was conventional in design and incorporated no special features. Figure 4 illustrates the temperature profile of the conventional test unit, and the temperature profile of the test unit with the convective-flow barrier. As indicated by the double peaks in the temperature profile, the convective-flow barrier is clearly effective in separating the heat-transfer due to conduction and convection. Line A indicates the minimum bottom edge-of-glass temperature for the conventional unit which was calculated by the thermographic computer software to be 7.8°C. Line B indicates the minimum bottom-edge temperature for the unit with a convective-flow barrier which was calculated by the

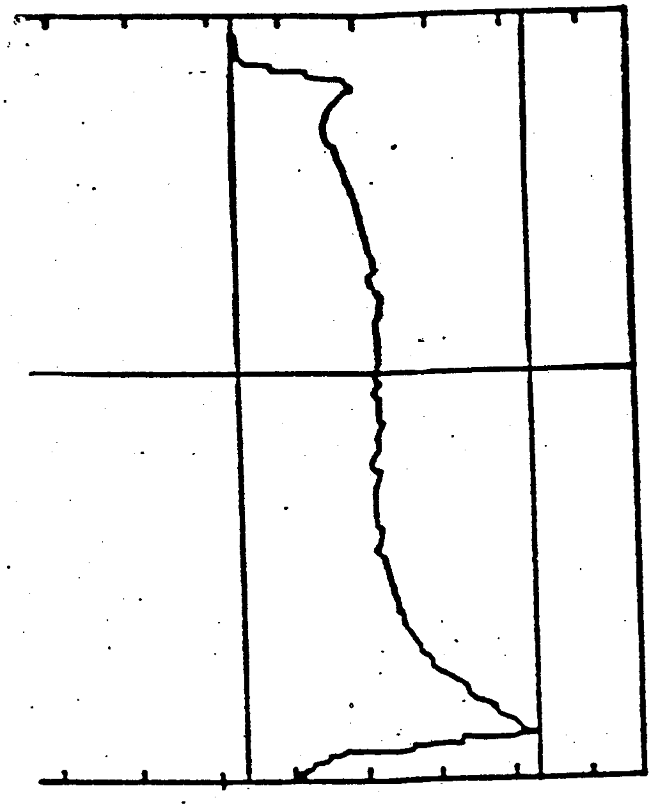


Fig. 4A Comparison of Temperature Profiles for a conventional unit

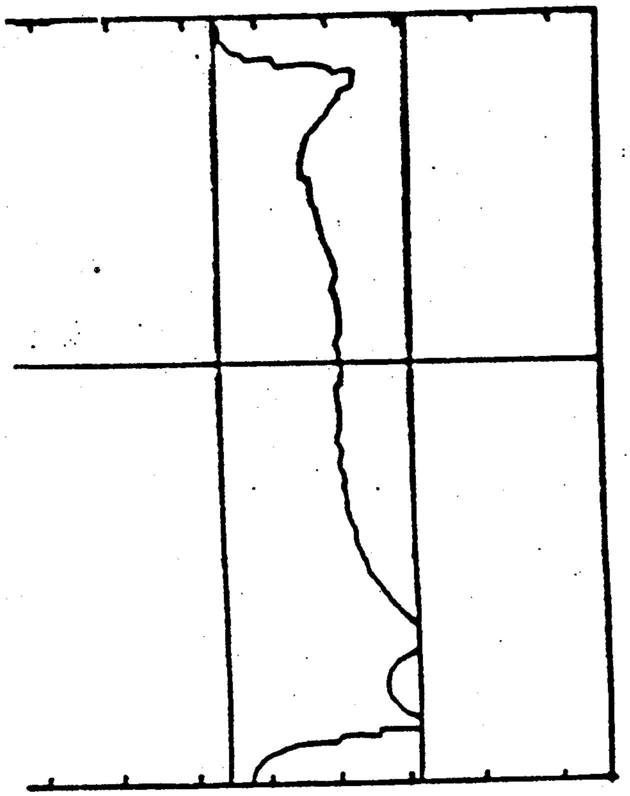


Fig 4B. Comparison of Temperature profiles with a vertical-fence barrier

thermographic computer software to be 11.3°C. As would be expected, the test results show that the maximum frame-surface temperatures of the two test units are similar. Line C represents the maximum top-edge frame temperature for the conventional unit which was calculated by the thermographic computer software to be 18.9°C. Line D represents the maximum top-edge frame temperature for the unit with the convective-flow barrier which was calculated by the thermographic computer software to be 18.8°C. The center-glazing temperatures of the two test samples are also similar. Line E represents that the center-of-glass temperature for the conventional unit is 13.9°C and Line F represents the center-of-glass temperature for the unit with the convective-flow barrier is 14.1°C.

In summary, these results show that convective-flow barriers are effective in increasing bottom edge-of-glass temperatures and as a result condensation is effectively eliminated at typical cold winter temperatures. However, the overall impact of relocating the cold spot due to convective flow is to create a larger area of moderately cold glass and this means that under extreme cold temperature conditions, condensation may occur over a much larger area than if the convective-flow barrier had not been installed.

EXPERIMENT TWO: Optimum Height of the Vertical-Fence Barrier

To determine the optimum height of the vertical-fence barrier for a particular size of glazing unit, a series of test units (14 inches wide x 20 inches high) were evaluated according to the same experimental procedures outlined in Experiment One. These test units incorporate various heights of vertical-fence convective flow barriers, including ½, 1, 2 and 4 inches. For the particular test unit size evaluated the thermographic test result showed that the ½ and 1 inch high vertical-fence had a minimal impact on the temperature profile. However, the 2 inch high vertical-fence significantly increased the minimum bottom edge-of-glass temperature while in contrast, the minimum bottom-edge temperature for the 4 inch high vertical-fence was about 2°C lower than for the 2 inch high fence. In summary, this experiment clearly shows that for this particular size of glazing unit and cavity width, the optimum height of the vertical-fence barrier at the bottom edge is about two inches.

EXPERIMENT THREE: Side-by-Side Comparison of Sealed Units with Vertical and Horizontal Convective-Flow Barriers

A side-by-side comparison test was carried out to determine the comparative effectiveness of a vertical-fence and a horizontal convective-flow barrier. The experimental procedures and equipment used were essentially the same as those described in Experiment One. To allow direct back-to-back comparison, the units were sized approximately 7" x 20". One test unit incorporated a ½" wide, horizontal barrier located 2" above the bottom edge. For this experiment, the cold-side temperature was measure to be between -19.5°C and 8.9°C and the warm-side temperature was measured to be 22.5°C. The thermographic test results show that while the minimum-glass temperature is only 0.3°C higher with a vertical-fence barrier, the average overall glass temperature is 0.7°C higher indicating that the vertical-fence design is more effective in reducing overall heat loss than the horizontal barrier.

EXPERIMENT FOUR: Side-by-Side Comparison of Sealed Units with and without an Insulating Spacer and both Units Incorporating a Vertical-Fence Barrier

A side-by-side comparison test was carried out to determine the effectiveness of a vertical-fence barrier for units with or without an insulating spacer. The experimental procedures and equipment used were essentially the same as those described in experiment one. As in experiment three, the units were sized approximately 7" x 20". Both test units incorporated a vertical-fence barrier at the bottom edge which was approximately 2" high, but one test unit was fabricated with a metal spacer and the other test unit was fabricated with an insulating foam spacer. For the experiment, the cold-side temperature was between -17.2°C and -16.5°C and the warm-side temperature was 23.5°C. The thermographic test results show that with an insulating spacer, the bottom edge temperature is 11.1°C while with a metal spacer, the bottom edge temperature is 8.2°C. These results indicate that convective-flow barriers are only fully effective when used in combination with high performance insulating spacers.

FURTHER RESEARCH UNDERWAY

1. Computer Analysis

Existing window thermal-performance, computer-analysis programs such as Window 3.1 and Vision 2.0 do not take into account convective-flow within the cavity space. At the Advanced Glazing Laboratory, University of Waterloo, research is underway to develop a 2-D finite-volume analysis program which will accurately model natural-convection loops within insulating-glass units.[2]

2. Thermographic Analysis

Because of the need to graphically map surface temperatures over a large area, thermographic infra-red analysis is a very effective research tool for studying convection flow within insulating glass units. Our company is continuing to carry out detailed thermographic analysis studies examining different types of convective-flow barriers and glazing designs. Our goal is to develop glazing designs which totally eliminate edge-of-glass condensation even at extreme cold-winter temperatures and high indoor temperatures.

3. Interferometric Analysis

In order to better understand the convective-flow patterns created by the different barrier designs, interferometric studies are being undertaken at the University of Western Ontario. This experimental procedure uses a Mach-Zehnder interferometer to produce interference-fringe patterns and this allows for the visualization of convective-flow patterns within the air or gas-fill cavity.[3]

CONCLUSIONS

Experimental results document that convective-flow barriers are effective technique for increasing bottom edge-of-glass temperatures. However because the barriers create a larger area of moderately cold glass, the bottom edge-of-glass condensation problem is not totally eliminated at extreme cold-winter temperatures and high indoor humidity levels.

ACKNOWLEDGMENTS

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The author also acknowledges the support of the Thermographic Analysis Laboratory of Lawrence Berkeley Laboratory, California.

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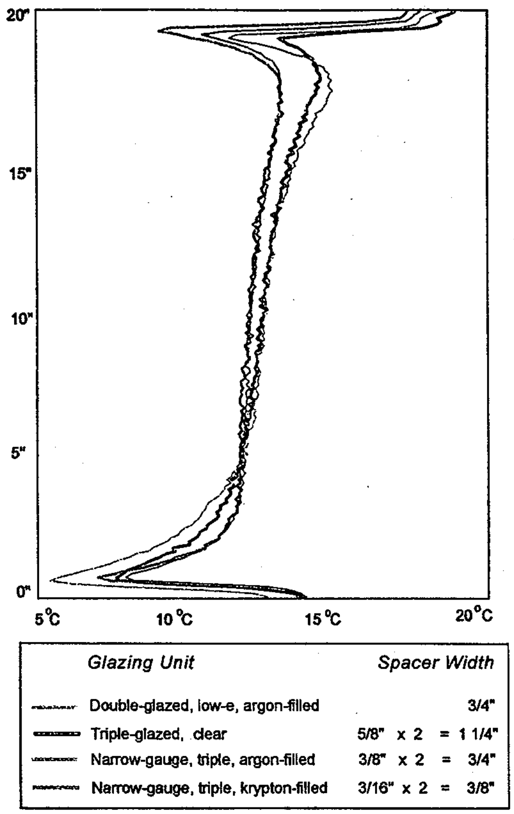
Appendix F: "Thermographic Testing Heralds Advent of Narrow-Gauge Triples" Edgetech Newsletter (Vol. 4, No. 2)

Thermographic testing heralds advent of narrow-gauge triples



Surface-Temperature Vertical Profiles

Ground-breaking thermographic testing, now underway at Edgetech's research and development facilities in Ottawa, has begun to produce some new and fascinating, fenestration-related results.

Carried out in a joint collaborative effort with CBD (Cantech), an international building science company, the first key result of the work so far is that narrow-width triple pane units, configured with clear-glass, gas-fill and Edgetech's silicone foam Super Spacer, appear to be the most cost effective means of achieving the twin goals of maximum condensation resistance and overall thermal efficiency.

"Narrow-gauge triples challenging low-e doubles in both performance and cost is quite a controversial finding," says Edgetech technical director, Michael Glover, "but also one we expect could propel this new tri-pane approach to the forefront of super window technology."

This is especially likely, says Glover, since it closes the gap between the public and the window industry on the issue of what constitutes improved thermal performance.

"Up until now, the IG industry has quite naturally concentrated on U-value ratings. However, such numbers mean virtually nothing to a would-be customer," he explains, "when compared to the only visual component of a more thermally efficient window, its ability to resist condensation. And in many cases they are not the same."

For instance, the overall U-value of high-performance doubles, those fitted with low-e glass, argon gas-fill and Super Spacer, is no different than the U-value of either typical triples (1 5/8") that are plain-glass, air-filled and foam-spacered, or Edgetech's narrow-gauge version, the latter being either argon or krypton gas-filled as well as foam spacered.

"However, their individual abilities to resist condensation certainly differ," says Glover, "especially along the bottom edge, where double glazed units, no matter what configuration, are more prone to the cold-edge effects of cross-cavity convection flow than triple-glazed units."

In the graph above, it is readily apparent that a bottom- edge-temperature difference of as much as 3°C (5.4°F) can be achieved using regular width tri-pane over high-performance doubles, "And that's enough to mean the difference between lots of condensation and no condensation whatsoever," says Glover.

While thermographically this comparison comes as no great surprise, "What's new and really quite important here," he explains, "is the fact that our testing shows that narrow-gauge triples are as adept as regular tri-pane at resisting bottom-edge condensation and that they fit snuggly and beautifully into double-pane frames."

In its first round of thermographic testing, Edgetech evaluated two different narrow-gauge options — argon-filled triples (OD 1 1/8") suitable for some wide-profile, PVC frames, and krypton-filled units (OD 3/4") useable in most other dual-pane frame designs, including wood.

"It's interesting to note just how narrow an air-space you can deploy in these triples," says Glover, "and still get significantly better bottom-edge results compared to high-performance doubles." As shown in the graph, employing krypton instead of argon allows for an amazing 50 percent spacer-width reduction, with the only result being a slight drop in temperature.

"In the end, there are two bottom lines that flow from what we've discovered here and both address concerns that are paramount to consumers. Narrow gauge triples offer much better condensation resistance than low-e, argon-filled doubles, and they do so with little or no extra costs."

By way of explanation, Glover says, that in comparing high performance doubles with narrow-gauge triples, the key pricing trade-off is between a low-e coating in the former and the latter's requirement for an extra lite of clear glass.

"A manufacturer's volume and location make all the difference," he states. "For example, the extra cost of a low-e coating can be as much as 70 cents/sq.ft in Eastern Canada, while in the U.S. mid-West it can turn out to be a few cents/sq.ft. less."

The cost differences associated with other components rise, fall or stay the same depending on the configuration in question. For instance, argon gas is so inexpensive that it doesn't matter whether the window is a double or a triple.

However, argon is used in the larger of the narrow-gauge triples (3/8" wide air spaces), and these units require 50 percent more spacer material than the standard 1/2" wide double glazed units.

On the other hand, slimmer-type, narrow-gauge triples employ 3/16" spacer widths, leaving edge-seal material costs pretty much the same as 1/2" doubles but they do require the use of krypton gas, though, which adds 40 cents/sq.ft. to the overall unit price.

Labor is always an important manufacturing cost, but in this instance automation has already begun to chip away at the traditionally higher levels associated with triple pane production. For example, automated glass cutting equipment has virtually eliminated any extra cost related to third-pane fabrication.

When it comes to assembly, the production of Super Spacer tri-pane has been greatly simplified by the use of the Butterfly Press in Lafond International's recently completed Super Shop operation (See Edgetech Newsletter — Fall 1993). "And as early as six months from now," Glover advises, "we'll see the complete Super Shop automation of tri-pane assembly, with the extra labor required reduced to a very minimum amount."

As far as Edgetech's thermographic testing is concerned, Glover has nothing but praise for the results that have been produced so far. "We've learned a lot about the comparative performance of doubles and triples and now we want to share this information with the IG industry as a whole."

The reason for wanting to do so is that presently many firms are faced with critical investment decisions regarding warm-edge production equipment, he says, "And in doing so, it's important they keep the future market for triple-glazed IG uppermost in their minds."

Especially for cold-climate locations, Glover predicts, "These narrow-width triples will become the industry norm" and Super Spacer, within a Super Shop assembly environment, is by far the best edge seal and spacer system for their production. Certainly that's the case when compared to thermally-broken metal spacers, which just can not be manufactured narrow enough for use in this application.

Super Spacer is also the only spacer system that is capable of really providing the high level of insulation necessary to prevent the sort of conductive heat loss and perimeter condensation one might expect in these reduced-width situations, says Glover

"With all this in mind, it's very much worth repeating and remembering, that while to date U-value improvement has been the industry's main thrust, the public meanwhile has fixed its attention on cold-climate condensation. It's therefore now up to IG makers to maintain overall thermal performance, yet increase condensation resistance, all the while keeping cost about the same."

"The type of thermographic analysis work we're doing shows exactly how to achieve this, and since the results so heavily favor the use of our high performance product, you can be absolutely certain we'll be spreading the word far and wide."