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LASER-SEALED EVACUATED WINDOW GLAZINGS

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Abstract

The design and fabrication of a highly insulating, evacuated window glazing have been investigated. A thermal network model has been used to parametrically predict the thermal performance of such a window. Achievable design options are predicted to provide a glazing with a thermal conductance less than 0.6 W/m^2K ($R > 10^oF\ ft^2\ h/Btu$) which is compact, lightweight and durable.

A CO_2 laser has been used to produce a continuous, leak tight, welded glass perimeter seal around 25 × 25 cm^2 test specimens. Various diameters of regularly spaced spherical support spacers were incorporated in the specimens as well as an integral SnO_2:F transparent, low emissivity coating for suppression of radiative heat transfer. Laser sealing rates of .06 cm/s were achieved at a 580°C glass working temperature with 400 W of continuous wave (CW) laser power.

Introduction

Large areas of solar windows are required in passive solar heated buidings. The heat lost through these windows by radiation and by conduction would greatly reduce the overall thermal efficiency of the building unless some insulation were used. Insulating curtains, shades, and shutters are used as occupant-actuated movable insulation to reduce losses at night and during other periods of low solar radiation. Inherently, insulating windows with multiple layers of glass and/or polymer films, with sealed gaps containing high molecular weight gasses, and with infrared reflective/low emissivity coatings are used to mitigate these losses[1]. One advanced state-of-the-art, commercial window glazing consists of two sheets of glass between which, in the sealed, gas-filled space, are suspended two sheets of polymer film both of which are coated with an infrared, reflective, low emissivity film. Such a window has a thermal conductance of approximately 0.8 W/m^2K (thermal resistance, $R = 7.27^oF\ ft^2\ h/Btu$) and a solar transmittance of about 36%[2].

The objective of our research has been to evaluate the technical feasibility of providing a more highly insulating window glazing by use of a vacuum gap and infrared reflective/ low emissivity coatings. Figure 1 shows the design schematically. This design is similar in principle to a vacuum dewar and has similar insulating potential. Theoretical calculations indicate that a thermal conductance as low as 0.5 W/m^2K ($R = 12^oF\ ft^2\ h/Btu$) may be achieved with an optimized design. Computer simulations of solar building performance (Fig. 2) have indicated that such a highly insulating window could provide net solar gain over the year, even in northern climates[3].

In order for an evacuated window glazing to be effective, a high quality vacuum $\sim 1.3 \times 10^{-3}$ Pa (10^{-5} Torr) must be established and maintained over periods of about 30 years. This requirement precludes the use of any polymeric materials for sealants and probably precludes the use of perimeter glass-to-metal seals as well. The seal we have chosen to evaluate is an all-glass seal.

Vacuum maintenance will require the use of a reactive metal getter inside the sealed space to remove outgassed and transmitted reactive gasses. Helium permeation may require a countermeasure, depending in detail upon the composition of the glass, the vacuum volume to surface area ratio, the coatings used, and the average service temperature. Effective and practical barriers to helium diffusion are known and are used commercially in dewars designed for use with liquid helium[4].

The integral, low emissivity coating is an essential and critical component in the evacuated window design. A large number of such coatings have been developed with high solar transmittances and low emissivities[5]. Most of these coatings may be economically applied by vacuum deposition in high throughput, mass production facilities. These coatings are likely to exhibit improved durability inside the evacuated space of a vacuum window; but only a few can withstand the temperatures required to seal them into the window.

Our initial efforts have predominantly focused on analyzing design options to arrive at an optimum in thermal and mechanical performance and on devising a fast and potentially economical sealing process.

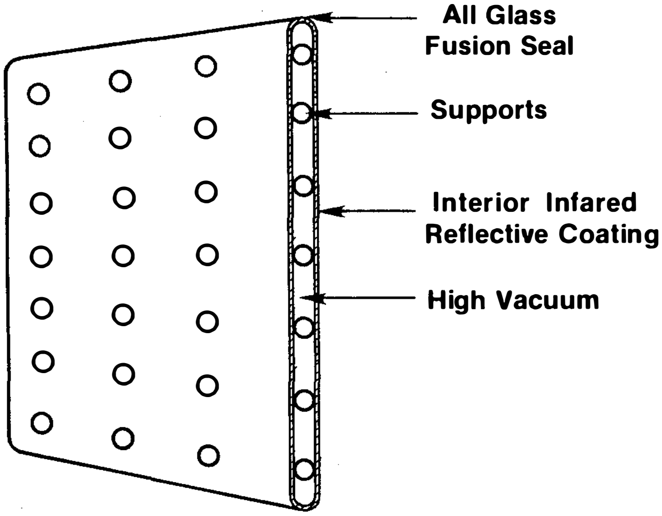

Figure 1. Schematic diagram of an edge sealed, all glass evacuated window glazing.

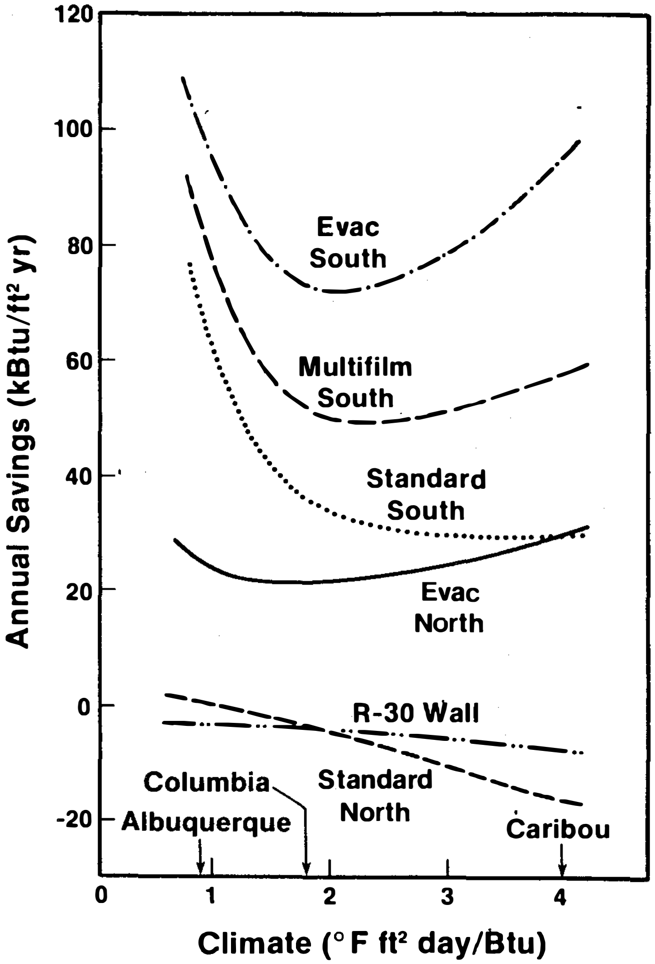

Figure 2. Predicted annual energy savings as a function of climate for different kinds and orientations of window glazings. The standard window has a solar weighted transmittance of 70% and an R value of 2.2. The evacuated window was assumed to have a transmittance of 58% and an R value of 12 (ref. 3).

Design Analysis

The thermal performance of the evacuated glazing has been modeled as a thermal network and studied parametrically. Figure 3 shows the elements of the design and how they were represented by thermal resistances and nodal temperatures. Thermal conductance through the spherical support contacts was based on published, analytical results[6]. Radiative transfer across the vacuum space was calculated explicitly using a T^4 temperature dependence, but assuming uniform temperatures over the area of the one meter square design window.

The thermal conduction through the edge seals around the window perimeter is excessive unless the effective thermal path length is increased by use of insulating edge baffles as shown in Fig. 3. Figures 4 through 7 summarize some of the most significant parametric analyses. The starred point in each figure is a design reference case with parameters defined in Table 1.

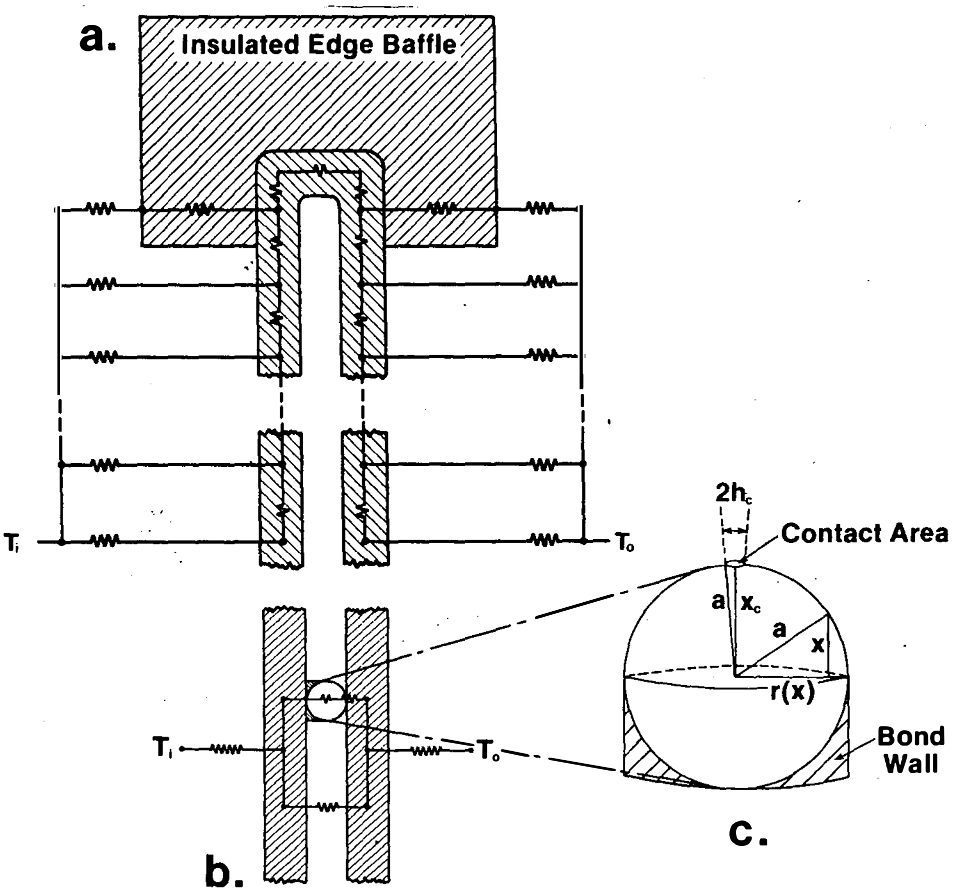

Figure 3. Thermal network model of evacuated window glazing: (a) insulated (baffled) perimeter, (b) spherical supports and parallel radiative heat path, (c) detail of spherical support.

Table 1. Baseline Parameters of Thermal Analysis

T_a - Ambient Temperature	= -20°C (-4°F)
T_i - Inside Temperatures	= 20°C (68°F)
d - Diameter of Spacers	= 3 mm (~ 1/8")
s - Spacing of Spheres	= 50 mm (~ 2")
δ_e - Edge Thickness	= 3 mm (~ 1/8")
δ_g - Glazing Thickness	= 3 mm (~ 1/8")
ε_1 - Glass Emittance	= .84
ε_2 - Infrared Reflector	= .05
ε_3 - Glass Emittance	= .84
ε_4 - Glass Emittance	= .84
A - Glazing Area	= 1 m^2 (~ 11 ft^2)
v - Wind Speed	= 6.7 m/s (15 mph)

Figure 4 shows the effect of coating emittance on thermal performance. A low emittance coating on one of the glass surfaces is essential; only a marginally added benefit is obtained from using low emittance coatings on both of the inner surfaces. Figure 5 shows the benefits of the insulating, perimeter edge baffle. Figure 6 shows the effect of the support sphere diameter and spacing (in a regular, square grid pattern) on thermal performance. A 10 cm spacing provides a conservative stress level in the glass sheets (Figure 7); a somewhat larger spacing may be acceptable.

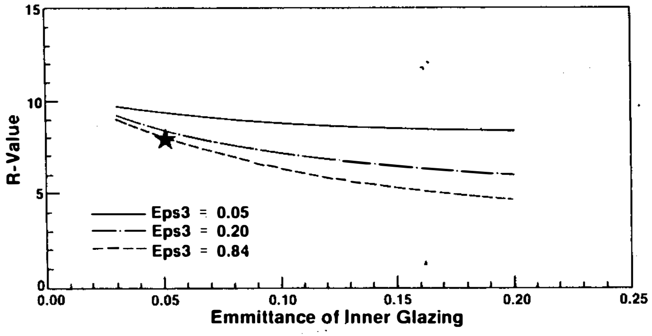

Figure 4. The effect of coating emittance on the thermal performance of an evacuated window.

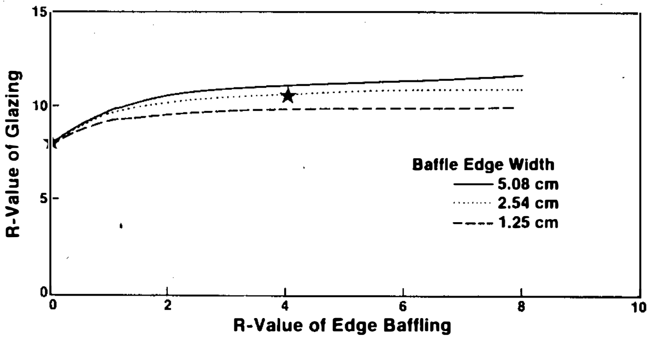

Figure 5. The effect of an insulated perimeter edge baffle on the thermal performance of an evacuated window.

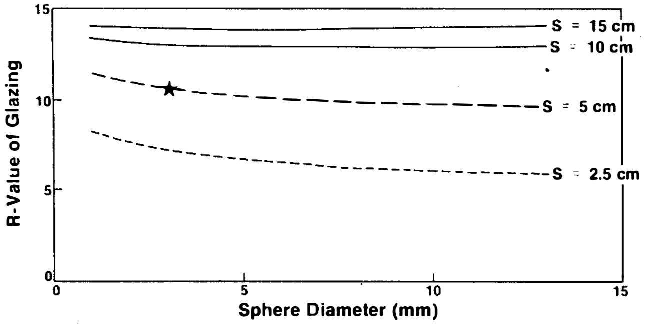

Figure 6. The effect of spherical support diameter and spacing on the thermal performance of an evacuated window.

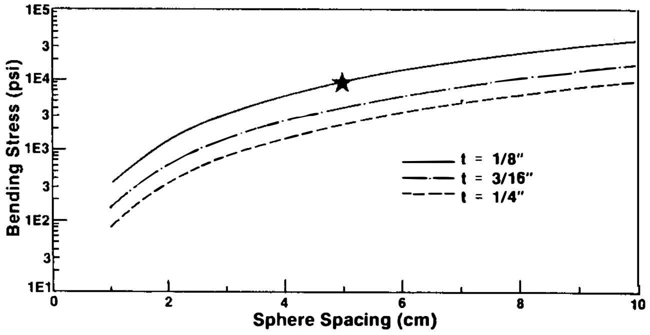

Figure 7. The bending stress due to atmospheric loading of an evacuated structure as a function of support spacing and glass thickness.

A finite element computer code, NASTRAN[7] is being used to predict the mechanical stresses in selected design cases. Preliminary results indicate that even in a 90 mph wind, the base case design window would experience a maximum tensile stress of 1971 psi near the edge, midway between corners. Under a thermal gradient typical of +20°C indoor and -20°C outdoor temperatures (68°F to -4°F) the maximum thermally-induced tensile stress occurs in the corners and is critically dependent on the compliance of the window support. In the worst case (rigid supports allowing no out-of-plane deflection at the perimeter) this tensile stress is 2263 psi. These stress levels are acceptably low, but will be further reduced by design improvements.

Laser Sealing Experiments

A 400-watt CW CO_2 laser* has been used to evaluate laser sealing as an option for fabricating an evacuated window. The potential advantages of laser sealing are: clean and efficient means of delivering localized power to the seal area; laser beam is easily directed, easily introduced into a vacuum furnace where the evacuated window could be sealed after receiving its low emissivity coating; 10.6 μm wavelength radiation is strongly absorbed by the glass matrix; and laser sealing is a potentially fast sealing method (using industrial process scale lasers).

In order to eliminate thermal shock fracture, it is necessary to preheat the glass to above its anneal temperture before laser sealing. A borosilicate glass was used to further improve the thermal shock resistance and also because it was available with a durable SnO_2:F low emissivity coating ($\varepsilon \sim 0.2$) which withstands the 580°C sealing temperature.** The spherical supports were bonded in place with sodium silicate in our test specimen fabrication experiments. However, we have had some success in spot-welding the spheres in place using the laser; with refinement this technique may become the preferred means of attachment in production.

The economics of laser sealing depend upon its speed. Experiments with our research scale laser were extrapolated to provide a rough estimate of the possible sealing speed with an industrial size laser. Figure 8 shows results of a series of experiments used to define the critical sealing speed parametrically. In these experiments 3 mm thick, flat

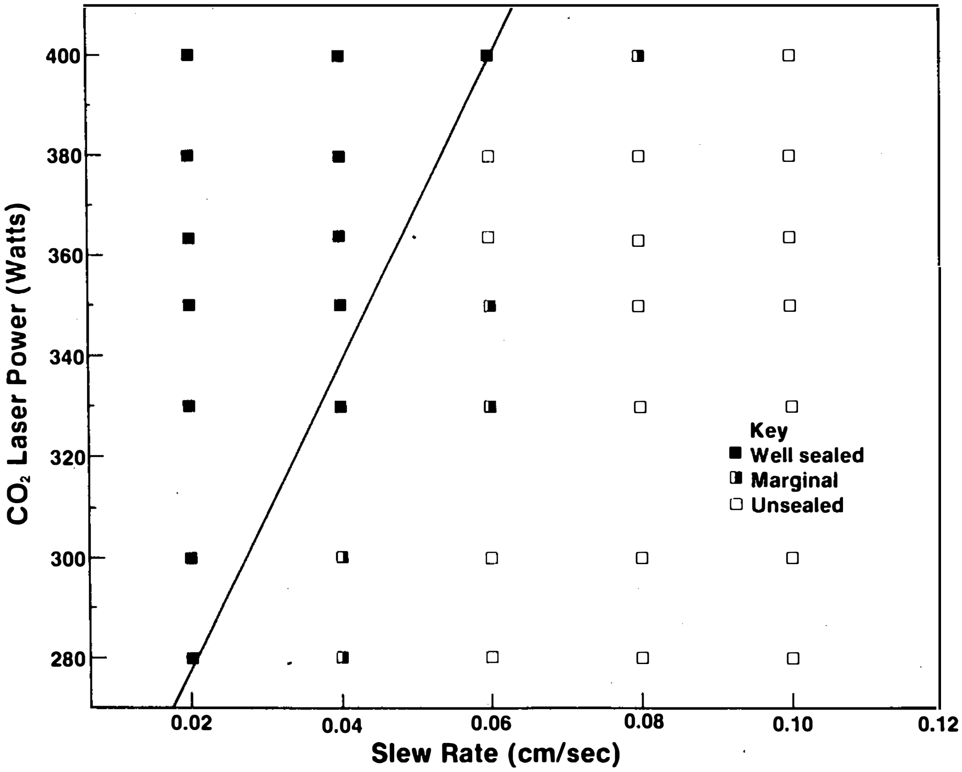

Figure 8. Results of CO_2 laser sealing experiments on borosilicate glass plates (3 mm thick) at 580°C; the effect of varying laser power as a function traverse speed across the glass surface (slew rate) on the type of seal obtained.

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*Coherent Everlase Model 325.

**Nesa glass from PPG.

sheets of borosilicate glass were welded at 580°C with a sharply focused (25 cm focal length lens) CO_2 laser beam in the TEM_{00} mode perpendicular to the glass surface. The speed of sealing and the power of the laser were varied systematically. The quality of the seal was judged by visual inspection and qualitative mechanical testing.

The maximum sealing rate R in cm/sec under these conditions can be expressed as:

$$R = \frac{P - 237}{2716}$$

where P is CW laser power in watts. If this expression is extrapolated to 5 kW, a typical industrial laser power, the sealing rate could be as high as 1.75 cm/s.

Complete, perimeter sealed test specimens 625 cm^2 have been fabricated with regularly spaced spherical supports and an integral SnO_2:F low emissivity coating. These units were fabricated in air; a partial vacuum was retained when the air sealed inside cooled from 580°C to room temperature. Fabrication of evacuated test units awaits availability of a vacuum furnace at our laser processing laboratory.

Conclusions

The design and fabrication of a sealed and evacuated insulating window glazing have been evaluated. An all glass, edge sealed window with integral, spherical supports and one low emissivity coating appears to have good performance characteristics. Such a window can provide a thermal conductance less than 0.6 W/m^2K ($R > 10$°F ft^2 h/Btu) in a compact (less than 10 mm thick) and lightweight (~ 14 Kg/m^2; 2.9 lb/ft^2) structure.

Laser edge sealing of such a structure has been demonstrated in air. Sealing speeds in excess of one cm/s can be predicted for industrial scale lasers (>3 kW CW power) from experiments with a <400 W CW CO_2 laser.

Much additional research and development are required to optimize and test the basic design concept. In particular: lower emissivity coatings which can withstand a 580°C process temperature in vacuum are needed; a reactive gettering system must be developed; helium permeation must be evaluated as a threat to vacuum integrity; fracture resistance of the structure must be evaluated, particularly in the vicinity of the spherical supports.

Acknowledgments

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