Review of Gas-Filled Window Technology: Summary Report

P. Sabatiuk

ABSTRACT

A survey of the state of the art of sealed insulating glass units filled with nonair gas mixtures (gas-filled windows) was conducted. The physical principles, potential performance, and technical problems associated with gas-filled windows were investigated, and commercially available windows of this type were identified.

Compared to air, certain gases and gas mixtures reduce the conductive and convective heat transfer across the space between window glazings (the interspace). This improvement in thermal resistance is especially significant when the radiative heat transfer across the interspace is reduced through the use of low emissivity films or coatings. The combination of gas filling and low emissivity films or coatings has produced double-glazed windows with U values of as low as 0.17 Btu/h·ft^2·°F (0.96 W/m^2·°C).

In Europe, several types of gas-filled windows are commercially available, and they are sold in large quantities. The most common fill gases used in Europe are argon and sulfur hexafluoride. The commercially available windows have U values of as low as 0.23 Btu/h·ft^2·°F (1.3 W/m^2·°C). In the United States, however, only two gas-filled windows are available and they are sold in small quantities. The U values of these windows are no lower than those of conventional double-glazed windows. The main reason for this difference in markets is the relatively high cost of energy in Europe, which has stimulated such advanced energy-conserving practices.

There are several obstacles to the eventual widespread use of gas-filled windows in this country. One is the lack of standardized test methods, specifications, and certification procedures for these windows. Another is a lack of knowledge about their long-term performance and reliability. A third major issue is the determination of the current cost-effectiveness of gas filling. Resolution of these issues will be the key to the development of consumer confidence and the establishment of a gas-filled window market in the United States.

INTRODUCTION

This report reviews the state of the art of sealed insulating glass units filled with nonair gas mixtures (gas-filled windows). The purpose of this review was to identify technical and other problems associated with gas-filled windows that may impede their eventual widespread use in the United States and to identify opportunities for research to solve these problems. This will assist the U.S. Department of Energy (DOE) Passive and Hybrid Solar Energy Program in the planning and evaluation of program research activities.

The approach taken in performing this review involved a number of tasks, but major effort was put into contacting manufacturers and suppliers of windows, window sealants, and industrial gases in order to locate companies with experience in this area. This included contacting both U.S. and European manufacturers of gas-filled windows. In addition, three government-funded laboratories involved with window technology were contacted: The Solar Energy Research

Paul A. Sabatiuk, P.E., Engineer, and Theodore D. Swanson, P.E., Project Manager, Mueller Associates, Inc., Consulting Engineers, 1401 S. Edgewood Street, Baltimore, Maryland

Institute, the Lawrence Berkeley Laboratory, and the Massachusetts Institute of Technology Laboratory of Architecture and Planning.

To determine what standards and test methods exist or are being developed for gas-filled windows, a number of national organizations were contacted, including the American Society for Testing and Materials, the National Bureau of Standards, the Sealed Insulating Glass Manufacturer's Association, the National Fenestration Council, the Flat Glass Marketing Association, the Glass Tempering Association, and the American National Standards Institute.

An additional effort involved conducting literature and patent searches. Several papers located were especially instructive with regard to the physical principles involved with gas-filled windows and their measured and potential thermal performance. A number of patents related to gas-filled windows were reviewed.

The remainder of this report is organized into separate sections describing (1) the basic technology of gas-filled windows, (2) their present commercial status, and (3) their technical and marketing barriers. These sections are followed by conclusions and recommendations. The appendix presents additional discussion and equations describing heat transfer in windows.

BASIC PERFORMANCE PRINCIPLES OF GAS-FILLED WINDOWS

The many benefits provided by windows in a building have been recognized and appreciated for hundreds of years. These benefits include daylighting, visual contact with the outdoors, and, when the windows are operable, the potential for ventilation and natural cooling. In addition, proper orientation and sizing can enable windows to positively impact a building's heating and cooling loads and to assist in energy load management. However, windows have traditionally been "energy losers" because of their low thermal resistance relative to other building envelope elements. Approximately five percent of total U.S. energy consumption is attributable to undesired heat gains or losses through windows. Their lack of thermal resistance is particularly undesirable in skin-dominated buildings with relatively little internal heat generation, such as residences. In typical (i.e., not passive) skin-dominated buildings, nearly all thermal losses in the winter and thermal gains in the summer through the envelope must be made up by the HVAC system. In addition, during the heating season, low window thermal resistance causes low surface temperatures, so radiative losses to the windows from building occupants are greater than losses to other envelope elements. This tends to cause discomfort for occupants adjacent to large window areas.

These factors point to the need for improving the thermal resistance of windows while maintaining their solar transmission and visual characteristics. This improvement can be accomplished through a number of techniques for impeding the conductive, convective, and/or radiative heat transfer through the window.

In addition to the actual window, the interior and exterior air boundary layers provide thermal resistance. The heat-transfer coefficients of these boundary layers have both convective and radiative components that depend upon a variety of factors, such as air and glass temperatures, sky and surface emissivities, wind speed, and wind direction. Consequently, the insulating values of these boundary layers change substantially under real conditions. A value of about 1.1 Btu/h·ft^2·°F (6.2 W/m^2·°C) is generally assumed for the combined inside and outside surface heat transfer coefficient for a single glazing of ordinary window glass. For single glazings with an emissivity (ϵ) of 0.84 (typical of ordinary glass), the <u>ASHRAE Handbook-1981 Fundamentals</u> prescribes a value of 1.10 Btu/h·ft^2·°F (6.2 W/m^2·°C) in the winter and 1.04 Btu/h·ft^2·°F (5.9 W/m^2·°C) in the summer.[1]

Virtually all of the thermal resistance for single glazing is provided by the surface boundary layers, since the thermal conductivity of glass is high (about 57 Btu/h·ft^2·°F [320 W/m^2·°C] for a 0.125-in [3.18 mm] thickness).[2] However, there are several ways of reducing the surface heat transfer coefficients and thus increasing the thermal resistance. One way is to reduce the forced convective transfer from the inside surface through the application of low ϵ films or coatings. As with all windows, movable insulating devices can also be used.

Multiglazed windows have "dead air" spaces between glazings that provide additional thermal resistance, but the enclosed airspace is not, however, actually stagnant. Convective motion can develop in response to applied temperature differentials across the window. For double-glazed windows, a variety of techniques can be utilized to improve thermal resistance. Besides reducing the surface heat transfer coefficients, it is also possible to reduce heat transfer between the panes. This can be done by using low ϵ films or coatings to reduce radiative transfer or by using any of the following techniques to reduce conductive and/or convective heat transfer: partitioning the interspace (the space between the glazings), increasing the width of the interspace, evacuating the interspace, and filling the interspace with a gas heavier than air. Although this report deals primarily with the last technique mentioned, it is important that the principles by which the other techniques work be understood, since their effects are interrelated. In other words, the use of any of these techniques may enhance or diminish the effectiveness of another technique used in conjunction with it. Detailed discussion of these techniques and their effects on window thermal performance can be found in the papers by Selkowitz, Glaser, and Ortega.[3-5]

Heat transfer across the interspace by conduction and convection is a function of the height and width of the interspace, as well as the thermal conductivity, viscosity, and thermal expansion coefficient of the interspace gas. When the interspace width is sufficiently small for a particular gas and window (interspace) height, convection is insignificant. Under these conditions, the temperature gradient across the interspace in the horizontal direction is essentially linear. However, as the interspace width is increased, a transition point is reached at which a convective cell forms in the interspace core. As the interspace is widened further, the convective cell widens accordingly while the boundary layers at the glazing surfaces remain nearly the same. Under these conditions, heat is transferred through the boundary layers by conduction and through the central core of the interspace by convection. Accordingly, there is a substantial horizontal temperature gradient through the boundary layers but not through the interspace center. There is, instead, a vertical temperature gradient within the convective cell, with the higher temperatures at the top of the cell. Within this "convective regime," the combined conductive and convective heat transfer across the interspace does not change significantly with variations in interspace width. In fact, most gases in this regime display a slight increase in heat transfer with increasing interspace width.

Based on this physical behavior, it is best to stay within the "conductive regime" in order to minimize heat transfer as well as interspace width. By using horizontal partitions in the interspace, the convective tendency is suppressed so that the interspace width can be increased significantly (thus increasing overall thermal resistance) before the onset of the convective regime. Another way of increasing the interspace width while maintaining the conductive regime is through the use of vertical partitions (additional glazings). These create a number of interspaces in series that reduce conductive heat transfer linearly with increasing interspace width.

Yet another approach to suppressing interglazing heat transfer is to fill the interspace with a single gas or mixture of gases other than air that have low thermal conductivity and/or high viscosity. Within the conductive regime, combined conductive/convective heat transfer across the interspace will be nearly proportional to the gas conductivity. However, the critical interspace width at which the transition from the conductive to the convective regime occurs is a function of the gas viscosity (and to an extent the thermal expansion coefficient). If the viscosity of the interspace gas is greater than that of air, then the critical interspace width will be greater than that for air. It should also be noted that nonair gases have sound attenuation properties different from those of air.

To gain a perspective on the relative reduction in heat transfer that can be achieved through gas filling (the use of nonair gases in the interspace), it is important to compare the relative contributions of the radiative and conductive/convective modes to the overall heat transfer. In a double-glazed window with ordinary glass and a 0.5-in (12.7 mm) interspace, approximately two-thirds of the heat transfer across the interspace is due to radiation and one-third is due to conduction/convection. Figure 1 shows total conductance across the interspace for a number of fill gases as a function of interspace width.[6] Based on this figure, it is clear that reduction of radiative exchange is of primary concern, which emphasizes the need for development of low ε films and coatings. *However, for performance, gas filling should be viewed as complementary to, rather than competitive with, low ε films and coatings.* In fact, nearly all gas-filled windows produced in Europe also utilize low ε films and coatings. When radiative transfer is severely reduced across the interspace, conduction/convection then becomes dominant, and any reduction in the latter mode attained through gas filling becomes more significant. Thus, the combination of gas filling and low ε films or coatings can produce windows with outstanding thermal resistance when compared with conventional windows.

There are many gases that have the required physical properties for conductivity and viscosity to improve window thermal resistance through filling the interspace. However, only a small number of these have the potential to meet all the practical requirements of this application. Following are requirements for such a gas:

1. It must be resistant to sunlight and ultraviolet (UV) light.

2. It must not react chemically with the window glass, seals, or framing.

3. It must be nontoxic and nonpolluting.

4. It must not readily diffuse through the window seal.

5. It must not condense in the interspace when exposed to extremely low outside temperatures.

6. It must be readily available and relatively inexpensive.

A number of gases that have been used in gas-filled windows experimentally and/or commercially are presented in Tab. 1. The physical properties of these gases that affect their performance in this application (particularly conductivity and viscosity) are included. Although all these gases are of interest, several cannot meet all of the practical requirements. SO_2 is toxic and has potential condensation problems due to its relatively high boiling point (14°F [10°C]) at atmospheric pressure. CCl_2F_2 (the refrigerant R-12) is a fluorocarbon that may have a negative effect on the environment if released into the atmosphere. Krypton, despite its excellent performance potential, is in short supply worldwide and may be too expensive to be cost-effective. The remaining gases appear to have outstanding potential, and these considerations will be discussed in further detail later. In addition, it has been discovered that certain gas mixtures are more effective insulators than any of the component gases individually. These mixtures will be discussed further.

TABLE 1
Physical Properties Of Filling Gases[a]

Filling gas	Molecular weight	Thermal conductivity,[b] (Btu/h·ft·°F)	Absolute viscosity,[b] (lb_m/ft·h)	Specific heat,[b] (Btu/lb_m·°F)	Density,[b] (lb_m/ft^3)	Prandtl number
Air	28.96	0.0145	0.045	0.24	0.081	0.75
Argon(Ar)	39.95	0.0098	0.052	0.12	0.111	0.66
CO_2	44.01	0.0093	0.034	0.20	0.123	0.73
SO_2	64.06	0.0054	0.029	0.14	0.183	0.78
Krypton(Kr)	83.70	0.0053	0.058	0.06	0.233	0.74
CCl_2F_2	120.91	0.0052	0.025	0.13	0.337	0.65
SF_6	146.05	0.0075	0.035	0.15	0.412	0.69

[a]Adapted from H. J. Glaser, "Improvements in Heat Insulation by Means of Insulating Glass," Journal of Glass Technology 50:10, p. 248.
[b]Values given are for 50°F (10°C)

Conversion formulas: 1 Btu/h·ft·°F = 1.73 W/m·°C; 1 Btu/lb_m·°F = 4.18 kJ/kg·°C; 1 lb_m/ft·h = 0.413 centipoises; 1 lb_m/ft^3 = 16.03 kg/m^3

It is of interest to examine the potential thermal performance that can be attained by gas-filled windows with and without low ε films or coatings. Glaser has performed extensive testing of double-glazed windows with different gas fillings and interspace widths.[7] These windows were tested with and without a low ε gold coating on one of the interspace surfaces. The emissivity of this coating was measured to be 0.065. Figures 2 and 3 present the U values for the uncoated and coated windows respectively. The lowest U value Glaser found for the conventional (uncoated) windows was 0.46 Btu/h·ft^2·°F (2.6 W/m^2·°C) for an SO_2 filling with a 0.35-in (8.9 mm) interspace. For this same interspace, air filling resulted in a U value of 0.55 Btu/h·ft^2·°F (3.1 W/m^2·°C). For an argon-filled window with a 0.79-in (20 mm) interspace, the U value was found to be 0.47 Btu/h·ft^2·°F (2.7 W/m^2·°C).

The gold-coated (low ε) windows displayed a marked improvement in thermal resistance over the noncoated windows. An argon-filled window with a 0.79-in (20 mm) interspace was measured to have a U value of 0.21 Btu/h·ft^2·°F (1.2 W/m^2·°C). A krypton-filled window with a 0.47-in (12 mm) interspace was measured to have a U value of 0.17 Btu/h·ft^2·°F (0.96 W/m^2·°C).

Clearly, the combination of gas filling and low ε films or coatings can produce windows with excellent thermal resistance. Through the use of additional glazings and very low ε films or coatings ($\varepsilon \approx 0.01$), windows with U values of 0.1 Btu/h·ft^2·°F (0.6 W/m^2·°C) or less may eventually be developed and produced cost-effectively. The appendix provides a more detailed discussion and the appropriate equations for calculating heat transfer through windows.

STATE OF THE ART OF GAS-FILLED WINDOWS

Commercially Available Products

With regard to the commercial status of gas-filled windows, there is considerable disparity between the United States and Europe. Only two such products are available in this country, and they are similar and have limited applications. In Europe, however, a wide variety of gas-filled windows is available, capable of performing a multitude of functions.

Two American companies produce gas-filled windows. As is typical for both the U.S. and European glass industries, neither of the companies markets its window directly. Instead, nearly all of the windows are sold to two of the largest window manufacturers in the country for assembly into finished products. The windows are nearly identical in that both are double-glazed, have a welded glass seal, and use CO_2 as the filling gas. Neither window has a low ε or reflective coating or film. Due to practical limitations of the welded seal process used in their manufacture, the maximum window dimensions, interspace width, and glazing thickness are relatively small. Both windows are produced in 9 x 12 in (0.23 x 0.30 m) or 12 x 12 in (0.30 x 0.30 m) sizes. The glass panes on one of the windows are 0.10 in (2.5 mm) thick and the interspace width is 0.188 in (4.8 mm) thick. The published U value is 0.55 Btu/h·ft^2·°F (3.1 W/m^2·°C). The glass panes and the interspace width on the other window are 0.125 in (3.18 mm). Because of this narrower interspace width, its U value is slightly greater (0.58 Btu/h·ft^2·°F [3.3 W/m2·°C]).

Clearly, these windows provide thermal performance comparable only to conventional double-glazed windows, and in fact, they have been filled with CO_2 to compensate for the narrow interspace widths. The true benefit of these windows is that the welded edges create a hermetic seal, thus providing the potential for an indefinite lifetime. It is this advantage that leads to their reason for existence: they are used almost exclusively for bow windows (curved bay windows composed of many lites of glass) for which replacement is difficult and costly.

The two companies have been producing the windows for 20 and 15 years each. Interestingly, both companies initially filled the windows with freon gases, but after a number of years encountered problems. Over a long period, contaminants (including water vapor) of very low concentration present in the fill gas of some of the windows gradually broke down the freon, causing an iridescent or blue color in the affected windows. In extreme cases, the glass was etched. Both companies were forced to replace many windows, and to avoid further problems, both began filling the windows with CO_2.

By contrast, many European companies market gas-filled windows. Although most of them do not manufacture their own windows, at least two large West German companies manufacture a wide variety of gas-filled windows and perform a substantial amount of related research and development. Their gas-filled windows represent what is now available in Europe relative to this product type.

One of these companies uses three different gas fillings in its commercial windows. The first filling is intended to provide maximum thermal insulation and is composed of approximately 95 percent argon and 5 percent air. It is used in either of two window types. One type uses a low transmittance, high reflectance coating on its inner interspace surface to reduce solar gain and increase thermal resistance. A number of metallic or metallic oxide coatings are available. The second window type has a very thin gold (low ε) coating on its inner interspace surface to provide relatively high transmittance and thermal resistance. The lowest U values for these windows are 0.26 and 0.28 Btu/h·ft^2·°F (1.5 and 1.6 W/m^2·°C) respectively.

The second filling is intended to provide maximum sound attenuation and is composed of from 40 to 60 percent sulfur hexafluoride (SF_6) with the remainder of the filling being air.

This filling is used in the low transmittance, high thermal resistance windows described previously, as well as in a window designed specifically for sound attenuation that has from two to four glazings.

These gas-filled windows all have organic seals. Polyisobutyl is used as the primary sealant, although silicone has been used. These are the sealants most commonly used in Europe.

This same company also produces a window that is very similar to the American CO_2-filled windows. It is double-glazed with low iron glass, has welded edges, and uses CO_2 as the fill gas. Its U value is about 0.51 $Btu/h{\cdot}ft^2{\cdot}°F$ (2.9 $W/m^2{\cdot}°C$), and it is used primarily for greenhouses.

The second European company mentioned offers a variety of window types comparable to that offered by the first company. However, they use only one gas mixture in their commercial windows. Although the exact composition is proprietary, this filling consists of SF_6 mixed with other gases. No more than 20 percent of the filling gas is air.

This gas is used in solar control, high transmittance, and sound attenuation windows. Like the first company, they use metallic or metallic oxide coatings on their solar control windows, which have U values of as low as 0.26 $Btu/h{\cdot}ft^2{\cdot}°F$ (1.5 $W/m^2{\cdot}°C$). Their high transmittance window, however, uses a low ε film laminated to the inner interspace glass surface rather than a coating. The sound attenuation windows have from two to four glazings, with a U value of 0.23 $Btu/h{\cdot}ft^2{\cdot}°F$ (1.3 $W/m^2{\cdot}°C$) for the quadruple-glazed window. They also use polyisobutyl for the primary sealant and polysulfide for the secondary sealant.

Tab. 2 summarizes commercially available gas-filled windows and their basic characteristics.

TABLE 2
Summary Of Commercially Available Gas-Filled Windows

Country of manufacturer	Window type	Filling gas	Number of glazings	Film or coating	Measured U Value[a] ($Btu/h{\cdot}ft^2{\cdot}°F$)
United States	Small lites for bow windows	CO_2	2	None	0.58
United States	Small lites for bow windows	CO_2	2	None	0.55
West Germany	Solar control (low transmittance)	Ar or SF_6	2	Metals or metal oxides (low τ, low ε)	As low as 0.26
	High transmittance	Ar	2	Gold (high τ, low ε)	As low as 0.28
	Sound attentuation	SF_6	2 to 4	Not known	Not known
	Greenhouse lites	CO_2	2	None	0.51
West Germany	Solar control (low transmittance)	SF_6[b]	2	Metals or metal oxides (low τ, low ε)	As low as 0.26
	High transmittance	SF_6[b]	2	Low ε film	Not known
	Sound attenuation	SF_6[b]	2 to 4	Not known	As low as 0.23

[a]Test procedure not known.
[b]Exact composition propritary. SF_6 is the primary component.
Conversion formula: 1 $Btu/h{\cdot}ft^2{\cdot}°F$ = 5.67 $W/m^2{\cdot}°C$

Current Market and Research and Development Efforts

As might be expected based on the availability of commercial products, the market for gas-filled windows is well established in Europe, whereas it is practically nonexistent in the United States. There are several important reasons for this. First, the general practice of energy conservation is more established in Europe than in the United States because energy prices have been substantially higher in Europe than in this country for many years. The combination of high energy prices and cold winters has provided the incentive in northern Europe to develop well insulated windows and, consequently, to use gas filling. In addition, the relatively low insolation levels in northern Europe during the winter lessen the importance of high solar transmission, thus encouraging the use of selective coatings.

The U.S./European market difference is clearly seen by comparing the respective sales volumes of gas-filled windows. The American companies combined sell fewer than one-quarter million square feet of their CO_2-filled windows per year. On the other hand, one West German company alone sells about 15 million square feet of low ε coated and/or gas-filled windows per year. At such a production level, the incremental cost of gas filling is quite small. The basic cost difference is in the additional required filling time, since the actual cost of argon and SF_6 are not great. For a standard 0.47-in (12 mm) interspace, the respective costs of argon and SF_6 are about \$0.003 and \$0.06 per square foot (\$0.03 and \$0.60 per square meter). Although the overall incremental cost of gas filling is difficult to isolate because of variations in the number of glazings, coatings, window size, and window quantity, it is estimated to be from \$0.10 to \$0.40 per square foot (\$1.00 to 4.00 per square meter) in the present European windows.

The gas-filling process has been the focus of considerable research and development in both Europe and the United States. Due to the substantial market, European efforts have been largely directed toward streamlining and speeding up the process. The filling devices have attained a great degree of sophistication over the past decade, and a skilled operator of such a device can fill from 600 to 700 ft^2 (60 to 70 m^2) of windows per hour. A number of U.S. industrial gas suppliers have also developed these devices to a high degree. One of these companies can now provide a window manufacturer with all the apparatus required for window filling for about \$10,000, a sum considerably less than the cost of most of the European devices. Their device simplifies filling by requiring only one hole in the window seal for the filling port. Previous devices required up to three filling ports.

This same company has also done other significant research and development related to high thermal performance windows. They have produced and tested a number of gas-filled windows as well as an evacuated window with a low ε coating and a measured U value of 0.08 $Btu/h \cdot ft^2 \cdot °F$ (0.5 $W/m^2 \cdot °C$). In addition, they have produced a krypton-filled window with a low ε coating and a measured U value of 0.21 $Btu/h \cdot ft^2 \cdot °F$ (1.2 $W/m^2 \cdot °C$). They have experimented primarily with argon and krypton, but have also worked with R-13, CO_2, and xenon. Although krypton is approximately 10 times as expensive as SF_6 and xenon is about 100 times as expensive as SF_6, they believe that even xenon may be cost-effective when used as a small percentage of the fill gas. A number of very effective gas mixtures have been formulated and tested. For instance, an argon filling with a small percentage of krypton has a better insulating value than a filling of argon only. They also found that a filling of krypton with a small percentage of argon has a better insulating value than a filling of krypton only.

TECHNICAL AND MARKETING BARRIERS

The filling of sealed insulated glass units with nonair gases presents a number of problems with regard to achieving and maintaining proper window performance. A primary problem is providing window seals that effectively prohibit the diffusion of gases into and out of the window interspace. Most sealants are selected for their resistance to the transmission of water vapor. Under normal conditions, the water vapor pressure differential between ambient air and an air-filled window interspace is very small, since water vapor makes up a relatively small portion of the atmosphere. However, when a window is filled with a gas not present (or of low concentration) in the atmosphere, the vapor pressure differentials become very large. For instance, if a window is filled with krypton, the krypton vapor pressure differential between the interspace and the ambient air is effectively 1 atm, since krypton is an insignificant component of the atmosphere. Another aspect of this problem is that different sealants are more permeable to some gases than to others. According to Graham's law of diffusion, this differential permeation can lead to a temporary difference in total pressure between the interspace and the ambient air. For example, if a window is initially filled with krypton and the window sealant permits oxygen in the atmosphere to diffuse into the window more rapidly than it permits krypton to diffuse through the sealant into the atmosphere, then the total pressure in the window will increase above atmospheric. This could then cause the window seals to rupture, the glass to bend, or, in the extreme, the glass to break.

Clearly, the diffusion problem in gas-filled windows is far more severe than it is in conventional multiglazed windows. In order for such windows to maintain their insulating qualities for many years, their sealants must be virtually impermeable to both the fill gases and atmospheric gases. One way to achieve total impermeability is to use welded glass seals. However, the welding process in both labor and energy intensive and has the added disadvantage of restricting window size and glazing and interspace widths. Solutions to such problems with the welding process are not imminent.

Another problem presented by gas filling is the potential degradation of one or more of the window components over a long period. This may result from the breakdown of a particular component or from a reaction between incompatible materials. The fill gases, low ε films or coatings, and window sealants must all remain chemically stable in the window environment. The degradation exhibited by the freon-filled windows described previously is clear evidence of what can occur.

There are several marketing barriers to the widespread use of gas-filled windows, particularly in this country. For one, the beneficial effects of gas filling cannot easily be seen or sensed by the builder or homeowner. Whereas the difference between a single-glazed and a double-glazed window is very evident, the effect of having argon rather than air in the window interspace is subtle and not widely understood. Without greater public awareness of the benefits of gas filling, it will be very hard to justify any extra window cost, as small as it may be. This problem is one that could be a barrier to the widespread use of low ε films and coatings as well.

These marketing problems could be largely solved through the development and implementation of standard test methods and performance certifications for gas-filled windows. Efforts to do so are under way in both Germany and the United States through the State Materials and Testing Institute (SMTI) and the American Society for Testing and Materials (ASTM), respectively. At present, the SMTI does not recognize the initial measured U values of gas-filled windows as being indicative of long-term performance on the basis that there is not sufficient evidence to verify that the fill gas mixture can be maintained over the life of the window. Both German companies discussed previously guarantee their gas-filled windows for five years against condensation, but, for the reasons discussed previously, this is not the same as guaranteeing against diffusion of all fill and atmospheric gases. The SMTI is finalizing a standard test method for these windows, and its completion is anticipated in the near future.

The ASTM is initiating similar efforts. The final standards will probably be modified versions of the existing "Standard Specification for Sealed Insulating Glass Units (E774-81)" and "Standard Test Method for Seal Durability of Sealed Insulating Glass Units (E773-81)." These standards collectively deal with window fogging and frost point as well as high humidity and accelerated weather cycle testing. One difficulty is that, since the frost point will be different for each fill gas or fill gas mixture, the standard for certification will have to vary with each fill gas or fill gas mixture. At this point, the ASTM has experimented with argon and the refrigerants R-11 and R-12.

CONCLUSIONS AND RECOMMENDATIONS

The results of this survey show that gas filling can significantly improve the thermal resistance of windows. It is also apparent that gas filling is most effective when the combined conductive and convective heat transfer rate across the interspace is greater than the radiative heat transfer rate. It is thus concluded that gas filling should be used in conjunction with low ε films or coatings in order to obtain the greatest thermal benefit.

Based on the European market and previous research and development work, the use of argon and SF_6 as fill gases is now cost-effective in certain climates and applications. Even the use of krypton, a far more expensive gas, may be cost-effective when used as a small portion of the fill gas to improve performance. These conclusions are, of course, contingent upon the maintenance of the window's thermal resistance throughout its lifetime. It is recommended that additional cost performance analysis consistent with the evaluation procedures established for the DOE's Passive Solar Materials and Components Program be performed.

The European market is also evidence of the market potential for high thermal performance windows using gas filling and low ε films or coatings. However, public awareness of the benefits of these windows must be increased. In addition, there are two major potential obstacles to the eventual widespread use of gas-filled windows. One of these is the present lack of standardized test methods, specifications, and performance certification for the windows. The successful development and implementation of such standards and certification will have a huge impact on consumer confidence and market growth. The other potential obstacle relates to the long-term performance of the windows. At present, serious questions exist with regard to the effectiveness of window sealants. There are also serious concerns about the long-term compatibility and stability of different combinations of window sealants, fill gases, and low flims or coatings. Quality products backed by long-term warranties will be needed.

Consequently, it is concluded that there are several areas of research and development where efforts could be undertaken to determine the extent of these technical problems and to find solutions to them. In particular, it is evident that a major need is the determination and development of effective sealants with regard to gaseous diffusion. At present there are virtually no substantiated test results in this area. Numerous companies are performing general research and development for window sealants, but comprehensive accelerated and/or long-term testing of gas-filled windows with various gases, sealants, and films or coatings is sorely needed. Another priority is the investigation of window material compatibility and stability. This would also require accelerated or long-term testing and could easily be coordinated with tests of sealant effectiveness.

Improving the manufacturing process used to gas fill windows does not seem to be a pressing concern. Substantial development has taken place in this areas over the past decade, and it does not appear to be an impediment to the expansion of the gas-filled window market.

A possible area for further investigation is the identification of additional high performance fill gas mixtures. It has been discovered that mixtures can provide significantly better insulating qualities than any of the individual component gases. A number of European and American companies have successfully identified and tested high performance mixtures.

Developing standardized test methods and certification for gas-filled windows is crucial to their commercial development. Without such methods or certification, industry and consumer confidence will be slow to grow and, as a consequence, so will the market. In the U.S., over 50 percent of the window market is supplied by small manufacturers, most of whom fabricate and apply their own sealants. Window certification is necessary to avoid the problems that would arise from poor quality control by a manufacturer.

REFERENCES

1. ASHRAE Handbook-1981 Fundamentals Volume (Atlanta: ASHRAE, 1981).

2. Ibid.

3. Stephen E. Selkowitz, "Thermal Performance of Insulating Window Systems," Lawrence Berkeley Laboratory Report #8835, 1979.

4. H. J. Glaser, "Improvements in Heat Insulation by Means of Insulating Glass," Journal of Glass Technology 50:10 (1977), pp. 248-256.

5. J. K. E. Ortega, "An Assessment of Low Emmitance/High Thermal Impedance Windows for Solar and Conventional Applications," Proceedings of the ASME Solar Energy Division Fourth Annual Conference (Albuquerque, ASME, 1982).

6. Selkowitz, "Thermal Performance of Insulating Window Systems."

7. Glaser, "Improvements in Heat Insulation."

APPENDIX
Calculation of Heat Transfer Through Windows

The U value of a window is a measure of the heat transfer rate through the window based on the temperature difference across the window and the window area. It can be defined as

$$U = \left(\frac{1}{h_o} + \frac{1}{C_W} + \frac{1}{h_i}\right)^{-1} \tag{1}$$

where

h_o and h_i are the outside and inside air boundary layer heat transfer coefficients, respectively, and C_W is the net conductance of the window system.

For a single-glazed window, C_W is extremely high compared to h_o and h_i because of the high thermal conductivity of glass, so the middle term in Eq. 1 is negligible. Both h_o and h_i have conductive, convective, and radiative components. For multiglazed windows:

$$C_W = h_c + h_r \tag{2}$$

where

h_c is the combined conductive/convective heat transfer coefficient and h_r is the radiative heat transfer coefficient.

The portion of the heat exchange that is radiative is given by the following equation:

$$h_r = \sigma \quad x\left(\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2}\right)^{-1} \quad x\left(\frac{T_1^4 - T_2^4}{T_1 - T_2}\right) \tag{3}$$

where

σ is Stefan's radiation constant, ε_1 and ε_2 are the glazing emissivities, and T_1 and T_2 are the glazing temperatures.

The combined conductive/convective portion of the heat exchange is given by the following equation:

$$h_c = \frac{k}{w} \quad (Nu) \tag{4}$$

where

k is the thermal conductivity of the fill gas, w is the interspace width, and Nu is the Nusselt coefficient.

In the "conductive" regime, the Nusselt coefficient is defined by the following equation:

$$Nu = a(Pr)\ (Gr)^b\ \left(\frac{L}{w}\right)^c \tag{5}$$

where

Pr is the Prandtl number, Gr is the Grashof number, L is the window height, and a, b, and c are constants.

The values of these constants in turn depend on the value of the Grashof number, which is given by the following equation:

$$Gr = \frac{gB(T_1 - T_2)w}{\gamma 2} \tag{6}$$

where

g is the gravitational constant, B is the gas thermal expansion coefficient, and γ is the gas kinematic viscosity.

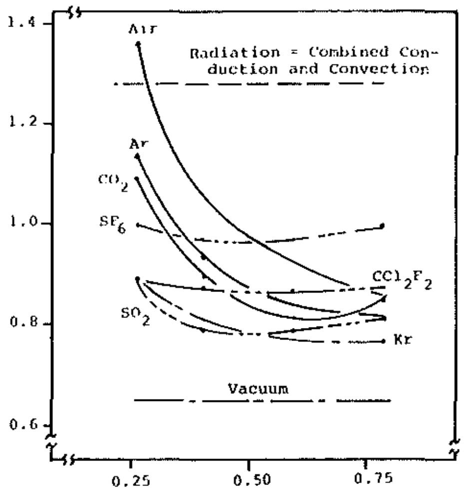

Figure 1. Total interspace conductance versus interspace width for double-glazed windows (glazing ε = 0.84 and ΔT across glazings = 18°F [10°C])[2]

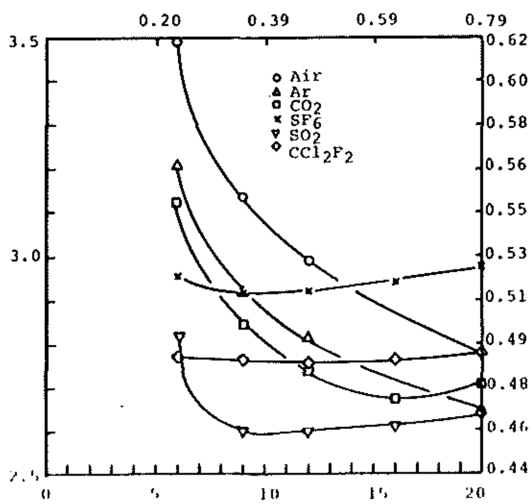

Figure 2. Overall window U value versus interspace width for uncoated double-glazed windows (glazing ε = 0.84 and ΔT across glazings = 18°F [10°C])[3]

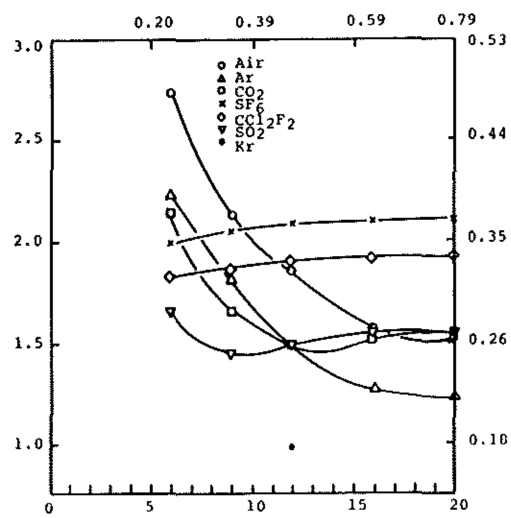

Figure 3. Overall window U value versus interspace width for gold-coated double-glazed windows (Inner interspace glazing surface ε = 0.065 and ΔT across glazing = 18°F [10°C])[3]