Design And Material Selection Factors That Influence The Service-Life And Utility Value Of Dual-Sealed Insulating Glass Units

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Summary: Insulating glass units are exposed to a variety of environmental factors, such as temperature and atmospheric pressure fluctuations, wind loads, working loads, sunlight, water and water vapour. The service life of a sealed insulating glass unit (IGU) critically depends on the perfect functioning of the edge-seal under these environmental influences. The water vapour permeability of the secondary insulating glass sealant plays only a subordinate role in the life expectancy of a dual-sealed IGU, since the resistance of the edge-seal to water vapour diffusion is determined almost exclusively by the low water vapour permeability of the polyisobutylene primary seal. However, great importance must be attached to the viscoelastic properties of the secondary insulating glass sealants, particularly to their tensile stress behaviour and their elastic recovery under service conditions, as these properties affect the ability of the primary seal to function. The resistance of the edge-seal to gas diffusion is influenced by the permeabilities of both primary and secondary seals. IGUs with very low gas loss rates, meeting the stringent requirements of the German and new European standards, can be produced by proper selection and design of the edge-seal components, particularly by either minimising or properly accommodating the movements occurring in the edge-seal as a result of the thermal stresses. The durability of the secondary seal has a strong influence on the service-life of dual-sealed IGUs, as it affects the transport mechanisms for moisture ingress and gas loss.

Keywords: Insulating glass unit, Sealant, Durability, Service-Life, Life Expectancy.

1 INTRODUCTION

The key function of an insulating glass unit (IGU) edge-seal system is to provide a gas- and moisture-barrier and to structurally bond two or more panes of glass together. This can be achieved best with a dual edge-seal system, where the primary, polyisobutylene-based seal provides the barrier function and the elastomeric secondary seal ensures the structural integrity of the IGU. In the year 2000, about 280 million m^2 of IGUs were manufactured globally. North America and Europe accounted for over 80% of this volume and about 2/3 of these IGUs were dual-sealed, with the market share of dual-sealed units being much higher in Europe (95%) than in North America (45-50%). Experience with dual-sealed IGUs has shown that service-lives of more than 25 years can be obtained, if the units are properly designed, manufactured and installed.

An IGU has reached the end of its service-life, when – under normal use conditions – moisture condensation (fogging) occurs within the inter-pane space. Fogging is caused by the diffusion of water vapour through the edge-seal and the resulting saturation of the desiccant. Modern, multi-functional IGUs are often filled with special gases, such as noble gases, SF_6 or mixture of these gases, in order to improve their heat and/or sound insulation quality. The differential in partial pressures of these gases within the IGU and the surrounding air causes them to diffuse, effectively resulting in a “dilution” of the gas(es) in the IGU by air. The dilution of the fill gases in turn affects the utility value of the IGU by degrading its heat and/or sound insulation quality. Thus, the quality of edge-seal strongly influences the service-life and utility value of an IGU.

2 ENVIRONMENTAL AND SERVICE DEGRADATION FACTORS

IGUs are exposed to various environmental and service factors that negatively affect their life expectancy (Wolf 1992, 1999). Literature on this subject often differentiates between physical and chemical stresses, although certain environmental influences, such as sunlight, exert both kinds of stress.

2.1 Temperature and its variation

High temperatures accelerate most physical and chemical processes, such as the ageing of the insulating glass sealant and the diffusion of gas or water vapour through the edge-seal. Temperature fluctuations produce variations in pressure within the

IGU. These exert mechanical stresses on the edge-seal, which are strongest for small units and unfavourable form factors (Feldmeier 1997). Furthermore, differences in thermal expansion of spacer bars and glass plates result in shearing and peeling forces in the edge-seal. The edge-seal temperature is influenced by the steady diurnal and annual ambient temperature variations; however, rapid changes in edge-seal temperature do occur; for instance, during a summer thunderstorm, when hail or cold water hits the heated outer glass pane. Even in quite moderate climates, such as Scotland, the edge-seal temperature in clear glass IGUs may vary by as much as 20°C within 2-3 hours (Garvin & Wilson 1998).

2.2 Air pressure and its variations

Permanent stresses on the edge-seal exert a highly negative influence on the service life of an IGU. Since they can be avoided through proper manufacture and installation procedures, this situation will not be further examined here. Changes in ambient atmospheric pressure result in temporary mechanical stresses on the edge-seal; these changes typically occur within the time span of several days. Much faster load changes occur with the sudden build up of pressure caused by a gust of wind or the change from pressure to suction produced with swirling winds. These rapid changes in wind load occur several hundred thousand times during the service-life of an IGU.

2.3 Sunlight

Sunlight exerts both physical and chemical stresses on the edge-seal. Visible and infrared components of the solar radiation thermally charge the IGU. The effect increases, if a tinted solar protection glass is involved, since then a larger portion of the visible light is also converted into thermal energy. The short wave component of the solar radiation may also induce photochemical processes in insulating glass sealants. Regular float glass is transparent to ultraviolet light down to a wavelength of about 280 nm (Spauszus 1975). In the case of a regularly glazed IGU, the unit's edge-seal is protected by the window frame; hence, no sunlight reaches the edge-seal directly. However, depending on the angle at which the sunlight strikes the glass surface, between 1% and 8% of the incident radiation finds its way to the edge-seal due to internal reflection in the glass panes (Van Santen 1984, 1986). The penetration length of this radiation into the depth of the rebate depends on the thickness of the glass pane (Marusch 1988). The glass adhesion of organic insulating glass sealants, such as polysulphides or polyurethanes, can be irreversibly destroyed by the high-energy short-wave spectrum (280-380 nm) of sunlight (Ludwig & Wolf 1986, Marusch 1988). Consequently, the edge-seal of organically sealed insulating glass panes is not to be freely exposed to the sunlight, but must be suitably protected, as in the case of sloped glazing, for example, by attaching strips, gaskets or tapes.

2.4 Water and water vapour

Water and water vapour may also cause both physical and chemical stresses on the edge-seal. Two of the major physical stresses are the water vapour diffusion through the edge-seal into the inter-pane space as well as the water absorption and the associated swelling of the insulating glass sealant itself. If the edge-seal of an insulating glass unit remains in direct contact with water for a protracted period of time, e.g. due to improper glazing, organic insulating glass sealants tend to absorb large quantities of water into their polymer matrix, thereby greatly increasing the volume of the edge-seal (Boesmans 1990, Ludwig & Wolf 1986). This swelling of the edge-seal inevitably results in an opening of the primary seal and, consequently, a higher rate of water vapour diffusion into the interior of the insulating glass unit. Glazing guidelines for IGUs therefore attach great importance to keeping the glazing rebate free of water. However, water and water vapour are also capable of triggering chemical reactions. By causing hydrolysis of chemical bonds at the glass surface, water can irreversibly damage the adhesion of insulating glass sealants (Ludwig & Wolf 1986, Shephard *et al*. 1999, Lowe 1992).

2.5 Synergetic effects

The stresses caused by the various environmental factors are not simply cumulative in their effect. Instead, their interaction results in a disproportionately higher stress on the edge-seal, a phenomenon known as synergism. Various studies (Feldmeier *et al*. 1984, Van Santen 1984, Ludwig & Wolf 1986, Lowe 1992) ascertained that the simultaneous action of water, elevated temperatures and sunlight constitutes the greatest stress on the edge-seal of an IGU. This degradative effect is most pronounced at the sealant/glass interface, often resulting in partial or complete adhesive failure of organic sealants, due to the channelling of UV radiation to the interface by total reflection within the glass panes. In the absence of water, free radicals are formed by the absorption of radiant energy and the resulting chain scission of organic polymers; however, these radicals tend to recombine, forming a somewhat different network configuration. In the presence of water, however, the radicals formed are terminated and cannot recombine, thus generating low molecular weight compounds that form a weak boundary layer. As a result, organic sealants exposed to UV light, water and elevated temperatures for prolonged periods of time fail progressively near the sealant/substrate interface.

3 DEGRADATION MECHANISMS AFFECTING INSULATING GLASS PERFORMANCE

Theoretical calculations based on moisture and gas diffusion through the edge-seal generally yield service lives far in excess of 25 years. Why is this theoretical life expectancy not achieved in normal service, with some units failing prematurely even within a few years of service? The theoretical calculations ignore the rigours that IGUs have to endure, the actions of sunlight, heat, wind loading, excessive moisture exposure due to improper glazing, etc., the resulting stresses, edge-seal defects due to poor workmanship, and – most importantly – the degradation of the edge-seal with ageing! The calculations are generally

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based on only one transport mechanism (diffusion through the edge-seal) and do not take account of changes in this transport mechanism or the advent of additional transport mechanisms resulting from the degradation of the edge-seal. The service life and gas retention of an IGU are influenced by the following factors:

- Exposure conditions (microclimate within window frame, external climate, wind loads, etc.)
- Dimensions of the insulating glass unit
- Quantity, type and initial loading of the desiccant
- Air or gas temperature and relative humidity during manufacture of the insulating glass
- Initial degree of gas filling
- Resistance of the edge-seal to diffusion of water vapour and gas
- Effective sealant cross-section through which the diffusion occurs
- Durability of the edge-seal

3.1 Diffusion through edge-seal

Considering all conditions as identical and neglecting the durability of the edge-seal for the time being, the service life and the utility value of an IGU should be the higher, the lower the amounts of water vapour and gas that diffuse through the effective cross-section of the edge-seal. The key parameters that need to be controlled, thus, are the permeability of the edge-seal and the effective cross-section.

3.1.1 Permeability of the edge-seal

During service, the edge-seal of the glazed IGU is exposed to a microclimate within the window frame or curtain-wall construction. Two major studies have been conducted in an effort to monitor this microclimate in terms edge-seal temperature, moisture and presence of liquid water over the period of several years (Feldmeier *et al*. 1984, Garvin & Wilson 1998). While in Central Europe edge-seal temperatures of clear glass IGUs seldom exceed 40°C, for tinted or coated glass units or in warm climates service temperatures may well reach 80°C and above for prolonged time-periods (Jacob & D’Cruz 1999). As a rule of thumb, the glass temperature increases by 10°C for every 200 W/m^2 absorbed sunlight radiation. Since the diffusion of moisture or gas occurs under service conditions, the temperature dependency of diffusion through an insulating glass sealant must be taken into consideration, which can be described by an exponential function of the inverse, absolute temperature (Arrhenius equation), where E_a is the activation energy of diffusion, R is the ideal gas constant, and T the absolute temperature:

$$\frac{P(T_2)}{P(T_1)} = \exp\left(- \frac{Ea}{R} \bullet \left(\frac{1}{T_2} - \frac{1}{T_1} \right) \right) \qquad (1)$$

Insulating glass sealants therefore exhibit a considerably higher moisture and gas permeability at elevated temperatures than at room temperature. For instance, as reported by Wolf (1985), the water vapour permeability of insulating glass sealants at 60°C is an average of six to eight times higher than at 20°C. The practical consequences of this must be examined. Although in Central Europe the edge-seal of an IGU is subjected to temperatures over 30°C for only about 20% of the year (Feldmeier *et al*. 1984), the IGU nevertheless sustains about twice as much damage by diffusing water during this brief summer period than during the remainder of the year, when temperatures under 30°C prevail. Higher temperatures in association with high humidity therefore drastically reduce the service life an IGU.

The activation energy of diffusion depends mainly on the polymer type utilised in the insulating glass sealant. The water vapour diffusion rates of silicone sealants vary less as a function of temperature than is the case for polyurethane or polysulphide sealants (Wolf 1985). As a result, the water vapour permeabilities of silicone and polysulphide insulating glass sealants tend to approach each other at elevated temperatures. Based on these findings, comparable service-lives should be expected for polysulphide and silicone single-seal IGUs – in contrast to frequently voiced arguments, which are based on water vapour permeabilities determined at room temperature. However, the service lives of such single-seal IGUs will be substantially shorter than those achieved with dual-sealed units.

Various authors have studied the temperature dependency of gas diffusion through organic elastomers, including PIB, silicone, and polyurethane elastomers (see Schuck 1980, Beckmann 1991, and literature cited therein). These authors consistently found silicone elastomers to have the lowest temperature dependency in gas permeability of all high molecular weight polymers studied. The activation energies for the diffusion of nitrogen and oxygen through silicone elastomers were 14 and 9 kJ/mole, respectively, while organic polymers typically showed activation energies for these gases in the range 28-52 kJ/mole. On the other hand, it should be noted that the silicone elastomers also had the highest absolute gas permeability of all elastomers studied.

However, since the majority of IGUs are dual-sealed, the diffusion resistance of a double layer system needs to be considered. The diffusion resistance of a plane-sheet laminate is the sum of the individual resistances of the various layers (Ashworth 1992):

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$$\frac{d}{P} = \sum_{i=1}^{n} \frac{d_i}{P_i} \tag{2}$$

When considering moisture diffusion, the water vapour permeability of the polyisobutylene (PIB) primary seal is far lower than that of the secondary seal, irrespective of whether the secondary seal is made of a silicone, polysulphide or polyurethane sealant. Therefore, the water vapour permeability of the dual edge-seal is determined almost exclusively by the permeability of the PIB primary seal:

$$P_1 << P_2 \;\Rightarrow\; \frac{d}{P} \cong \frac{d_1}{P_1} \tag{3}$$

Experimental studies into dual edge-seal systems (Massoth & Wolf 1988) confirm this approximation; hence, it could be assumed that the service life of a dual-sealed IGU in the field would depend solely on the PIB primary seal, and that it is therefore irrelevant which sealant might be used for the secondary seal. This is not the case, however, as will be discussed later.

Table 1. Overall argon gas permeabilities of dual edge-seals.

Sealant Types	*Argon Permeability* ($cm^2/(s\ cmHg)$) Single Seal	 Dual Seal
Polyisobutylene (PIB)	$5.0\ 10^{-11}$	----
Polysulphide	$1.5\ 10^{-10}$	$6.82\ 10^{-11}$
Polyurethane (Polybutadien)	$8.0\ 10^{-10}$	$8.00\ 10^{-11}$
Polyurethane (Polyether)	$2.8\ 10^{-9}$	$8.24\ 10^{-11}$
Silicone	$3.7\ 10^{-8}$	$8.33\ 10^{-11}$

In the case of gas diffusion, one needs to consider the individual contributions to the overall permeability of the dual-seal, which depend on the nature of the permeating gas. Table 1 shows the overall gas permeabilities of various dual edge-seal systems for argon, the most commonly used fill gas. The values were calculated from the experimentally determined gas permeabilities of the individual seals (Geilich 1987) using eqn. (2), and assuming primary and secondary seal depths of 6 and 4 mm, respectively. As can be seen, the overall gas permeabilities of polyurethane or silicone based dual seals are between 17% and 22% higher than the respective PIB/polysulfide dual seal. This is a rather small increase, when compared with the effect of the effective seal cross-section, through which the diffusion occurs (to be discussed later), or when considering the temperature dependency of gas permeability. For example, the nitrogen permeability of the polyurethane elastomer studied by Beckmann (1991) increased by a factor of 17, when changing the measurement temperature from 20°C to 80°C. This increase is typical for the organic elastomers studied, since the activation energy of 40 kJ/mole of the polyurethane elastomer corresponds quite well to the average activation energy found for this class of elastomers (43.9 kJ/mole). Since the ratio between the gas permeabilities of various gases in organic elastomers remains about the same (Schuck 1980), one can assume a similar increase for the argon permeability of the edge-seal. Given a defect-free primary seal installation, this suggests that the majority of IGU gas loss occurs during periods of elevated edge-seal temperature.

3.1.2 Effective diffusion cross-section

The first, and most important, factor that influences the effective cross-section for the diffusion of moisture and gases is proper workmanship during IGU manufacture. The primary seal must be properly dimensioned, must be free of voids, and completely wet the spacer and glass contact surfaces. For conventional IGUs (rigid spacer), the primary seal cross-section is determined by the pressing operation which occurs after the two glass panes and the PIB coated spacer have been assembled. The pressure must be maintained over a sufficient period of time to allow the PIB sealant to flow and to completely wet the spacer and glass surfaces. The strength and duration of the pressure must be controlled to achieve primary seal dimensions of 0.3-0.4 mm in width and about 5-6 mm in depth.

In the case of rigid spacers, the degree to which the primary seal opens up during periods of positive pressure differential is determined by the tensile stress with which the secondary seal resists this applied force. In practice, positive pressure differentials occur at low atmospheric pressures or at high temperature, whereby temperature is responsible for most pressure differentials. Temperature induced pressure differentials also excert a higher force on the edge-seal than do wind loads or atmospheric pressure variations (see Fig. 1, adapted from Van Santen 1986). Therefore, the tensile stress behaviour (Young’s modulus) of secondary sealants at elevated temperatures must be considered.

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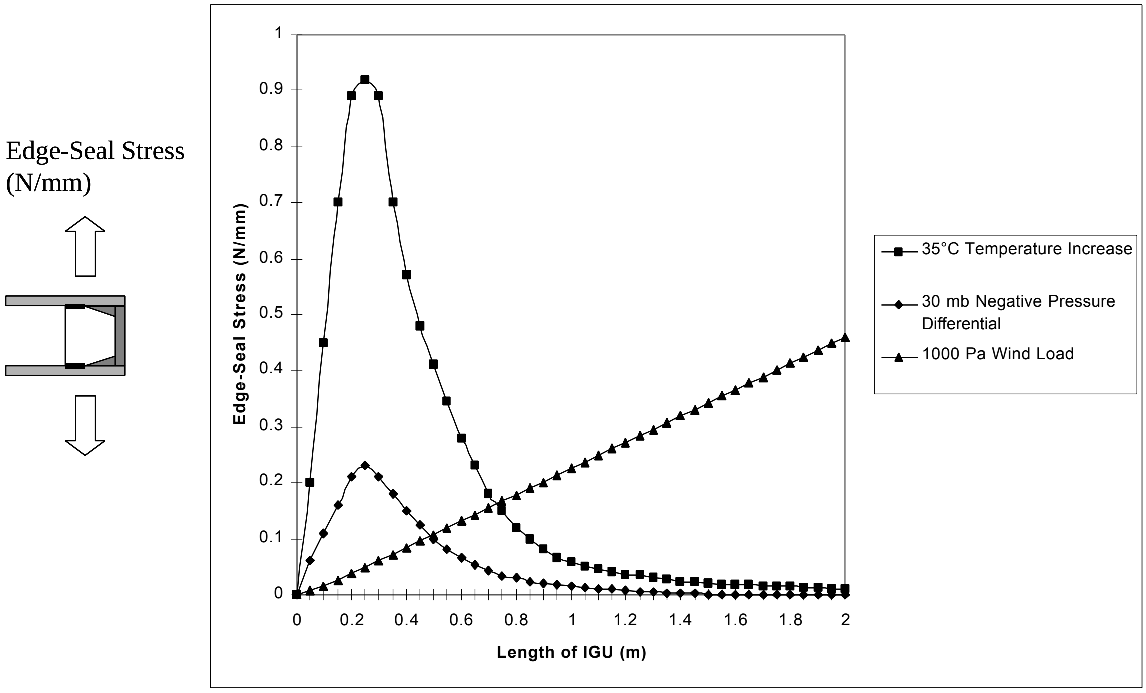

Figure 1. Edge-seal stress as a function of IGU length for various loads

O'Brien & Stewart (2000) modelled the thermal movements occurring in the edge-seal of a large IGU (1.5 x 2.1 m^2 size) as a result of temperature variations (-30°C to +60°C) for three commercially available spacer bars of different material and design using finite-element analysis. The model was based on nylon corner keys for the aluminium and galvanised steel spacers and bent corners for the stainless steel spacers. The nylon corner keys were assumed to be solid and firmly bonded to the spacers; while the bent corners were modelled as solid, bent metal corner keys, also firmly bonded to the spacers. Since actual bent corners are hollow, the model tends to overestimate the stresses for this corner design. As expected, at the low temperature, the corners are pulled inwards, resulting in a bending angle >90°; while at the high temperature, the corners are pushed outwards, resulting in a bending angle <90°. Figure 2 shows the deformed corner shapes for the aluminium spacers exaggerated by a factor of 100. Monitoring the changes occurring in PIB primary seal thickness around the circumference of the IGU, O'Brien & Stewart found that the stainless steel spacer had, by far, the least effect on the change in cross-sectional area, while the aluminium spacer had the largest effect, as can be seen in Table 2. This finding is in line with the sequence expected based on the difference in thermal expansion coefficients between spacer material and float glass. Thus, changes in the effective diffusion cross-section, resulting from a differential in thermal movements, are likely to account for the observation of performance differences of IGUs made with different spacer materials.

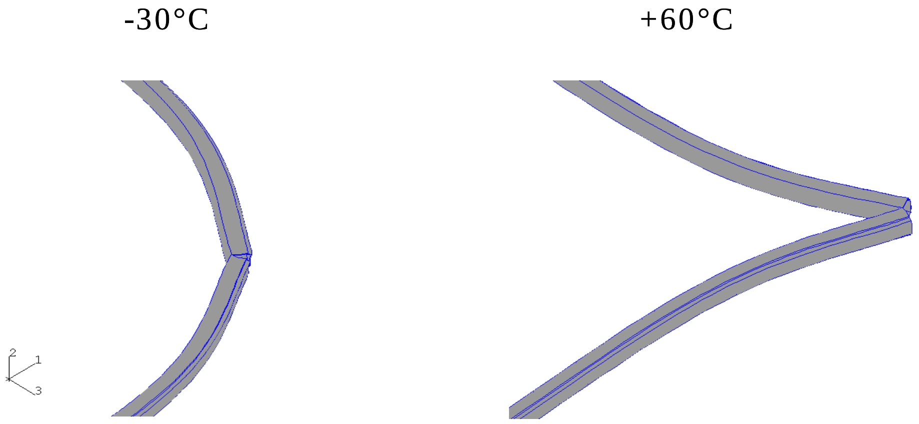

Figure 2. Corner deflection of aluminium spacer frame (exaggerated by factor 100)

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Table 2. Deformation of PIB primary seal as a function of spacer material

Temperature	*Deformation of PIB seal (%) for spacer material*		
(°C)	*Aluminium*	*Galvanised*	*Stainless steel*
+60°C	+51%	+42%	+6%
-30°C	-60%	-36%	-4%

A further factor affecting the service life and utility value of an IGU is the time during which the opening in the primary seal occurs. Irrespective of the type of secondary sealant used, the opening occurs for the duration of the positive pressure difference. As discussed above, the degree of opening depends on the tensile stress of the secondary sealant. However, once the positive pressure differential decreases and an equilibrium is reached between inside and outside pressure, the length of time, required by the edge seal to close the primary seal, varies, depending on the degree of elastic recovery of secondary sealant utilised. Sealants with a low elastic recovery exhibit plastic flow in their stress strain behaviour; due to this relaxation mechanism their tensile stress decreases during maintained extension. As a result, when the applied force is eliminated, they are no longer capable of quickly closing the primary seal to its original size. If the secondary seal does not recover completely, the primary seal remains permanently deformed. Since the opening of the diffusion pathway occurs primarily at elevated temperatures, a secondary sealant with poor elastic recovery at elevated temperatures markedly shortens the service life of an IGU.

Apart from the fluctuations in temperature and atmospheric pressure, the ambient moisture level exerts an indirect influence on the opening and closing of the primary seal. At high moisture levels, and even more so in direct contact with liquid water, secondary sealants absorb water, which increases their volume and degrades their mechanical properties. In general, the lower the crosslinking density of the polymeric sealant network, the higher the water pick-up is. For the most part, the extent of the negative effects caused by the water pick-up is directly proportional to the amount of water absorbed. The swelling of the secondary sealant results in an opening of the primary seal, whereby the effective diffusion cross-section is increased.

3.2 Changes in transport mechanisms induced by edge-seal ageing

As mentioned before, exposure of an IGU to environmental or service degradation factors causes ageing of the edge-seal. This ageing can induce other transport mechanisms for the ingress of moisture or loss of gas. An indication that such ageing occurs during the service-life of an IGU is the increase in moisture penetration over time. Without ageing, under steady-state conditions, and at a time far from saturation of the desiccant, moisture ingress into an IGU per time unit should be a constant. As the IGU approaches saturation of the desiccant, moisture ingress should slow down, since the partial pressure differential equilibrates. However, measurements undertaken on units undergoing repeated humidity and temperature cycles in the laboratory as well as on those installed in the field often show a non-linear increase in moisture penetration with exposure time (Van Santen 1986, Marusch 1988), as shown schematically in Fig. 3.

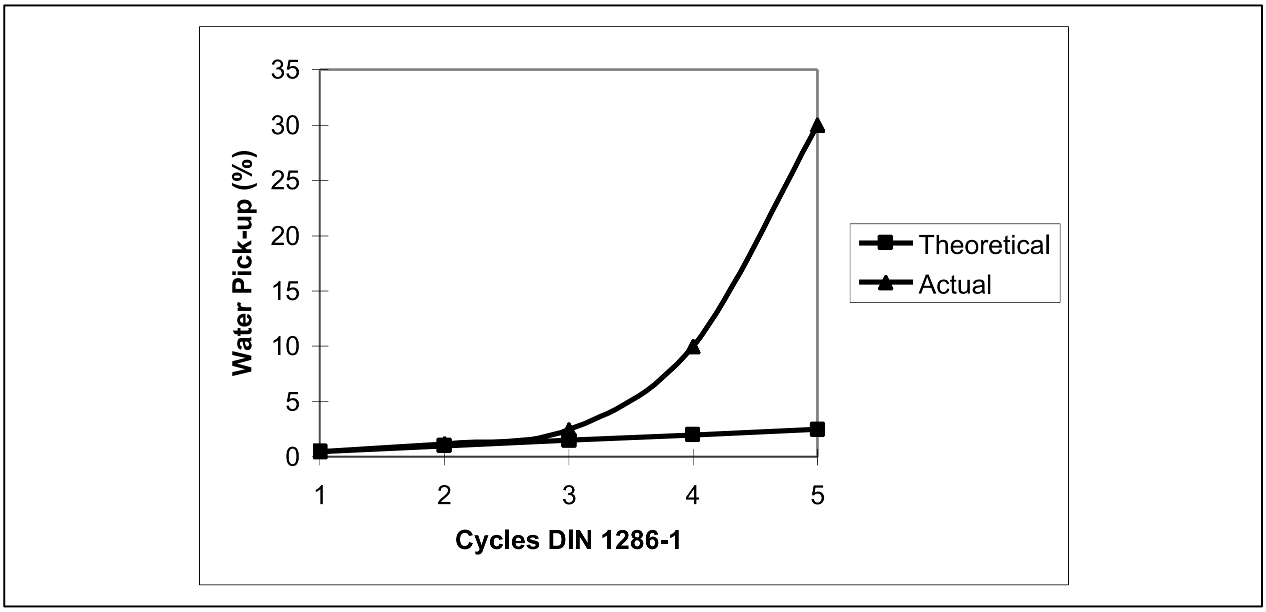

Figure 3. Non-linear behaviour of actual water pick-up with IGU ageing

One explanation for this phenomenon, favoured by Van Santen (1986), is the physical degradation of the primary seal, caused by the temperature and pressure induced movement in the edge-seal. Due to this repetitive movement, the primary seal may fail either cohesively or adhesively. Both failure mechanisms have indeed been observed in service, often combined with a migration of the PIB primary seal into the visible inter-pane space. Recently, much progress has been made in the design of spacer bars that allows reduction or elimination of this failure mechanism by restricting the ability of the PIB seal to migrate (Paci 1999).

As mentioned before, even in a regularly glazed IGU, a certain percentage of the incident light reaches the edge-seal via total reflection within the glass panes. When exposed to the destructive effects of the short wave spectrum of sunlight for prolonged periods of time, organic sealants may lose their glass adhesion. Schlensog (1986) monitored the evolution of organic sealant delamination from the glass substrate by using polarisation microscopy. The study showed that, before adhesive or boundary (thin-film) failure becomes visually detectable in the edge-seal, microscopic delaminations occur which, upon continued exposure, grow and interconnect, leading to macroscopic failure. It is highly likely that both moisture and gases migrate along this interfacial damage zone before macroscopic failure occurs, possibly with the moisture ingress accelerating this failure mechanism (Lefebvre *et al*. 1989); however, until now, this interfacial transport mechanism has not been experimentally verified for IGU edge-seals.

The repetitive shearing and peeling forces, caused by the differential in thermal expansion of spacer bar frame and glass plates as a result of edge-seal temperature variations, induce a high stress in the edge-seal, which may be compounded by ageing effects. Shear movements in joints induce a tensile stress component close to the sealant/substrate interface that is approximately twice as high as the original shear stress; this explains why sealants under shear tend to fail close to the substrate surface (Wolf & Iker 1992). If a secondary seal hardens in service, the resulting increase in tensile stress may cause partial or complete loss of adhesion.

4 PREDICTION OF IGU SERVICE-LIFE

Various national accelerated test methods have been developed for the assessment of IGU performance (Burgess 1999). All of these methods are acknowledged to be without scientific verification, yet the methods have some corroboration through years of field experience, and sometimes are backed by systematic field correlation studies. However, as discussions during the development of international ISO and EN standards have shown, there is no generally accepted understanding of the interactions of the degradative factors influencing the service-life of IGUs. As pointed out by Burgess, already early-on during the development of the Pr-EN 1279 standard (EN 2000), it became apparent that no one actually knew what test regimes were most onerous on IGU edge-seals. The investigations within the CEN committee showed that low temperatures did not cause IGU failure, but that sustained high humidity, rather than high humidity cycling, was the main driver of moisture into sealed IGUs. However, the committee felt that they could not ignore low temperatures or cycling and agreed to split the test regime into two parts, one with high humidity cycling, and one with constant high humidity and temperature. The CEN committee also agreed to assess the performance of IGUs based on the moisture pick-up of the desiccant, the method used in the German standard DIN 1286-1 (DIN 1994), since this method allowed establishment of relative performance levels. The CEN test method is now thought to be more onerous than any existing national standard and to ensure a service life of the IGU in excess of 25 years (Burgess 1999).

Table 3 shows the water pick-up measured on the desiccants of various dual-sealed IGUs after exposure to temperature/humidity cycling according to DIN 1286-1 (DIN 1994) as well as after three months of constant high temperature (55°C) and high relative humidity (100%) (Wolf 1992). As can be seen, substantially higher moisture penetration was observed in the constant climate test than in the cyclic test. Interestingly, silicone dual-sealed IGUs exhibited the lowest moisture penetration of all units tested; contrary to what would be expected when considering the water vapour permeability of the secondary IGU sealants alone. Under constant high temperature and humidity, the performance advantage of silicone sealed IGUs becomes even more pronounced; the moisture penetration of the organic sealed IGUs is about three times as high as that of the silicone sealed units. Since the desiccant's water pick-up is inversely proportional to the life expectancy of an insulating glass unit, this finding indicates the by far superior service-life of silicone dual sealed IGUs when compared to those sealed with polysulphide or polyurethane sealants.

Table 3. Water penetration into IGU after different accelerated exposures.

Secondary sealant	*Water pick-up (weight %) after DIN 1286-1*	*Water pick-up (weight %) after 3 months 55°C and 100% rel. humidity*
Polysulphide 1	0.5	5.4
Polysulphide 2	0.8	5.6
Polyurethane 1	0.5	4.2
Polyurethane 2	0.6	4.5
Silicone 1	0.4	1.5
Silicone 2	0.4	1.6

The CEN committee also decided to adopt the requirements of the German DIN 1286-2 standard (DIN 1989) by restricting the gas loss rate to <1.0% per year. Annex B of pr-EN 1279-3 (EN 2000b) discusses the relationship between artificial and natural ageing with regard to thermal and sound insulation. Based on studies done on gas losses experienced by IGUs over a period of 10 years of service, the CEN committee assumes that a gas loss rate <1.0% per year after accelerated ageing ensures a total gas loss of <5% over 25 years of service. On the assumption that the improvement of the U-value with 100% argon filling is 0.4 W/(m^{2}K), this gas loss results in a deterioration of $\Delta U < 0.04$ W/(m^{2}K). Gas-filled IGU passing the requirements of DIN 1286-2 or Pr-EN 1279-3 are being manufactured successfully with polysulphide, polyurethane or silicone secondary sealants. However, since the requirements for gas-filled IGUs are especially demanding, some design and material selection factors must be carefully considered.

5 INFLUENCE OF DESIGN AND MATERIAL SELECTION ON SERVICE-LIFE

Table 4 provides an overview of the key material-specific performance characteristics of elastomeric secondary IGU sealants (for a more detailed discussion see Wolf 1992).

Table 4. Performance characteristics of elastomeric secondary IGU sealants.

Material property	*Polysulphide*	*Polyurethane*	*Silicone (alkoxy)*
Resistance of glass adhesion to sunlight	Poor	Poor	Excellent
Resistance of adhesion to water (long-term exposure)	Good to moderate	Moderate	Excellent to moderate
Elastic recovery			
at 23°C	Moderate	Good	Excellent
at 60°C	Poor	Moderate	Excellent
Change in Young's modulus with temperature	Very high	Moderate	Low
Water-swelling	Very high	High	Low
Water-vapour permeability			
(3 mm sheets) (g/(m^{2}d)	7-9	3-6	7-16
at 20°C	40-60	20-30	40-100
at 60°C			
DIN 1286-1 water pick-up (weight %)	0.5-1.2	0.4-0.7	0.4-0.6
dual-sealed IGU			
Argon permeability (0.6 mm sheets)			
(10^{-10} cm^2/(s cmHg))	1.5-1.8	8-30	250-400
DIN 1286-2 gas loss (% p.a.)	0.4-0.9	0.6-1.0	0.7-1.0
dual-sealed IGU			

Clearly, the key performance advantage of polysulphide sealants is their low gas permeability, which allows them to tolerate poor workmanship, at least up to a certain degree. The poor resistance of glass adhesion to sunlight prohibits the use of polysulphide and polyurethane sealants in structural glazing or roof glazing applications. Polyurethane generally show better physical properties and lower water-vapour permeability than polysulphide sealants; their main selling feature, however, is their lower price. The past ten years have seen an overheated competitition between polysulphide and polyurethane IGU sealants for market share in Europe. The resulting price war has forced some manufacturers to drastically lower the polymer content of their sealants and finally has caused the major manufacturer of polysulphide polymer and sealants to withdraw from the market (Anonymous 2001). There are now indications that premature failure rates of some polysulphide sealed units in the field have increased again, at least for certain installation conditions (wooden window frames) in Germany, ending the period of more than 20 years of increasing IGU performance achieved by continuous development of IGU components, assembly and quality assurance methods.

Silicone sealants, on the other hand, excel in the resistance of their glass adhesion to sunlight, making them the material of choice for structural and commercial glazing as well as demanding roof glazing applications. With over 20 years of experience with silicone sealants globally, the excellent performance and service-life of silicone dual-sealed IGUs have been demonstrated. One drawback of silicone sealants is their high gas permeability. However, recent experience has demonstrated

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that argon-filled, silicone dual-sealed IGU can be manufactured, which reliably pass DIN 1286-2 requirements, if certain design, manufacturing and quality assurance aspects are being met.

First, it has been demonstrated that IGU edge-seal systems, which have the ability to accommodate some movement within the spacer itself, place less stress on the primary seal and thus ensure low gas loss rates under accelerated and actual service-life conditions. Examples of such spacers that have been used in IGUs passing DIN 1286-2 are the Chemetall or Teroson TPS (see, for instance, Unger 1999) and Edgetech Super Spacer®. Second, IGU edge-seal systems that minimise differential thermal movement, especially within the sensitive corner region, tend to perform significantly better in terms of gas loss rates than systems with high thermal movements, as discussed earlier. IGUs of different designs, but based on stainless steel spacers, have passed the DIN 1286-2 requirements, while same or similar systems based on aluminium or galvanised steel spacers have failed. Companies that have successfully qualified IGUs based on stainless steel based edge-seal designs are St. Gobain, Cardinal Glass, Veltherm, and Interpane. Third, when using stainless steel spacers, those designs that minimise the amount of PIB primary seal migration into the inter-pane space should be preferred.

Bent spacer-frame corners, gas-filling techniques integrated into the IGU assembling process (rather than filling via holes drilled into the spacer), improved, semi-automatic PIB application equipment and in-line (heated) PIB primary seal presses have all substantially contributed to the minimisation of gas loss and helped with the improvement of quality and service-life of IGUs. The trend towards "warm-edge" IGUs favours the above mentioned edge-seal systems. Today, silicone dual-sealed IGUs can be produced that not only excel in their durability and longevity, but also reliably meet the stringent requirements for gas retention, and therefore provide optimum service-life and utility value.

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