Abstract

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 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-seal insulating glass unit, since the resistance of the edge seal to water vapour diffusion is determined almost exclusively by the low water vapour permeability of the PIB primary seal. On the other hand, 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, as these properties affect the ability of the primary seal to function.

In the case of gas-filled insulating glass units, the gas permeability of the secondary seal exerts a great influence on the gas leakage rate, since the gas permeabilities of organic primary and secondary sealants are approximately equal. When silicone sealants are used for the production of gas-filled insulating glass units, additional measures must be taken to ensure a gas-tight edge seal.

Keywords: Environmental influences, insulating glass units, illustrations, service life.

1 The development of sealed insulating glass units

Although the invention of the organically sealed insulating glass unit goes back to the 1940’s, the commercialisation of this type of insulating glass did not occur before the late 1950’s. During the 1960’s, it became rapidly apparent that, of the three basic types of the insulating glass edge seals - soldered, welded or sealed - the organic edge seal would prevail because of its technical and economical advantages.

The search for the optimum construction produced a whole series of insulating glass systems based on organic edge seals. Although each of these systems had certain advantages, very often they were outweighed by the disadvantages, and as a consequence these products disappeared relatively quickly from the market. Furthermore, during this stormy period of development only a few manufacturers of insulating glass had the necessary manufacturing know-how or employed adequate quality controls. Many smaller businesses began manufacturing sealed insulating glass units without having a thorough knowledge of the technology involved.

In the second half of the 1970’s, manufacturers of insulating glass units dealt more intensively with applying suitable quality assurance methods and further improving the design of the edge seal. Figure 1 shows the type of edge seal, which has been in most common use since the end of the 1970’s. A distinction needs to be drawn between the single-seal and the dual-seal insulating glass systems. With the former, the
groove above the spacer is sealed with just one sealant. With the dual-seal system, an additional thermoplastic seal is applied between spacer and glass panes.

Due to the consumer’s demand for a longer service life for insulating glass, the trend in Europe is clearly in favour of the dual edge seal system. Assuming that good quality assurance criteria are adhered to, a dual-seal insulating glass unit can be expected to have a service life of over 25 years. Around 70 million square meters of insulating glass were manufactured in Europe in 1990, over 85% of which were of the dual-seal design.

Since the beginning of the 1980’s, a whole series of testing and requirements standards have been introduced for insulating glass, these serving as the basis for the various national quality certification programmes (quality kite marking). This quality certification is requested by the insulating glass manufacturer and is conducted by independent, government-approved testing institutes. The certification is based on the testing and quality requirements specifications listed in Table 1.

The objective of quality certification of insulating glass units is to reject units with detectable flaws as early as the production stage by performing regular and simple tests within the scope of the factory’s own monitoring programme. This not only protects the consumer, it also saves the manufacturer avoidable consequential costs. The manufacture of insulating glass units has therefore been incorporated into a continuous chain of external and/or internal quality controls, beginning with the control of the insulating glass components such as glass, spacer and sealant, passing through the supervision of the manufacturing quality, and ending with the statistical final inspection and testing of the finished insulating glass unit.

2 Environmental influences on the insulating glass edge seal

Figure 2 shows the most important environmental factors, which installed insulating glass units have to withstand. It is obvious that the life expectancy of a bonded insulating glass unit is closely governed by the correct functioning of the primary and secondary seals. Literature on this subject often differentiates between physical and chemical stresses, although certain environmental influences, such as sunlight, exert both kinds of stresses.

2.1 Temperature
Temperature fluctuations produce differences in pressure within the insulating glass pane. These exert a strong mechanical stress on the edge seal, especially in the case of small units and unfavourable form factors (Figure 3). Furthermore, differences in thermal expansion result in shearing and peeling forces in the edge seal. Figure 4 shows the frequency with which certain temperatures occur in the area of the edge seal of a regularly glazed insulating glass unit over the course of one year. Low temperatures may exert a negative effect on the flexibility of the edge seal, whereas high temperatures accelerate most physical and chemical processes, such as the ageing of the insulating glass sealant and the diffusion of water vapour through the edge seal.

2.2 Atmospheric pressure/wind pressure
In the same way as temperature fluctuations, changes in atmospheric pressure also produce mechanical stresses on the edge seal. Added to these are rapid changes in
wind loads, such as a sudden build up of pressure caused by a gust of wind or the change from pressure to suction produced with swirling winds. The high frequency with which such pressure loads occur - several hundred thousands times during the service life of an insulating glass unit - and the speed with which the changes in load occur, place extreme demands on the elasticity and the ageing resistance of the insulating glass sealant.

2.3 Working loads
Movements resulting from the normal usage of the window generally exert extremely little or no influence on the life expectancy of the insulating glass unit. Naturally this presumes that the insulating glass unit is glazed into the window casement in compliance with generally accepted technical guidelines and that a flexible bearing exists between the unit and the window frame itself thanks to the use of backing tapes and glazing sealants or suitable gaskets. However, repeated abrupt movements, such as occur when the window casement unintentionally slams shut, produce a high mechanical load on the edge seal.

2.4 Sunlight
Sunlight exerts both physical and chemical stresses on the edge seal. The infrared component of the radiation thermally charges the insulating glass unit. This effect increases, if a tinted solar protection glass is involved, since then a portion of the visible light is also converted into thermal energy. Even on cold days, temperatures of up to 60°C can be achieved in the inter-pane space of such tinted insulating glass units. The resultant stresses in the edge seal are the same as produced by changes in temperature.

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. In the case of a regularly glazed insulating glass unit, the unit’s edge seal is protected by the casement; hence no sunlight strikes the edge seal directly. However, some 3% of the total light falling on the glass area of the window finds its way to the edge seal due to the total reflection in the glass panes (Figure 5). The glass adhesion of organic insulating glass sealants, such as polysulphides or polyurethanes, can be irreversibly destroyed by the high-energy short-wave spectrum of sunlight. 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.

Sunlight is regarded as perhaps the most important ageing factor due to the attendant thermal and photochemical effects [1-3].

2.5 Water, 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 condensed water for a protracted period of time - due to improper glazing, plugging of the drainage holes or whatever reason - organic insulating glass sealants absorb large quantities of water into the polymer
matrix, thereby greatly increasing the volume of the edge seal. 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. In their glazing guidelines the manufacturers of insulating glass therefore attach great importance to keeping the glazing rebate free of condensed 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 the insulating glass sealant. This process can be accelerated quite considerably under certain circumstances. It is well known from earlier days that, in cases where the backbiting of insulating glass units with putty was not free of voids, rapid condensation-failure of the units occurred, since water, penetrating into the putty, released the aggressive fatty acids, these then, combined with the water, rapidly attacked the edge seal.

This cause of damage has been greatly reduced in continental Europe since the introduction of new glazing guidelines, which do not tolerate the back-filling of sealed insulating glass units with putties with the exception of a small number of cases.

2.6 Oxygen, Ozone
Oxygen and ozone cause gradual oxidation and embrittlement of organic insulating glass sealants, particularly at elevated temperatures.

2.7 Aggressive atmospheric contaminants
These include gases such as chlorine, hydrogen chloride, sulphur dioxide and nitric oxides, the latter two being major components of acid rain. Depending on the concentration in which these gases occur, they can be expected to exert considerable chemical stresses on the edge seal. Detailed studies into this aspect are not yet available, however.

2.8 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. In a study into the ageing behaviour of insulating glass units conducted by the Institute für Fenstertechnik (Institute for Window Technology) for the German Federal Ministry for Construction [4] it was ascertained that the simultaneous action of water, elevated temperatures and sunlight constitutes the greatest stress on the edge seal of an insulating glass unit.

3 Selection and treatment of insulating glass components
The durability of an insulating glass unit is governed by the correct selection and treatment of the various components, such as glass, spacer, desiccants and sealants, by the processing quality during manufacture and by the correct glazing of the finished unit. The requirements on the insulating glass components, which do affect the functioning of the edge seal, will therefore be discussed briefly below.

3.1 Spacers
Aluminium and galvanised steel have proven popular materials for spacers. The cavities of the spacer profiles have to be large enough to accommodate the required quantities of desiccant. A spacer frame filled on four sides should be capable of holding minimum 40 grams of desiccant per running meter. Particular attention should be paid to the profile surface. Only dry, dirt free spacers, which have not been contaminated by chemical additives, provide suitable adhesion surfaces for insulating glass sealants. Adhesion surfaces can be chemically contaminated during the machining of the spacer section, since release agents such as stearic acid, graphite or petroleum may be used in this process.

These additives prevent the insulating glass sealant from gaining sufficient adhesion to the spacer frame. The trend towards dark-coloured window casements is accompanied by increasing use of anodised spacer sections. The grits and grinds created during the anodising process are removed with chemical agents, which may also detrimentally affect the adhesion properties of the insulating glass sealant.

It is therefore essential to regularly check the adhesion of the insulating glass sealant on the spacers being used, particularly, if a new type of spacer is to be used. The literature describes a series of adhesion tests of greater or lesser value. However, the following test procedure has proven particularly suitable for testing both one- and two-component insulating glass sealants and also includes the influence of water on the adhesion. The sealant is applied to the spacer section in the form of a 5 - 6 mm thick bead and is then spread out to a thickness of approximately 3 mm using a trowel. This specimen is stored for 24 hours in a closed glass container with a moisture-saturated atmosphere produced by spreading out damp cloths. The specimen is subsequently stored in water at a temperature of 50°C for 6 hours. Immediately after removing the specimen from the water, the adhesion of the sealant is examined by making a cut into the sealant and trying to peel it off. Ideally, the separation always occurs in the sealant itself, the adhesive failure, measured by the area of insufficient adhesion, should not exceed 30%.

The shape of the spacer is largely unrestricted provided it shows good mechanical stability and allows good, tightly sealed corner connections. In Europe, the type of spacer, which has become most common in practice, is the "economical spacer section" which reduces the quantity of insulating glass sealant required. It should be noted, however, that even this section type requires a minimum sealant depth (Figure 6) of 3 mm over the spacer when manufacturing standard insulating glass units. In accordance with the sealant manufacturer’s specifications, higher minimum sealant depth is required for sealing gas-filled insulating glass units.

As already mentioned above, the polyisobutene primary seal displays only plastic deformation characteristics. The constantly repeating pumping motions of the edge seal can result in a cohesive or adhesive failure of the PIB seal during the ageing of insulating glass units. This considerably reduces the life expectancy of the insulating glass unit since the water vapour can then penetrate through the rupture of the primary seal much more rapidly. The chances for a primary seal failure can significantly be reduced by using grooved spacers (Figure 7). The enlarged layer thickness greatly reduces the mechanical stress on the PIB primary seal.

The corner connections must be mechanically stable to avoid any adverse effect on the frame stability during the entire production process. Furthermore, the corners must
be sealed well to prevent the finished insulating glass from exhibiting any weak points for the diffusion of water vapour or gas.

There are four types of corner designs:

- welded corners - without corner keys
- plug-type corners - with metal corner keys
- soldered corners - with metal or plastic corner keys
- bent corners - with butt joint on the spacer side or with one plug-type corner

The most common corner design is the plug-type connection with metal or plastic corner keys. In order to ensure the tightness of the corner connections, the corner keys should be provided with recesses into which the secondary insulating glass sealant can penetrate, by this considerably extending the diffusion paths. Figure 8 shows such plug-type corners with recesses for the sealant. With this type of corner design, the viscosity of the sealant should be sufficiently low to allow the sealant to penetrate as far as possible into the recesses.

Various processes for manufacturing insulation glass units also use the primary PIB sealant to seal the plug-type corners. This is particularly advisable if the sealing is performed by means of an injection device. "Pressing in" the PIB by hand does more harm than good and should therefore be avoided. The corner keys should also have recesses along the edge so that the PIB sealant can run continuously around the corner.

Flash-butt welding of corners necessitates simple section forms and a minimum wall thickness of 0.8 mm. Ultrasonically soldered corners require special corner keys. The soldered spacer frame must not be subjected to excessive stress, otherwise hairline cracks may occur in the solder.

On the European insulating glass market, there is a clear trend towards bent spacer corners. This technology, which is available from various manufacturers, is based on the bending of four corners at right angles combined with the jointing of the spacer on the long side, or the bending of only three corners in combination with the fourth corner being plugged. The first of the two variants eliminates the corners and thus the weak points altogether, whereas the second approach at least reduces the penetration of water vapour via the corner connections to one quarter. In all tests according to the various national requirement standards, such as DIN 1286 [5] or BS 5713 [6], insulating glass units with bent corners perform considerably better than units with plug-type or soldered corners.

3.2 Glass
Flat glass sheets must be stored at a dry location protected from the elements (warehouse). If they are subjected to high humidity or even rain, alkalis are leached from the surface of the glass. The glass sheets "bake together", the glass surfaces become dull and they cannot be used for manufacturing insulating glass units. Even flat glass, which is stored properly, is generally contaminated on the surface. The contaminates may consist of organic substances such as oils or greases or inorganic substances such as silicate dust. The glass panes are generally cleaned in glass-washing machines equipped with separate prewash and rinse zones to ensure perfect cleaning of the
glass. The use of small quantities of active washing substances (detergents) in the prewash cycle has proven to be beneficial. The rinse zone, however, must be operated with demineralised water. The temperature of the water for both the prewash and the rinse phase must be at least 40°C.

### 3.3 Desiccant

Desiccants are used to absorb the moisture trapped in the inter-pane space during the production of the insulating glass unit as well as the moisture, which diffuses into the insulating glass unit during its service life. If sealants containing solvents are used in manufacturing insulating glass units, desiccants such as silica gel or 10 Å molecular sieve must be used which are able to adsorb solvents such as toluene or methyl ethyl ketone; otherwise there is the danger of a solvent dew point occurring in the inter-pane space.

### 3.4 Insulating glass sealants

The quality of the edge seal, and, consequently, the durability of the insulating glass unit is governed to a considerable degree by the type of sealants used. As already mentioned, the majority of insulating glass units today is manufactured using the principle of the dual seal. The primary seal of polyisobutene - frequently referred to simply as "butyl" - is thermoplastic and is used to reduce the water vapour and gas permeability of the edge seal. The PIB primary seal also serves as a fixing aid in the assembly of the spacer frame and the two glass panes.

Well-formulated polyisobutene sealants have the following features:

- high degree of resistance to light and heat ageing
- low permeability for water vapour and fill gases
- high surface tackiness and wettability
- good skin compatibility

The adhesion of the PIB seal to glass and spacer is purely physical in nature and is therefore not resistant to the protracted exposure to water. Polyisobutene is thermoplastic, which means that the strength of this sealant decreases rapidly as the temperature increases. Due its low hydrolytic resistance, its thermoplasticity and its lack of elastic recovery, the polyisobutene seal on its own is unable to guarantee a functioning edge seal under the various environmental stresses. An external, elastic seal - known as the "secondary seal" - is therefore required for this purpose.

Elastic secondary sealants are currently manufactured on the following raw materials bases:

- polysulphide (Thiokol®) two-component
- polymercaptane two-component
- polyurethane two-component
- silicone one- and two-component

Also represented on the market, although it enjoys only a small share, is the group of hot melts. These are one-component, thermoplastic sealants, which are heated to processibility and set again upon cooling.
In order to ensure good processibility and long-term functioning of the insulating glass edge seal, secondary insulating glass sealants should display the processing and material properties shown in Tables 2 and 3.

Tables 4 and 5 show the typical properties of insulating glass sealants on the basis of different raw materials [7]. Although insulating glass sealants on one and the same raw material base can still vary considerably in their formulations, the strengths and weaknesses resulting from the individual raw material base can be roughly outlined as follows:

3.5 Polysulphide sealants
Polysulphide insulating glass sealants are marketed only in the form of two component formulations. Crosslinking occurs through the reaction of mercaptoterminal disulphide oligomers after addition of oxidants such as lead dioxide or manganese dioxide with formation of further disulphide bridges. Approximately 70% of all insulating glass sealants are still being produced on this base. It is also the raw material base with which the longest field experience exists not only in Europe but also throughout the world. However, it should be pointed out that modern polysulphide sealants are by no means comparable with the formulations developed twenty years ago.

In the 1960’s, the initial phase in the development of self-adhering two-component polysulphide insulating glass sealants, phenolic and epoxy resin additives were used to enhance adhesion. Adding phenolic resins did improve the glass adhesion significantly, however these resins were found to cause fogging of the insulating glass units, due to organic condensates formed on the inside of the glass panes. These condensates were easy to spot, since they were of a yellowish or brownish hue, depending on the degree of their ageing by oxygen, heat and ultraviolet radiation.

In some instances, epoxy resins are still utilised as adhesion promoters and reactive resins in the “polysulphide epoxy sealants”, since adding epoxy resins not only improves adhesion but also greatly reduces water vapour permeability. This is why this type of sealant was recommended for years particularly for the manufacture of single-seal insulating glass systems. On the other hand, polysulphide epoxy sealants are extremely brittle; their tensile stress is about 1.0 MPa even at 25% extension and they do not permit any great absorption of movements, consequently glass frequently breaks, especially in small insulating glass units.

Regular polysulphide insulating glass sealants, as they are commercialised today, contain functional trialkoxysilanes as adhesion promoter. The functional organic group reacts with the polysulphide polymer during the compounding of the sealant. After the sealant has been applied, the alkoxy groups condensate with the silanol groups of the glass surface. The glass adhesion of the polysulphide insulating glass sealants thus results from the formation of siloxane bonds, as is the case for silicone sealants. It is therefore not surprising that the poor UV resistance of the glass adhesion displayed by polysulphide sealants is not caused by the deterioration of the siloxane bonds to the glass surface, but by degradation of the disulphide bonds in the polymeric backbone.
Until about 1985, lead dioxide was virtually the only oxidant used in the hardener component (part B) of polysulphide insulating glass sealants. Due to the toxicity of lead dioxide and the resultant difficulties with the handling and waste disposal of such sealants, manganese dioxide is predominantly used nowadays for vulcanising polysulphide insulating glass sealants, however, frequently still in combination with small quantities of lead dioxide as reaction initiator. The use of manganese dioxide as a hardener also results in an improvement in the ultraviolet light stability of the glass adhesion compared to that of polysulphide sealants vulcanised with lead dioxide. Due to the manufacturing process, polysulphide polymers contain a certain amount of free sulphur, which may cause incompatibility of polysulphide sealants with some glass coatings.

Polysulphide insulating glass sealants show a comparatively low permeability for fill gases such as argon or sulphur hexafluoride, whereby no special measures are required for manufacturing gas-filled insulating glass units apart from the greater edge seal bite. The life-expectancy of insulating glass units sealed with polysulphide sealants is, however, reduced by the low ultraviolet light stability of the glass adhesion and the high level of swelling produced by water absorption. Both mechanisms result in higher water vapour diffusion through the edge seal.

3.6 Polymercaptane sealants
Chemically this product group is closely related to the polysulphides and also has practically the same cure mechanism as the latter. Both product types therefore exhibit a very similar behaviour. As for polysulphides, polymercaptanes are also only available as two-component formulations. Disadvantages compared to the polysulphides, however, are the longer cure time and the poorer adhesion characteristics of the polymercaptanes. Furthermore, the glass adhesion of polymercaptanes is rapidly destroyed by ultraviolet light.

3.7 Polyurethane sealants
As is the case with polysulphide and polymercaptanes sealants, rapid cure with polyurethanes is guaranteed only for two-component formulations. Polyurethane insulating glass sealants are based on liquid polybutadiene polymers with terminal hydroxyl groups, which are chain-extended and cross-linked with aromatic diisocyanates by forming urethane groups. The properties of the polyurethane sealants are, therefore, largely determined by those of the polybutadiene backbone [8].

Polyurethane insulating glass sealants are characterised by good mechanical properties, especially high flexibility at low temperatures, and by a very low water vapour permeability. Disadvantages include the toxicity of the hardener component (diisocyanates), the sensitivity of the cure with respect to deviations in the mix ratio of more than +/- 10%, and the high degree of swelling caused by water absorption. Insulating glass sealants on a polyurethane base also exhibit a somewhat higher permeability for fill gases than those on a polysulphide base.

3.8 Silicone sealants
This product group encompasses one- and two-component formulations on the basis of different cure systems. All silicone insulating glass sealants feature superior mechanical properties, which are only slightly affected by the ambient temperature and a glass adhesion with extremely high resistance to ultraviolet light. In damp climates silicone insulating glass sealants absorb only very small quantities of water. Due to this fact they exhibit extremely low water swelling compared to organic insulating glass sealants. As will be demonstrated later, the low water swelling of the silicone sealants is one of the factors responsible for the excellent performance of silicone sealed insulating glass units in tests according to the various national certification standards. The high permeability of silicone sealants to argon is a disadvantage, however this can be overcome by constructive measures when manufacturing gas-filled insulating glass units.

3.9 Neutral cure two-component silicone sealants
Neutral cure two-component insulating glass silicone sealants were introduced to the European market at the beginning of the 1980’s. In the USA experience with them goes back about five years longer [9]. Curing of these sealants occurs by reaction of alkoxy silanes with hydroxyl endblocked silicone polymer, resulting in the formation of an elastomer network and an alcohol as cure by-product. The major advantages of these sealants are the outstanding mechanical properties, the excellent glass adhesion, and the low water swelling, as mentioned above, which are typical for all silicones, but also the chemically neutral cure system, which ensures good compatibility with all substrates encountered in the manufacture of insulating glass units. The two-component cure system allows adjusting the pot life and the speed of cure to the individual manufacturing requirements.

3.10 One-component silicone sealants
Acetoxy cure silicone sealants, which give off acetic acid during cure, have already been used in Europe for the manufacture of insulating glass since the end of the 1960’s. Neutral cure silicone insulating glass sealants, however, have only been available on the European market since the beginning of the 1980’s [9]. The products for which the longest experience exists are based on the alkoxy cure system, recently also oxime cure insulating glass sealants have been introduced onto the market. All one-component silicone formulations enjoy the positive application and performance properties typical for silicone sealants. Being one-pack products, they do not require any mixing and are ready-to-use. One-component silicone insulating glass sealants can be applied from cartridges, pails or drums using low-cost dispensing equipment. The advantage of alkoxy neutral cure silicone sealants lies in the fact that they do not corrode galvanised spacers or glass coatings and show relatively low water-vapour permeability. While oxime cure sealants do not corrode galvanised steel spacers either, incompatibilities have been observed with some glass coatings.

3.11 Hot melt sealants
Hot melt insulating glass sealants are based on butyl, partially crosslinked butyl, ethene acrylate, ethene vinyl acetate, block SBR, or polyamides. With this type of sealant, no chemical curing occurs; a hot melt sealant is rather converted into a processible state by heating the product above its melting point and letting it set again by
cooling. The obvious advantage of this product group is the rapid setting and the resultant fact that the finished insulating glass units can be shipped soon after manufacture. However, since no chemical cure takes place during the sealant setting, the material remains thermoplastic and its mechanical properties are therefore largely dependent on the temperature. Since the glass adhesion is purely physical in nature, it can be destroyed by protracted contact with water. Hot melt sealants can be applied with fairly simple dispensing equipment, which, however, requires heating of the drum and the transfer hoses to avoid premature setting of the sealant.

4 Life expectancy of insulating glass units

Over the course of time, water vapour diffusing in via the edge seal results in a saturation of the desiccant in the spacer, hence water condenses in the inter-pane space of the insulating glass unit, terminating its service life. The service life or the "life expectancy" of an insulating glass unit depends on the following factors:

- the dimensions of the insulating glass unit,
- the quantity, type and initial loading of the desiccant,
- the air temperature and relative humidity during the insulating glass manufacture,
- the resistance of the edge seal to water vapour diffusion, and
- the effective sealant cross-section through which the water diffusion occurs.

If all conditions are assumed identical and only the influence of the edge seal itself is considered, the life expectancy of an insulating glass unit should be the longer, the lower the amount of water vapour that diffuses through the effective cross section of the edge seal. The life-expectancy of a single-seal insulating glass unit is, thus, determined by the water vapour diffusion resistance of the insulating glass sealant used to prepare the edge seal. However, in order to estimate the life expectancy of such an insulating glass unit, the temperature dependency of the water vapour permeability of the insulating glass sealant needs to be considered. After all, the ageing of insulating glass is not isothermal at room temperature; on the contrary, as Figure 4 already illustrated, the edge seal is subject to a broad temperature distribution. The temperature dependency of an insulating glass sealant's water vapour diffusion rate or, more precisely, of its permeability P is described by the Arrhenius’ equation.

Insulating glass sealants therefore exhibit considerably higher water vapour permeability at elevated temperatures than at room temperature. As Table 6 reveals, the water vapour diffusion rate at 60°C is not just three times higher than at 20°C, it is an average of six to eight times higher. If the results of permeation tests [10] are plotted on a graph such as in Figure 9, it is apparent that the activation energy of diffusion depends mainly on the polymer type utilised in the insulating glass sealant. Consequently the water vapour diffusion rate of silicone sealants varies less as a function of temperature than is the case for organic sealants with a polysulphide base.

The practical consequences of these results must be examined: Although in Central Europe the edge seal of an insulating glass unit in subjected to temperatures over 30°C for only about 20% of the year, the insulating glass unit 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 tempera-
atures in association with high humidity therefore drastically reduce the life ex-
pectancy of an insulating glass unit. Since the diffusion rate of silicone sealants is less
dependent on temperature than in the case of organic sealants, the water vapour per-
meabilities of silicone and polysulphide insulating glass sealants tend to approach
each other at elevated temperatures. For single-seal insulating glass units (without
PIB primary seal) this study therefore indicates a comparable life expectancy of poly-
sulphide and silicone sealed insulating glass units - in contrast to frequently voiced
arguments, which are based on water vapour permeabilities determined at room tem-

Once the temperature dependency of an insulating glass sealant’s water vapour
diffusion rate is known, the life expectancy of a single-seal insulating glass unit can
easily be mathematically estimated, as has been demonstrated by Backman and others
[12-15]. Figure 10 is a graphical representation of the influence of the water vapour
diffusion rate on the life expectancy of a single-seal insulating glass within the scope
of Backman’s model.

Since the majority of the insulating glass units manufactured in Europe are dual
sealed, however, the water vapour permeability of the dual-phase insulating glass
sealant system and its dependency on temperature must be taken into account. The
water vapour diffusion resistance of a plane-sheet laminate is the sum of the individ-
ual resistances of the various layers:

The water vapour permeability of the PIB primary seal is by far lower than that of
the secondary seal, irrespective of whether the secondary seal is made of a silicone,
polysulphide, or polyurethane sealant. The water vapour permeability of the edge seal
is, therefore, determined almost exclusively by the permeability of the polyisobutene
sealant:

Experimental studies into dual-phase insulating glass seal systems [16] confirm
this theory, hence it could be assumed that the life expectancy of a dual-seal insulat-
ing glass unit 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. It is not unusual for an insulating glass unit not to
even realise its regular service life, which is limited by the inward diffusion of water
vapour. Such premature failure occurs, for example, when the insulating glass sealant
loses its adhesion to the glass. Both the initial adhesion to the glass surface as well as
the ageing behaviour of the sealant/substrate bond are determined by the type of seal-
ant utilised. Consequently, use of different insulating glass sealants will lead to differ-
ent probabilities of premature failure of the insulating glass unit. This is indeed the
case, however the probability of failure depends on the type of ageing the insulating
glass unit is exposed to. If, for example, an inclined window in the roof area is con-
sidered, where the insulating glass sealant is exposed to incident sunlight - even only
indirectly, due to the total reflection of the light inside the glass pane -, the probability
that insulating glass units sealed with organic insulating glass sealants will fail pre-
maturely is considerably higher than for others which were sealed with silicone sea-
lants. On the other hand, if one considers the insulating glazing of a swimming pool,
where water has collected in the window rebate due to a design error, the probability
of premature failure is determined by the hydrolytic stability of the sealant’s glass ad-
hesion. In such a case, sealants with an epoxy polysulphide base might perform better than those with a silicone base.

However, the assumption that the life expectancy of a dual-seal insulating unit is essentially independent of the secondary sealant selected, does not apply for the regular life expectancy either. Why is this the case? The assumption made at the outset that all boundary conditions remain the same and are independent of the selection of the secondary sealant is not valid. The decisive factor is the effective sealant cross section through which the water vapour diffuses. As already mentioned, the water vapour diffusion rate of PIB is considerably lower than that of the secondary sealant. The resistance of the secondary sealant to the transport of water vapour through the edge seal will therefore be completely ignored in the following study. Instead only its mechanical properties will be considered.

The effective cross section of the PIB primary seal through which the water vapour diffuses is determined by:

- the workmanship during manufacture of the unit,
- the pressure differential between the inter-pane space and the outside world,
- the dimensions of the panes,
- the tensile stress with which the secondary sealant resists an expansion of the edge seal, and
- the ambient moisture.

Pressure differentials between the inter-pane space and the environment may result from fluctuations in the ambient temperature and pressure or from sun shining on the insulating glass unit. These pressure differentials are temporary by nature; equilibrium will always be re-established. The cause of a permanent pressure differential between the inter-pane space and the environment may be the installation of the insulating glass unit at a geographical elevation which is different from that at the place of manufacture, however this situation will not be examined here.

The effect that the bulging of the insulating glass inwards and outwards at the centre of the pane exerts on the edge seal varies as a factor of the size of the pane. As already shown in Figure 3, the smaller the insulating glass unit, the greater the load on the edge seal is. The degree to which the primary seal opens up when there is a positive pressure differential between the inter-pane space and the outside climate is therefore determined by the tensile strength with which the secondary sealant resists this applied force. The tensile stress of the secondary sealant is itself a function of the temperature and - although to a much lesser extent - of the equilibrium moisture content in the sealant. In practice, positive pressure differentials occur at low atmospheric pressures or at high temperatures, whereby the temperature is responsible for most positive pressure differentials. The tensile stress behaviour of the secondary sealant at high temperatures must therefore be examined. Figure 11 shows the tensile stress values at 25% extension for various insulating glass sealants at room temperature, at 40°C and at 60°C. It is readily apparent that the tensile stress behaviour of polysulphide sealants exhibits the greatest dependency on temperature, followed by polyurethane sealants, whereas the silicone sealants disclose only a small dependence of tensile strength on the temperature. Due to the strong softening of the polysulphide
sealants at elevated temperatures, they lose most of the initial tensile strength they possess at room temperature.

A further factor affecting the service life of the insulating glass unit is the time during which the opening in the primary seal exists. Certainly this is the case for all of the secondary sealants used - irrespective of the material base - for the duration of the positive pressure difference. As just indicated, the size of the opening is a function of the tensile stress still present at elevated temperatures. 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 kind of secondary sealant utilised.

The cause for this lies in the differing elastic recovery of the secondary insulating glass sealants. Sealants with a low elastic recovery exhibit plastic deformation components in their stress strain behaviour; due to the plastic flow (cold flow) 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. The effect the elastic recovery behaviour of secondary insulating glass sealants has on the opening and closing of the primary seal is presented schematically in Figure 12.

Polyurethane and silicone sealants are characterised by a very high elastic recovery, whereas polysulphide sealants exhibit distinct signs of a cold flow even at room temperature. Figure 13 compares the elastic recovery of different secondary insulating glass sealants at 23°C and at 60°C. For this purpose, ISO 7389 test specimens were extended by 25% for 24 hours and stored at the test temperatures. The stress on the test specimens was then relieved and, one hour later, a test was conducted to ascertain the extent to which they had recovered their original form.

The differences are particularly noticeable at 60°C; a temperature at which a fast recovery is particularly important for the performance of the insulating glass unit. If the secondary sealant does not recover completely, the primary sealant remains permanently deformed. As a result, a higher diffusion area is available for the passage of the water vapour for a certain length of time, until a negative pressure differential arises which again closes the primary seal. A low elastic recovery of the secondary sealant at elevated temperatures, thus, markedly shortens the service life of the insulating glass unit.

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, the secondary sealants store water in their polymer matrix, which increases their volume and degrades their mechanical properties. For the most part, the extent of these negative effects is directly proportional to the amount of water stored. The volume increase of the secondary sealant results in an opening of the primary seal, whereby - and this exerts an especially negative effect precisely at high moisture levels - the extent of the diffusion cross section is increased. The secondary insulating glass sealants differ greatly in their propensity to store water in their polymer matrix. Figure 14 shows the amount of water absorbed by secondary insulating glass sealants in the form of their per cent weight gain while stored in 40°C water for 36 days. Due to the chemical nature of their polymer skeleton, polysulphide and polyurethane insulating glass sealants store considerably higher quantities of water than do silicone insulating glass sealants.
How do the various material properties of the secondary insulating glass sealants interact? Is the water vapour diffusion rate of the secondary insulating glass sealant or its mechanical properties decisive for the life expectancy of an insulating glass unit? There is no universally valid answer to this question. The interaction of the various material properties differs for every sealant. The ultimate effect of the interaction between the material properties can be examined through experiment, however, by determining the amount of water absorbed by the desiccant after subjecting the insulating glass units to a humidity/temperature accelerated ageing test cycling. The difference between the initial weight of the desiccant and the weight after concluding the accelerated ageing equals the quantity of water vapour that has diffused into the insulating glass unit during the test.

Table 7 shows the water pick-up measured on the desiccants of various dual-sealed insulating glass units following a humidity/temperature cycling test in accordance with DIN 1286, Part 1 [5]. It clearly reveals that the water pick-up of the desiccant was the lowest for the silicone dual-sealed insulating glass units examined. The difference in the behaviours of the secondary insulating glass sealants is even more striking, when the units are exposed to the worst conceivable climate: storage at constant high temperature and high humidity. To this end the insulating glass units were stored for three months at 55°C and 100% relative humidity. Table 8 shows the water pick-up measured on the desiccants of the various dual-seal insulating glass units as a function of the secondary sealants utilised.

The water pick-up of a polysulphide sealed insulating glass unit is almost twice as high as that of a silicone sealed unit. Since the desiccant’s water pick-up is inversely proportional to the life expectancy of an insulating glass unit - the more water vapour diffuses into the unit, the shorter its life expectancy -, it can be assumed that dual-seal insulating glass units manufactured with silicone sealants have a far higher life expectancy than those sealed with polysulphide or polyurethane sealants.

5 Service life of gas-filled insulating glass units

Filling the inter-pane space with special gases such as argon, sulphur hexafluoride, FCCs or combinations thereof, in place of dry air, results in an improvement of the thermal insulation capacity and/or the sound absorption of insulating glass units. The gas exchange between the inter-pane space of the insulating glass unit and the earth’s atmosphere is determined by the permeability of the edge seal and the partial pressure differential for each of the diffusing gases.

The earth’s atmosphere is composed primarily of the following gases:

<table>
<thead>
<tr>
<th>Gas</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen (N₂)</td>
<td>78.09%</td>
</tr>
<tr>
<td>Oxygen (O₂)</td>
<td>20.95%</td>
</tr>
<tr>
<td>Argon (Ar)</td>
<td>0.92%</td>
</tr>
</tbody>
</table>

The atmospheric pressure at sea level is 1013 HPa, whereby the individual gases forming the earth’s atmosphere exert a partial pressure based upon their fraction of the whole atmosphere. The partial pressure of oxygen at sea level thus is 212 HPa.
(20.95% of 1013 HPa), for example. In the case of an insulating glass unit filled with argon, the partial pressure of the argon inside the insulating glass unit therefore differs from that in the outside atmosphere, although no overall difference in pressure exists between the atmosphere and the inter-pane space. The rate of the diffusion process is determined by the difference between the partial pressures inside and outside the system under consideration.

The argon gas inside the insulating glass unit will therefore seek to diffuse through the edge seal to the outside atmosphere. For their part, the nitrogen and oxygen in the earth’s atmosphere will attempt to diffuse into the insulating glass unit to balance out the partial pressure differences. Each gas acts independently based on the partial pressure differentials and the edge seal’s permeability for each of these gases. Due to its nonpolar character and low atomic size, argon has a higher diffusion rate through the insulating glass edge seal than oxygen or nitrogen at the same partial pressure differential. An insulating glass unit will therefore lose argon more rapidly than oxygen and nitrogen diffuse into the unit. As a consequence, an under-pressure forms in the insulating glass unit, its magnitude being determined by the leakage rate of the edge seal. As the argon concentration in the inter-pane space decreases, so does the thermal insulation capacity of the unit, until finally it reaches that of an insulating glass unit filled with air. There are, therefore, good reasons for keeping the gas diffusion through the edge seal as low as possible.

The gas exchange process will, however, increasingly slow down over time, since the partial pressure differentials decay as the gas in the unit is diluted with air. A newly manufactured, gas filled insulating glass unit will see the highest gas exchange in its first year of installation. Assuming no physical degradation of the edge seal due to weathering, the exchange rate then drops every year thereafter relative to the exchange that occurred in the previous time period. If exchange rates remained constant, a perfectly filled unit with a 5% annual exchange rate would be expected to be air filled at the end of a twenty years time period. Since, however, the exchange rates decay as a function of the pressure differentials, this unit should actually still be 36% gas filled at the end of the said time period. The average gas fill level over the twenty years period, which is relevant for the average thermal insulation to be expected from that unit during this period of time, is 68%.

In Europe, the German DIN 1286, Part 2 [5], has assumed a leading role as a quality standard for gas-filled insulating glass units, since it is the first and, so far, the only quality standard for such insulation glass units. In the interest of European standardisation, the CEN committee TC129/WG4 is in the process of preparing a European standard which shall however be based largely on DIN 1286. The DIN 1286 tolerates a maximum leakage rate of 1% per annum.

As in the case of water vapour diffusion, the gas leakage rate is determined by the design of the edge seal as a whole, not just by the secondary sealant. Nevertheless, great differences exist between water vapour diffusion and argon diffusion through the edge seal: Whereas the PIB primary seal exhibits a very low permeability for water vapour and the secondary seal therefore has virtually no influence on the resistance of the edge seal to water vapour diffusion, the argon permeability of the polyisobutene is significantly higher, about the same as that of polysulphide sealants. The argon permeability of the secondary sealant therefore plays a much more important role. Table 9 compares the argon and sulphur hexafluoride permeabilities of thin
membranes of secondary insulating glass sealants to the gas leakage rates of dual-seal insulating glass units sealed with the same sealants. A basic finding is that all sealant types exhibit a considerably higher permeability to argon than to sulphur hexafluoride. Polysulphide sealants have the lowest argon permeability, followed by the polyurethane sealants, whereas silicone sealants intrinsically have a considerably higher permeability. Modifications in the formulation of silicone sealants, however, permit a significant reduction of their argon permeability. Hence one cannot speak in general of one silicone argon permeability.

Polysulphide sealants may be utilised for the production of gas-filled insulating glass units without necessitating major changes in the design of the edge seal. It is merely necessary to increase the depth of the secondary seal in accordance with the specifications of the sealant manufacturer. Silicone sealants, however, require additional action to achieve an edge seal, which is as gas-tight as possible. Particular attention is to be paid to the corner connections of the insulating glass spacer and the closure of the gas fill holes since the largest leaks usually occur at these points [17]. With the increased use of bent-corner spacers and the development of silicone sealants with low gas permeability, the regular production of silicone-sealed, gas-filled insulating glass units, which meet the requirements of DIN 1286, Part 2, is within reach.

6 Summary

After a development phase of over forty years, insulating glass units have now achieved a quality standard, which ensures an average service life of twenty to thirty years. The major prerequisite for the high service life of sealed insulation glass units is the permanent functioning of the edge seal.

The water vapour permeability of the secondary insulating glass sealant plays only a subordinate role in the life expectancy of a dual-seal insulating glass unit, since the resistance of the edge seal to water vapour diffusion is determined almost exclusively by the low water vapour permeability of the PIB primary seal. On the other hand, 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, as these properties affect the ability of the primary seal to function.

In the case of gas-filled insulating glass units, the gas permeability of the secondary seal exerts a great influence on the gas leakage rate, since the gas permeabilities of organic primary and secondary sealants are approximately equal. Within the group of elastic insulating glass sealants, the polysulphides exhibit the lowest, silicones the highest gas permeability, however the permeability can be greatly influenced by modifications in the sealant formulation. When silicone sealants are used for the production of gas-filled insulating glass units, additional measures must be taken to ensure a gas-tight edge seal, even where special silicone sealants with low argon permeability are involved. Here, the use of bent-corner spacers has proven particularly advantageous.

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