

Key factors governing technologies used on the growing China Insulating Glass Market.

Jean-Paul Hautekeer, Global Market Manager, Dow Corning SA
Dr. Andreas T. Wolf, Scientist, Dow Corning, Global Construction Industry
William Zhou China Technical Service Manager Dow Corning (Shanghai)

Keywords

1=silicone 2= Insulating Glass 3=China

Abstract:

The Insulating Glass (IG) market is undergoing a spectacular growth in China due to the nation wide effort on Energy Saving, creating major investments in manufacturing capabilities as well as raw material supply. However, the nature of the Chinese building market as well as its diverse climate conditions requires specific considerations in the choice of the technologies used to manufacture IG units to ensure customer satisfaction on longevity and performances. One can underline the high proportion of high rise buildings even for residential use; the higher tolerances faced in the construction, a very diverse and unique source of climatic conditions from heat, cold, humidity to pollution and last but not least the limitations in getting educated and quality conscious workforce. The paper will review in more details those parameters and compare them with the key characteristics of the different available sealing technologies to help the Industry Professionals in their IG system choice.

1. Functions and Properties of the IGU Edge-Seal

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 under all relevant loads, such as occur during manufacture, transportation, installation, and service (see Figure 1). The regular service life and performance of an IGU are affected by the diffusion of moisture and gases through the effective cross-section of the primary seal. The majority of premature failures of IGUs, i.e. field failures within a few years of installation, are caused by loss of adhesion of the secondary seal [1].

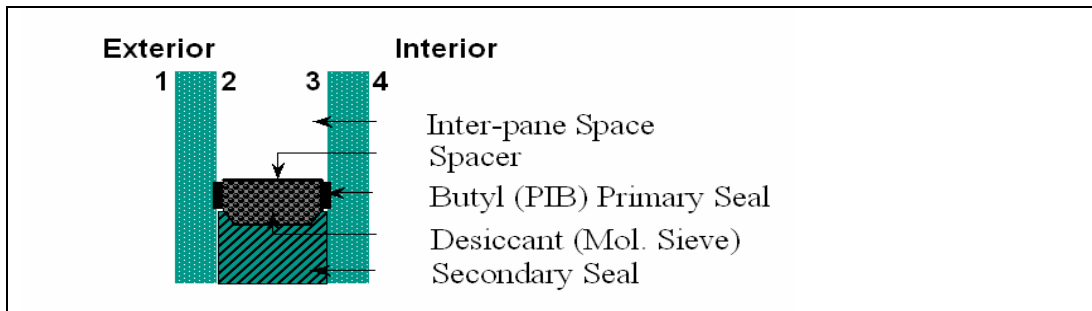


Figure 1 – Dual-Sealed Insulating Glass Unit

2. Stresses on the Edge-Seal of Insulating Glass Units

IGUs are exposed to a variety of environmental factors, such as temperature and atmospheric pressure fluctuations, wind loads, working loads, sunlight, water and water vapor that negatively affect their life expectancy [2]. 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 [1-4] 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 channeling of UV radiation to the interface by total reflection within the glass panes.

Therefore, an IGU edge-seal must have the following properties:

- Durability, i.e. resistance against environmental factors (both in terms of physical properties and adhesion)
- Structural strength that constrains movement in the edge-seal to minimize changes in the effective diffusion cross-section of the primary seal
- Low moisture- and gas-permeability under service conditions

3. Properties of Silicone Dual-Sealed Insulating Glass Units

As has been discussed before, actual IGU are exposed to a microclimate that strongly deviates from the ambient climate and is typically characterized by high temperatures and high humidity and, depending on the glazing (installation) situation, also high ultraviolet light levels.

So, why do silicone-sealed IGUs perform that well in such an environment? It is for the following reasons:

- Silicone dual-seal IGU have a lower moisture penetration rate under actual service conditions, because
 - in dual-seal IGUs, the permeability of the edge-seal is almost exclusively determined by the permeability of the primary (PIB) seal, and
 - silicone secondary sealants do a better job in maintaining a low effective cross-section for diffusion through the primary seal (as will be discussed, this is a result of their higher Young's modulus and higher elastic recovery at elevated temperatures as well as their tendency to swell very little under the influence of high moisture or water)
- Silicone dual-seal IGU achieve a higher life expectancy under actual service conditions, because
 - Physical properties and adhesion of silicone secondary sealants are very little affected by the key environmental ageing factor, i.e. ultraviolet light, heat and humidity.

3.1. Moisture-Permeability of Dual-Seal Insulating Glass Units

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:

$$\frac{d}{P} = \sum_{i=1}^n \frac{d_i}{P_i} \quad (1)$$

When considering moisture diffusion, the water vapor 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, polysulfide or polyurethane sealant. Therefore, the water vapor permeability of the dual edge-seal is determined almost exclusively by the permeability of the PIB primary seal:

$$P_1 \ll P_2 \Rightarrow \frac{d}{P} \cong \frac{d_1}{P_1} \quad (2)$$

Experimental studies into dual edge-seal systems [5] confirm this approximation. Figure 2 shows the moisture permeability of nine different commercial silicone and polysulfide secondary seals compared with that of the corresponding dual-seals. As can be seen, the moisture permeability of silicone sealants depends on their formulation. While in general the polysulfide

sealants tested have lower moisture permeabilities (at room temperature) than silicone sealants, these differences almost disappear, when the dual seal configuration is considered. It is important to note that, for experimental reasons, the moisture permeabilities were measured on a membrane thickness of 3 mm for the secondary seal and 1 mm for the primary seal. In an actual IGU, the typical thickness of the secondary seal would be about 4 mm that of the primary seal about 4-6 mm. With such an increased thickness of the PIB primary seal, there is essentially no difference in the moisture permeability of silicone or polysulfide dual seals, as can be calculated with equation (1).

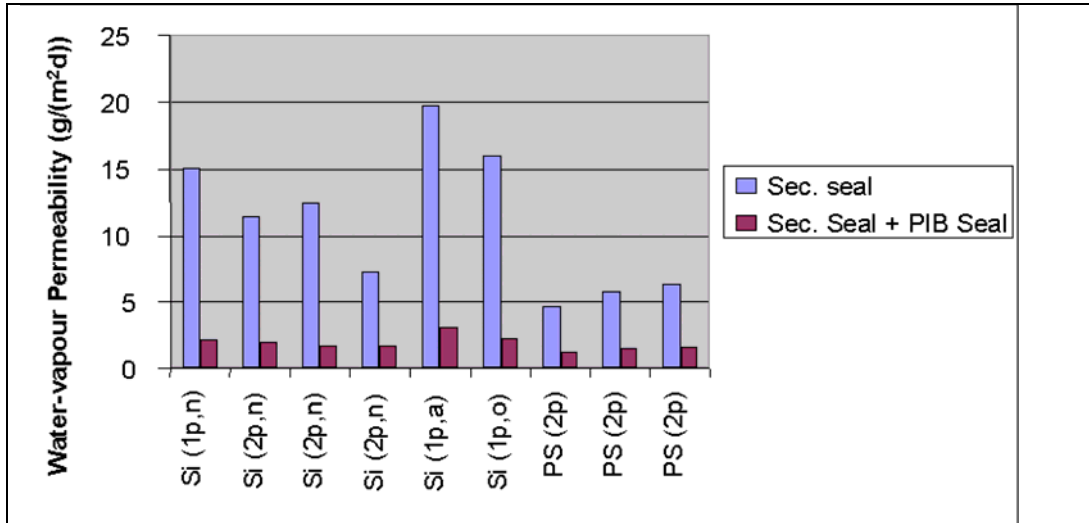


Figure 2 – Moisture Permeability of Secondary Seals and Dual-Seal Systems
 Notation: 1p, 2p: one- and two-part, n: neutral cure, a: acetoxy cure, o: octoate cure

3.2. Maintaining the Effective Diffusion Cross-Section of the Primary Seal

Obviously, the amount of moisture diffusing through the primary seal shows a linear dependency on the width and an inverse dependency on the depth of the primary seal (the wider and the thinner the primary seal, the higher the moisture diffusion). Therefore, maintaining the effective cross-section of the primary seal (as established after manufacture of the IGU) is very important for the longevity of the IGU.

Fluctuations in atmospheric pressure as well as heat gain from solar radiation causes pressure differentials between the gas enclosed in the inter-pane space and the outside atmosphere; these pressure differentials in turn then cause deflections in the IGU panes (see Figure 3).

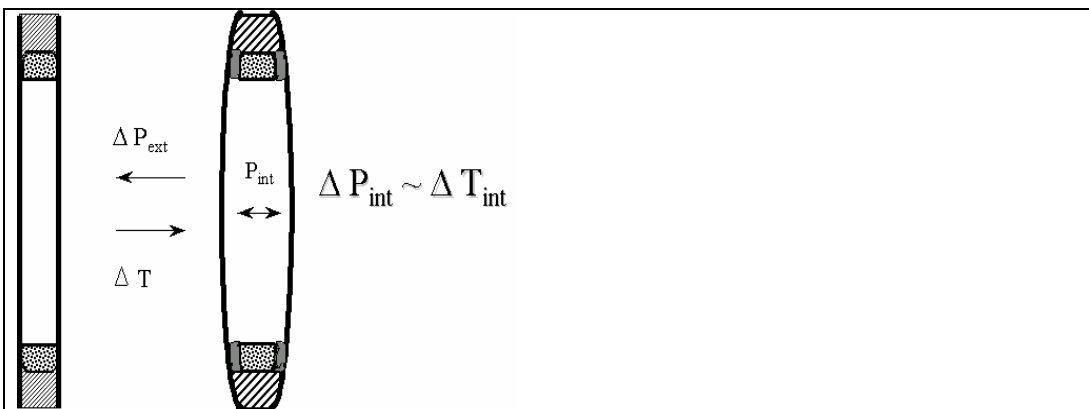


Figure 3 – Bulging of Glass Panes in an IGU Caused by Positive Pressure Differential

The effect that the inwards and outwards bulging of the glass panes exerts on the edge seal varies with the dimensions of the IGU. The induced stress is highest for small IGUs or units with high aspect ratio (one long side and one short side) as well as units with wide inter-pane space. The degree to which the primary seal expands when there is a positive pressure differential (higher pressure in the IGU than outside atmosphere) depends on the tensile stress (Young's modulus) with which the secondary seal resists this applied force. The tensile stress of the secondary seal itself depends on the temperature. In practice, high temperatures are responsible for most positive pressure differentials. As has been discussed before, the edge-seal in IGUs can easily reach temperatures of 60-80°C during summer. Therefore, the tensile stress behavior of secondary sealants at these elevated temperatures must be examined.

Effect of Temperature on Young's Modulus of Secondary IG Sealants

Figure 4 shows the temperature-dependency of the Young's moduli of various commercial secondary IG sealants based on silicone, polyurethane and polysulfide.

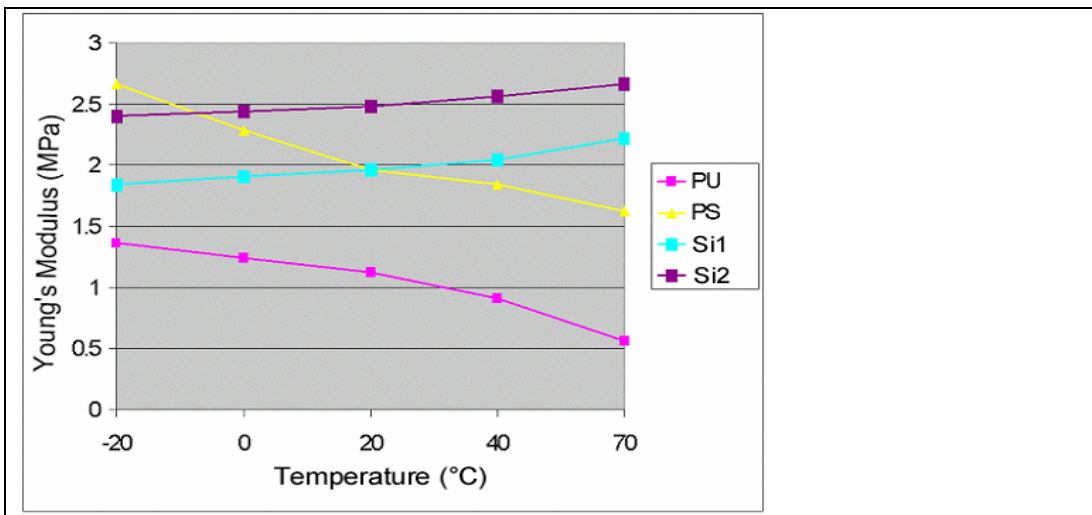


Figure 4 – Young's Moduli of Secondary IG Sealants as a Function of Temperature

As can be seen, both silicone sealants show behavior typical for ideal elastomers; their Young's moduli increase slightly with temperature. On the other hand, the moduli of the two organic sealants show a strong dependency on temperature: they harden at low temperatures and soften at elevated temperatures. This behavior is typical of materials with at least a partial thermoplastic character. For instance, the Young's modulus of the polyurethane sealant at 70°C is only about 1/3 of the value at -20°C. Because of their partial thermoplastic character, organic secondary IG sealants are less capable of resisting the expansion of the primary seal at elevated temperatures, thus more moisture diffuses into organically sealed IGU during periods of elevated temperature and humidity.

Effect of Temperature on Elastic Recovery of Secondary IG Sealants

The amount of moisture diffusing through the primary seal obviously is also dependent on the time duration during which the primary seal expands (the longer the seal expands, the more moisture diffuses into the IGU). The primary seal will certainly expand to a certain degree (depending on the Young's modulus of the secondary seal) during the duration of positive pressure differential. However, once the positive pressure differential ceases to exist, the time period, required by the secondary seal to return the primary seal to its original shape, varies, depending on the elastic recovery of the secondary seal (see Figure 5). As with the Young's modulus, the elastic recovery of a secondary IG sealant depends on the temperature.

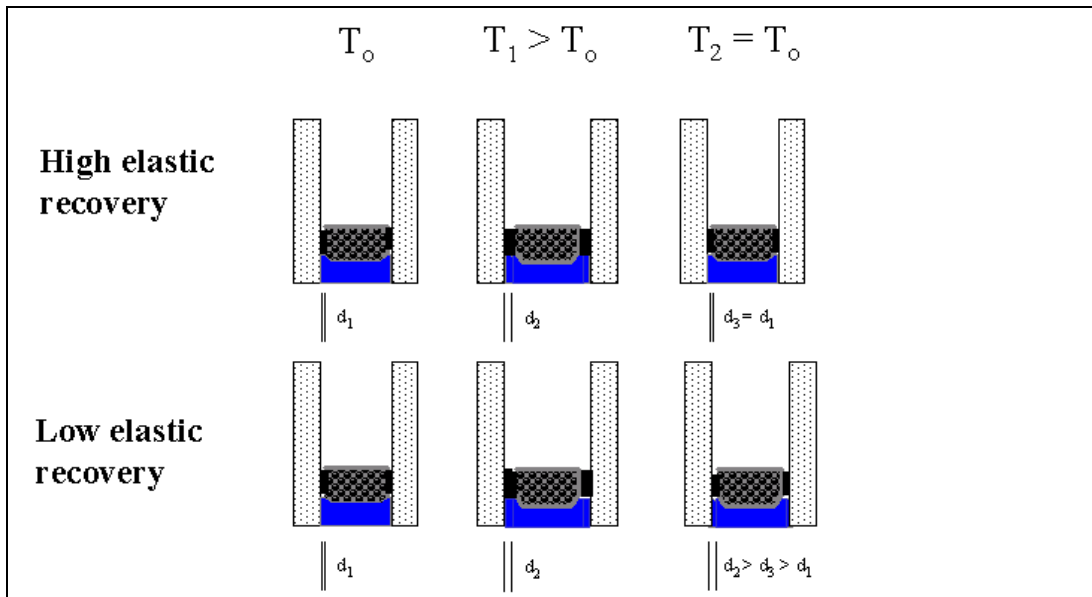


Figure 5 – Effect of Elastic Recovery on Returning the Primary Seal to its Original Shape

Figure 6 shows the temperature-dependency of the Young's moduli of various commercial secondary IG sealants based on silicone, polyurethane and polysulfide. As can be seen, the elastic recovery of all sealants decreases with temperature. However, while the silicone sealant shows the highest elastic recovery and only a very moderate reduction with temperature, the elastic recovery of the organic sealants tested decreases dramatically with temperature. As in the case of the Young's modulus, the thermoplastic character of the organic sealants influences the elastic recovery behavior: due to relaxation mechanisms (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 returning the primary seal to its original size. If the secondary seal does not recover completely, the primary seal remains permanently deformed. Consequently, a higher area is available for the diffusion of moisture for a certain period of time, until a negative pressure differential arises, which compresses the primary seal.

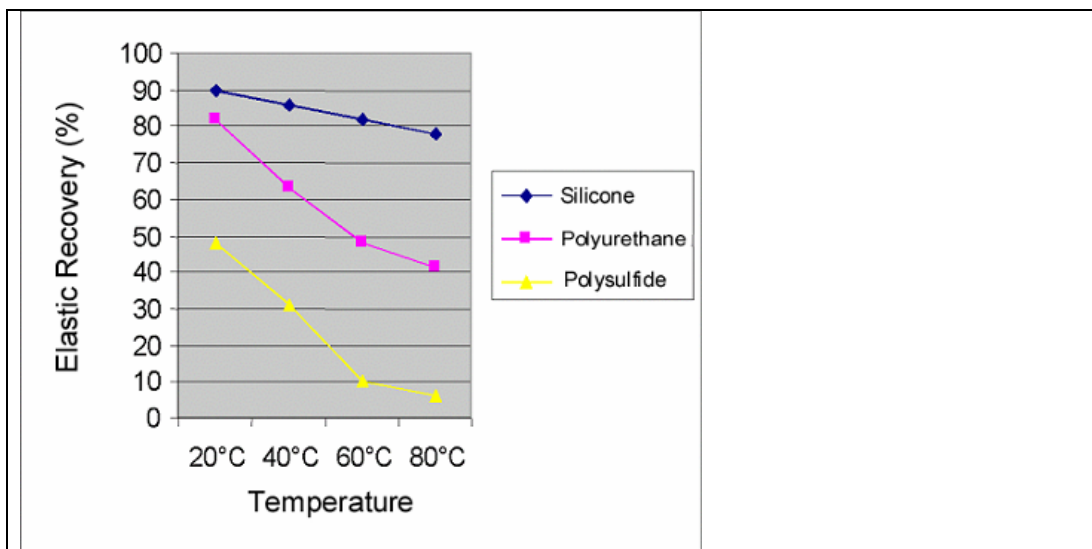


Figure 6 – Elastic Recovery of Secondary IG Sealants as a Function of Temperature

Water Pick-up and Swelling of Secondary IG Sealants

At high moisture levels or under water immersion conditions, secondary IG sealant store water in their polymeric network, 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 pick-up. The volume increase of the secondary IG seal results in an opening of the primary seal, whereby the effective diffusion cross-section is enlarged.

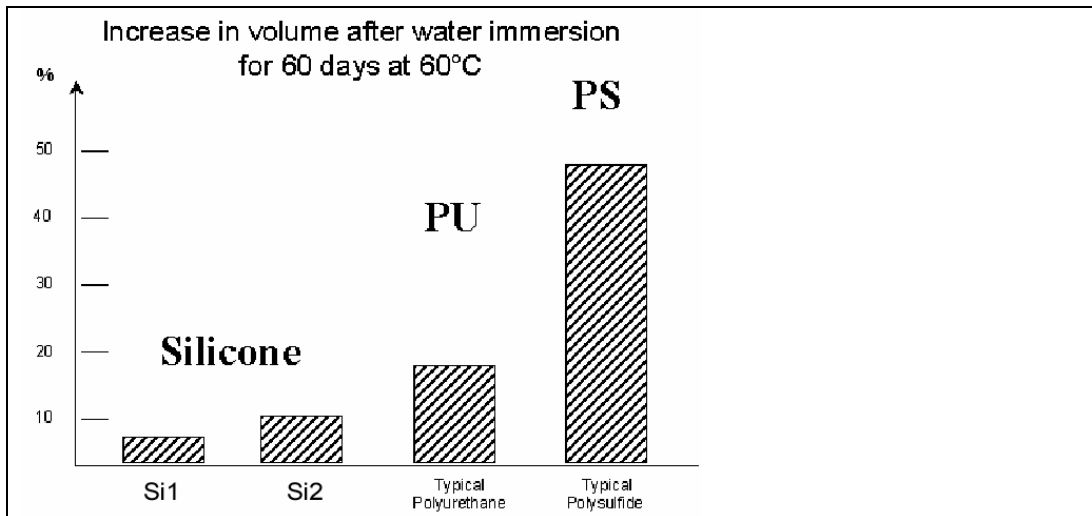


Figure 7 – Water Pick-up (Weight Gain %) of Secondary IG Sealants

Due to the chemical nature of their polymeric backbone, polysulfide and polyurethane sealants store considerably higher quantities of water than do silicone sealants.

3.3. Durability of Secondary IG Sealants

Contrary to organic sealants, both the adhesion and physical properties of silicone secondary IG sealants show excellent resistance against the combined effects of water, ultraviolet light and heat [6]. Figure 10 shows the changes in 25% secant moduli and tensile strengths of two silicone IG sealants during 20,000 hours of QUV weathering [7,8]. Specially formulated silicones are the only secondary IG sealant materials meeting or exceeding the requirements of standards for IGU used in structural glazing.

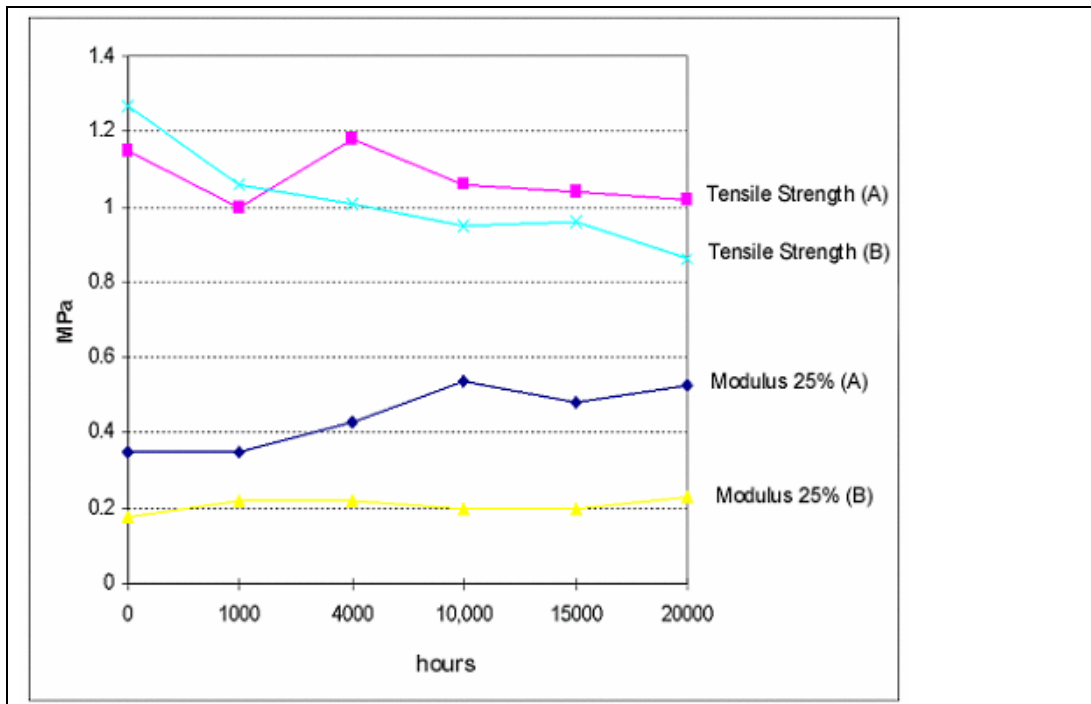


Figure 8 – Changes in 25% Secant Moduli and Tensile Strengths of Silicone Secondary IG Sealants During QUV Weathering

4. Comparison of Silicone and Organic Secondary IG Sealants

Figure 9 provides an overview of the key material-specific performance characteristics of the cured elastomeric secondary IGU sealants (for a more detailed discussion see [2]).

<i>Material property</i>	<i>Polysulfide (PS)</i>	<i>Polyurethane (PU)</i>	<i>Silicone (alkoxy) (Si)</i>
Resistance of glass adhesion to sunlight	Good	Moderate	Excellent
Resistance of adhesion to water (long-term exposure)	Good to moderate	Moderate	Excellent to moderate
Elastic recovery at 23°C	Moderate	Good	Excellent
Elastic recovery at 60°C	Poor	Moderate	Excellent
Change in Young's modulus with temperature	Very high	Moderate	Low
Water-swelling	Very high	High	Low
Water-vapor permeability (3 mm sheets) (g/(m ² d) at 20°C	7-9	3-6	7-16
Water-vapor permeability (3 mm sheets) (g/(m ² d) at 60°C	40-60	20-30	40-100
Argon permeability (0.6 mm sheets) (10 ⁻¹⁰ cm ² /(s cmHg))	1.5-1.8	8-30	250-400
Water pick-up (weight %) of dual-sealed IGU	0.5-1.2	0.4-0.7	0.4-0.6
Gas loss (% per year) of dual-sealed IGU	0.4-0.9	0.6-0.9	0.7-0.9

Figure 9 - Performance characteristics of cured elastomeric secondary IGU sealants

Clearly, the key performance advantage of polysulfide sealants is their low gas permeability, which allows them to tolerate poor workmanship, at least up to a certain degree (voids in the primary seal still lead to accelerated gas leakage, however, the gas loss is slow enough not to visually noticed). The limited resistance of glass adhesion to sunlight prohibits the use of polysulfide and polyurethane sealants in structural glazing or roof glazing applications. Polyurethanes generally show better physical properties and lower water-vapor permeability than polysulfide sealants; their main selling feature, however, is their lower price.

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 that argon-filled, silicone dual-sealed IGU can be manufactured, which reliably pass DIN 1286-2 and EN 1279-3 requirements.

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 minimization of gas loss and helped with the improvement of quality and service-life of IGUs. 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 insulation value.

This is because the properties of the polyisobutylene (PIB) primary seal and those of the silicone secondary seal complement each other very well. Table 2 shows the information provided in Table 1 in simplified form and considers the effect of combining the primary PIB seal with the various secondary seals.

<i>Material property</i>	<i>PS</i>	<i>PU</i>	<i>Si</i>	<i>PIB</i>	<i>PIB/PS</i>	<i>PIB/PU</i>	<i>PIB/Si</i>
Resistance of glass adhesion to sunlight	++	+	++++	+++	++	+	++++
Resistance of adhesion to water (long-term exposure)	++	+	+++	--	++	+	+++
Elastic recovery							
at 23°C	+	++	+++	--	+	++	+++
at 60°C	--	+	+++	--	--	+	+++
Change in Young's modulus with temperature	--	+	+++	--	--	+	+++
Water-swelling	--	-	+++	+	--	-	+++
Water-vapor permeability							
at 20°C	++	+++	+	++++	++++	++++	++++
at 60°C	+	++	+	+++	+++	+++	+++
Argon permeability (0.6 mm sheets)	+++	++	--	++++	++++	+++	++
Overall performance of dual-sealed IGU					++	++	+++
IG for Structural Glazing (SSG)					--	--	++++
Water pick-up (weight %) of dual-sealed IGU					++	+++	++++
Gas loss (% per year) of dual-sealed IGU					+++	++	++

Figure 10 – Combined performance characteristics of primary and secondary IGU sealants

As can be seen, silicone dual-sealed IGUs provide the best overall performance and can be used in demanding applications, such as

- High-quality residential and commercial glazing
- Applications involving high exposure to ultraviolet light, e.g. green houses, roof glazing, structural glazing
- Applications involving specialty glass types (laminated glass, low-E glass, reflective solar protection glass, etc.)

- Applications involving high levels of heat or humidity and/or cold climates
- Transportation applications (trains, buses, etc.)

Finally, it should be mentioned that there are also key differences in the characteristics of the wet (uncured) sealants. Silicones are far less sensitive to mixing problems (deviations from the specified mixing ratio) than polyurethane sealants. Furthermore, silicones are more 'worker-friendly' in terms of industrial hygiene considerations than both polyurethane and polysulfide sealants.

5. References:

- [1] Feldmeier, F., Heinrich, R., Hepp, B., Schmid, J. and Stiell, W., *The Ageing Behavior of Insulating Glass* (in German), Institut für Fenstertechnik, Rosenheim, Germany, October 1984.
- [2] Wolf, A.T., 'Studies into the life-expectancy of insulating glass units', *Building and Environment*, **27** (3), pp. 305-319 (1992).
- [3] Van Santen, N., 'The ageing behavior of insulating glass - laboratory tests to predict the long-term performance of insulating glass units' (in German), *Glaswelt*, **39** (3), pp. 12-20 (1986).
- [4] Lowe, G.B., *The Durability of Adhesion of Sealants to Glass*, Ph.D. Thesis, De Montford University, Leicester, England (1992).
- [5] Massoth, A. and Wolf, A.T., 'Studies into the water-vapor permeability of single- and dual-phase insulating glass sealant systems', *Kautschuk und Gummi, Kunststoffe*, **41** (9), pp. 882-887 (1988).
- [6] Wolf, A.T., Ed., *Durability of Building Sealants, RILEM State-of-the-Art Report*, RILEM Publications, Cachan, France, 2000.
- [7] ASTM G53-96 Standard Practice for Operating Light- and Water-Exposure Apparatus (*Fluorescent UV-Condensation Type*) for Exposure of Nonmetallic Materials, American Society for Testing and Materials, West Conshohocken, Pennsylvania, USA, 1996.
- [8] Wolf, A.T., 'Durability of silicone sealants', *Durability of Building Sealants, RILEM State-of-the-Art Report*, A.T. Wolf, Ed., RILEM Publications, Cachan, pp. 253-273 (2000).