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Experimental Study on Durability of IGU Sealant Constructions

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The saving of energy has been an important topic for the last years. However, not only for building constructions but also in the field of naval architecture the energy revolution affected the used materials. Insulation glass units (IGU) are used on ships, because of their increased thermal insulation value, but their known problem of durability remains. Already after a few years, naval insulating glass units fog up on the inner site of the glass panes and get unusable. The insulating glass units are exposed to higher stress in the naval environment compared with building constructions. We have to consider comparatively high wind loads that results in thick glass packages. The dead weight of the outer panes are usually transferred via the edge sealant. Structural Sealant Glazing Systems (SSGS) without mechanical self-weight support are commonly used. Furthermore, there is the contact with saline water and high UV-radiation. Because of the movement of the ships around the world, the climatic load assumptions for stationary buildings do not apply. All these loads cause a pillow effect and stress the edge sealant to a point of an increased moisture transfer into the cavity. We conducted two-month artificial ageing tests according to DIN EN 1279-2. The experimental investigation included 67 insulating glass units and reference specimens, which are composed of 4 mm fully tempered glass and 12 mm cavity between the panes. The scope included bent and connected spacers, a variety of secondary sealant systems with an emphasis on novel permanent pressure equalisation structures. After the tests, it was possible to compare the moisture penetration of different edge sealant systems. Furthermore, we compared the aged with reference insulating glass units. We used these data to analyse the impact of the artificial ageing program on the sealants durability. The experimental investigation shows that the climatic loads have a strong influence on the gas transfer through the edge sealants of the insulating glass units. Systems, which enable the insulating glass unit to connect the gas cavity with the ambient air, absorb less moisture compared with reference systems. The results will allow us to evolve more durable sealant systems. Additionally, we can optimise the artificial ageing program for marine glazing products.

Keywords: Insulating Glass, Edge Sealant System, Durability, Pressure Equalisation, Marine Glazing

1. Introduction

1.1. State of the Art

Insulating glass units consist of two or more glass panes and a spacer from stainless steel, aluminium or plastic that keeps the panes at a defined distance (figure. 1). A two-stage sealing system ensures the structural bonding and impermeability of the insulating glass units (IGU). The primary sealing is made of polyisobutylen (PIB) and is arranged between the panes and the spacer, normally with a thickness of 0,25 mm on each side of the spacer. The primary sealing is responsible for the impermeability of the insulating glass unit while the secondary sealing ensures the structural bonding on the back of the spacer. Elastomeric materials, such as polysulfide (PS), polyurethane (PU) and silicone (S), fit this purpose.

The spacer contains a desiccant. It gathers remaining humidity and extends the lifetime of the insulating glass unit. Inert gas (argon, krypton or xenon) fills the cavity between the panes to improve the thermal insulating value. Most of the time argon is used because krypton and xenon are rare and more expensive. The lifetime of an insulating glass unit is limited by the relative humidity in the cavity between the panes and the gas leakage rate (not part of the paper). The moisture in the cavity condenses at the glass surfaces if the desiccant is saturated. The defect insulating glass unit is not transparent at room temperature anymore and has to be replaced.

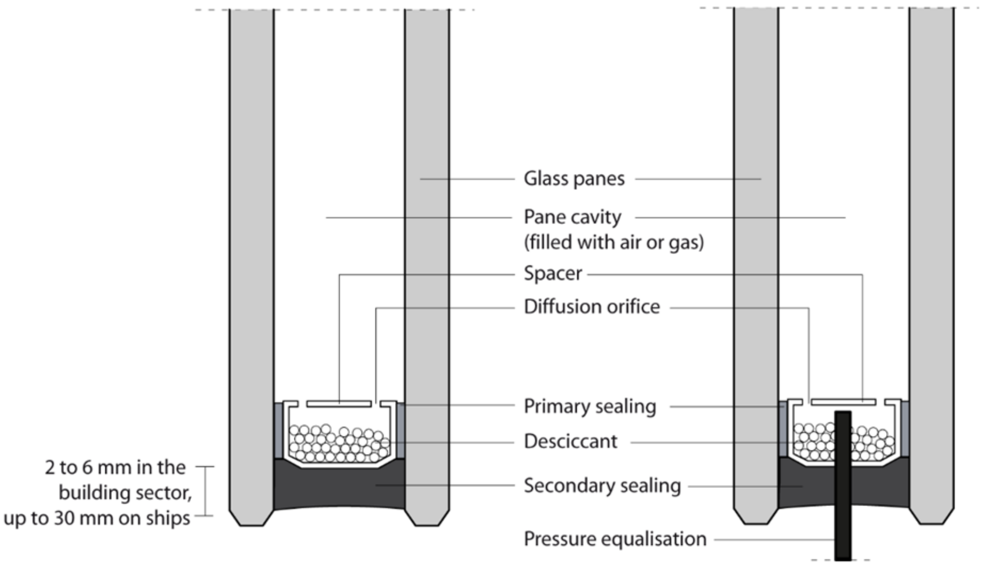


Fig. 1 Simplified illustration of insulating glass units without (specimen A – F) and with (specimen G) a pressure equalisation

As vessels travel around the world, the maintenance of IGUs takes place in the harbour where extensive crane services are necessary in a limited time schedule. Thus, the insulating glass manufacturers in the shipbuilding sector increased the thickness of the secondary sealing. In the building sector, 2 to 6 mm of secondary sealing on the back of the spacer is commonly used. In marine insulating glass units, the edge has a size of up to 30 mm. Despite this solution, the insulating glass units on vessels cannot withstand the maritime environmental sufficiently long and get unusable after a few years. Other solutions for durable marine glazing units are not present at this time.

The aim of this research work is the improvement of marine glazing units by using a permanent pressure equalisation (see figure 1) to minimise the impact of the climatic loads and increase the durability.

1.2. Requirements

Because of reasons like energy saving and comfort, insulating glass units are used on cruise liners and ships on inland waters. Generally, two-sheet insulating glass is used in the ship's hull (cabin, salon, pontoon bridge). Nowadays, insulating glass units made according to building construction principles with an increased thickness of the secondary sealing are in use on vessels. These IGUs cannot resist the impact of the maritime environmental and fog up on the inner site of the glass panes (figure 2). That is why glazing units are damaged after only a few years, sometimes after a couple of month.

Fig. 2 Insulating glass units with moisture in the closed cavity between the glass panes

Vessels are in action around the world that is why the replacement of few glazing units is connected with expensive material and personnel costs. The results are elaborate and cost-intensive repairs and regular exchanges of defect insulating glass units. Therefore, the number of defect insulating glass units is almost negligible only the maintenance cycle is important for the cost reduction.

1.3. State of Research

Since the insulating glass unit was invented, engineers tried to improve the durability. Nowadays, two-stage sealing systems with a spacer are the most used system. To improve the system, the materials, the thickness and chemical components are subject to change to reach a longer lifetime of the insulating glass unit. Buddenberg investigated the effect of a change of materials on the climatic loads to reach a gas-proof edge sealant system (Buddenberg 2015).

Currently there are two ways to enable the insulating glass unit to exchange pressure with the ambient air. Either there is a closed cavity between the glass panes that can be opened and closed with a valve (non-permanent) or there is an opening for the whole lifetime of the insulating glass unit (permanent). The benefit is a reduced stress on the edge sealant system (Rose 2015).

The valve is used during the transport the glazing trough high level differences to accommodate pressure differences between the closed cavity and the barometric air pressure. Such structures exist in different versions like in the patent of Zurn (2003). Because of the possibility to seal the cavity with the valve after the barometric pressure equalisation, these glazing can be handled like an insulating glass unit without pressure equalisation. It is assumed that the inert gas does not leave the cavity during a short time opening of the vale. Thus, the cavity can be filled with argon or another inert gas and is standardised in the DIN EN 1279-1 (2015). The disadvantage is that as soon as the valve is closed, the climatic loads from the change in temperature and the change in atmospheric pressure keep stressing the edge sealant system.

An additional solution is a system with a permanent opening that connects the cavity with the ambient air. The detriment of this structure is that it cannot be filled with inert gas, because it is in a permanent exchange with the ambient air. There are a lot of ideas for the practical implementation (Küffner 1987, Hagen 2008). Research institutes investigate on the influence of the climatic loads on the gas permeability. Rose (2015) found that insulating glass units with a permanent pressure equalisation significantly reduce the displacement of the glass panes due to climatic action. Therefore, this method is suitable to decrease the stress on the sealing system and increase their long-term durability.

2. Approach

2.1. Specimen

First, we have to analyse which components affect the durability of the edge sealant system. In this study aluminium spacers with connected and bent corners were used (type A/B, table 1). Thereby, type A is considered as the reference edge sealant system.

Table 1: Tested specimens

Type	Spacer Corner	Primary Sealing	Secondary Sealing	Description	Number of Specimens
A	Bent	Polyisobutylen	Polysulfide 6 mm	Reference	13
B	Connected	Polyisobutylen	Polysulfide 6 mm	Spacer Corner	9
C	Bent	-	Polysulfide 3 mm	Without primary sealing	9
D	Bent	Polyisobutylen	Silicone 6 mm	Silicone as secondary sealing	9
E	Bent	Polyisobutylen	Polyurethane 6 mm	Polyurethane as secondary sealing	9
F	Bent	Polyisobutylen	Polysulfide 6mm	Ceramic Coating	9
G	Bent	Polyisobutylen	Polysulfide 6 mm	Pressure equalisation	9

Next part of the edge sealant system is the primary sealing. Nowadays, polyisobutylen is state of the art because of its high denseness. To improve this sealing we can modify the thickness of the polyisobutylen and the size of the spacer simultaneously. In this study, the effects of the size was not analysed. One specimen was tested without a primary sealant (type C, table 1) to show the impact on the level of gas tightness.

To investigate which material was suitable for the secondary sealing in a maritime environment, the three most used materials were part of specimens of type A, D and E (table 1). Thus, the impact of the material on the tightness of the edge sealant system is evaluated.

Ceramic coatings on the inner side of the outer glass pane (position 2) are standard for marine glazing units to protect the sealants from UV-radiation. To exclude any influence of the ceramic coating on the gas tightness of the edge sealant system, type F specimens were tested.

Finally, we proved the functionality of the pressure equalisation by installing an air tube that connected the cavity between the glass panes with the ambient air (type G, table 1). The air tube had an inner diameter of 1 mm and a length of 2 m, the material is polytetrafluorethylene. The combination of the length and the inner diameter enabled the specimens to adjust the pressure from the climatic loads, but it is supposed to prevent a permanent exchange of the ambient air and the gas in the cavity. To make sure that the climatic conditions inside the climatic chamber did not influence the pressure equalisation, the endings of the air tubes were placed outside the climatic chamber (figure. 3).

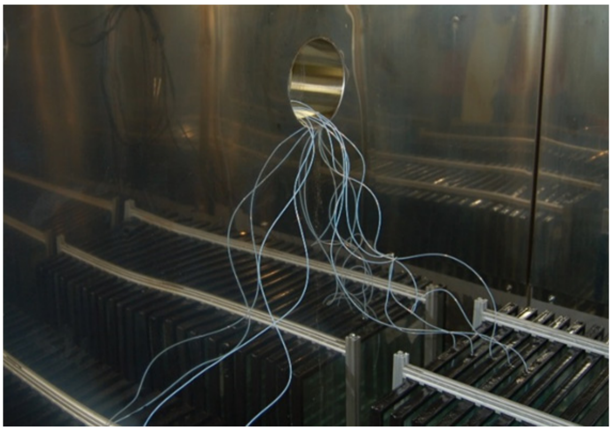


Fig. 3 Air tubes connect the insulating glass units and the outside of the climatic chamber

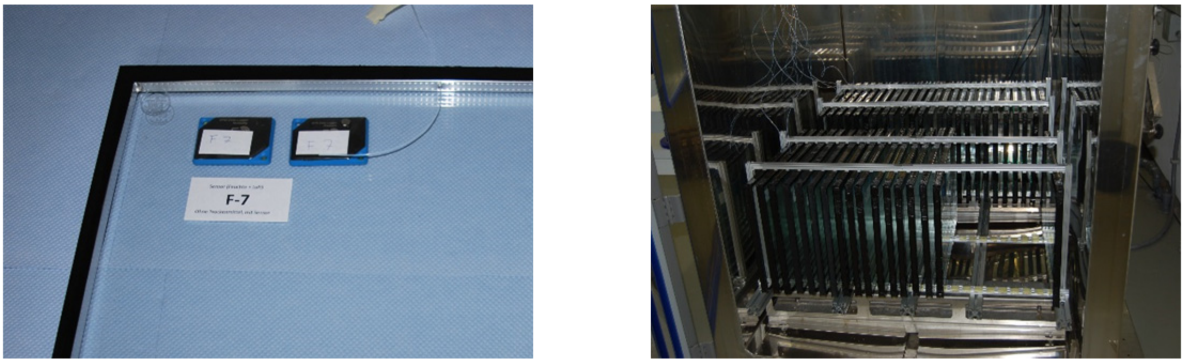
The size of all specimens is based on DIN EN 1279-2 (2015) with a width of 352 mm and a height of 502 mm. The glazing construction is built up of two 4 mm fully tempered glass panes and a cavity with a width of 12 mm. In this experimental setup, specimens for each type A-G were tested (Table 2). The specimens were separated for different use in the program. Four specimens of type A were produced to examine the moisture load before the artificial ageing starts. This start value applied for all tested specimens. Furthermore, there were seven specimens of each type for the artificial ageing and two specimens as reference. The reference specimen were stored under constant laboratory conditions (23°C, 50 % r.h.) while the rest of the specimens were artificially aged in the climatic chamber. There were also specimens without desiccant for the use of data loggers, this is explained in the next chapter.

Table 2: Tested specimens according to the use in the test program

Type	Total number of specimens per type	Thereof, specimens for		
		Start value determination	Artificial ageing tests	Reference
A	13	4	7	2
B-G	9	-	7	2
total	67	4	49	14

2.2. Laboratory Testing

The artificial ageing and the data acquisition were realised in the Friedrich-Siemens-Laboratory of the Institute of Building Construction at Technische Universität Dresden. Preliminary tests were performed with measuring sensors with a cable connection between the sensor and the measuring computer. Thus, the cables interfered the edge sealant. That was why in the presented test realisation wireless data loggers was used (figure 4 a). Thus, the edge sealant system was produced without any disturbance.



a) b)

Fig. 4 a) Data loggers in the closed cavity between the glass panes, b) Test specimen in the artificial ageing chamber

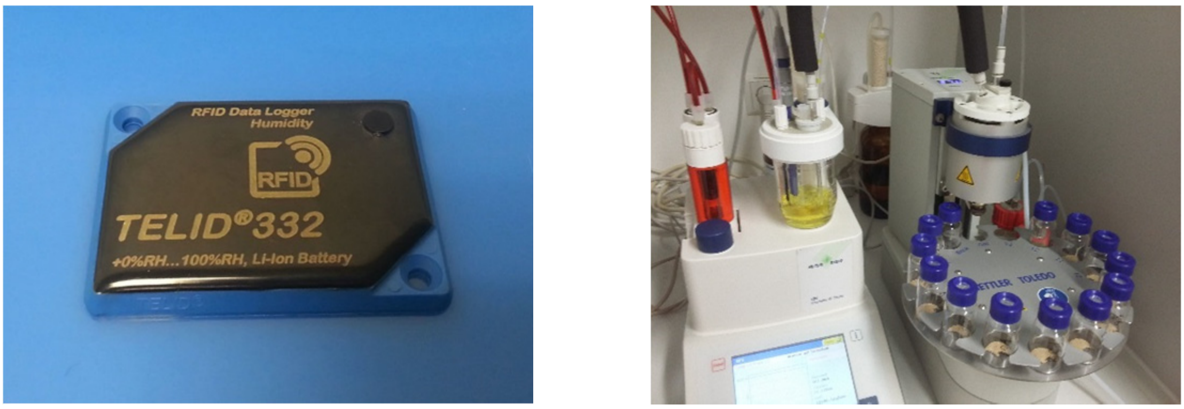
For artificial ageing, 49 test specimens were placed in the climatic chamber. Thereby, attention was paid that the insulating glass units stood vertically in the manufactured frame (figure. 4 b). It was ensured that the insulating glass units were not prone to additional loads caused by the frame. Thus, the climatic loads in the climatic chamber influenced the humidity absorption only.

2.3. Data Acquisition

For the permanent data recording two different data loggers of the company "Mycrosensis" have been used. One data logger recorded the temperature and the relative humidity (figure 4 a and 5 a), the other one recorded the barometric and the atmospheric pressure. The desiccant would take up all the incoming moisture and prevent measurement of the changing humidity inside the specimens. Therefore, all insulating glass units, which were equipped with data loggers, were produced without desiccant. The pressure measuring would be influenced by this effect also. To illustrate this point, reference specimens with desiccant were equipped with data loggers for comparison (table 3). The used data loggers started to work at the day the insulating glass units were produced at a measuring rate of 30 min^{-1}, they stopped to record at the end of the artificial ageing.

Table 3: Tested specimens according to the use of data loggers

Type	Total number of specimens per type	Thereof			
		With desiccant		Without desiccant	
		With data logger	Without data logger	With data logger	Without data logger
A	13	1	10	2	-
B-G	9	1	6	2	-
total	67	7	46	14	-



a) b)

Fig. 5 a) Telid 332 Data logger for temperature and relative humidity, b) Karl-Fischer-Titrator in use with desiccant specimen

Another possibility to quantify the penetrating humidity is the Karl-Fischer titration (figure 5 b), which is described in the DIN EN 1279-2. The titrator measures the fraction of moisture within the desiccants weight. To determine a start value the moisture content of four specimens was controlled at the date of delivery (see table 2). It was assumed that the desiccant took moisture while the insulating glass units were produced. The specimens that were artificially aged and the reference specimens were analysed after the artificial ageing.

2.4. Artificial Ageing Tests

The artificial ageing accelerates the damage of the edge sealant systems and thereby increases the amount of penetrating moisture. The more humidity penetrates the insulating glass unit, the more obvious is the difference between the analysed edge sealant systems. Therefore, the mandatory testing for moisture absorption in the DIN EN 1279-2 inspired the used artificial ageing only. To simulate marine conditions, the maximum and minimum temperature was adapted and the temperature cycle conditioning was extended to eight weeks without the seven weeks of constant temperature conditioning (figure 6).

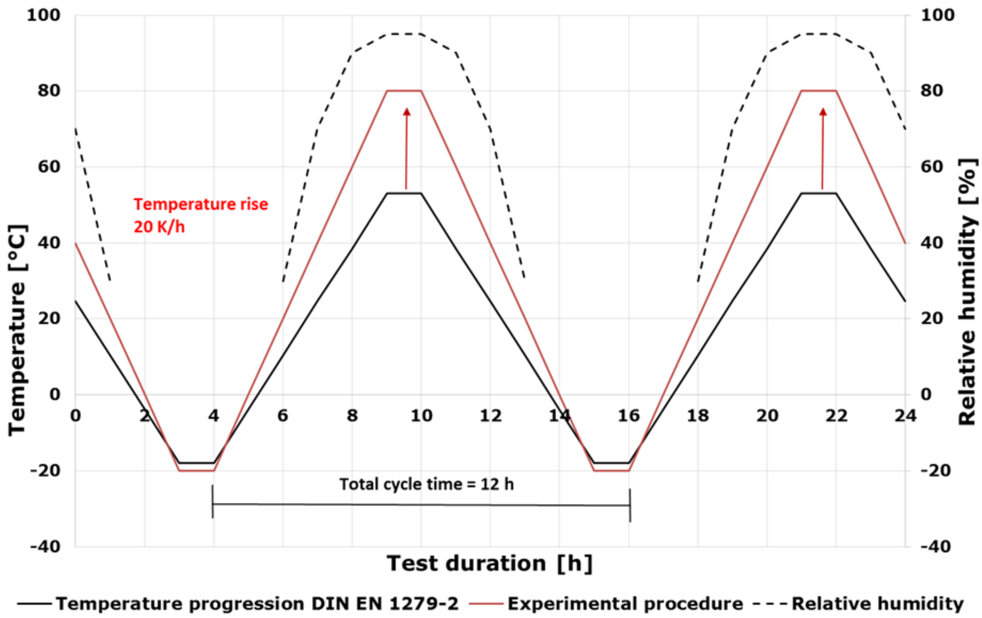


Fig. 6 Comparison of the artificial ageing program according to DIN EN 1279-2 and the experimental test

To adjust the temperature range without changing the test duration of one cycle, the temperature increase between the minimum and maximum was set to 20 K/h. Thus, during the artificial ageing every cycle consisted of one hour of constant +80°C and one hour of -20°C. Between these constant plateaus, two areas with a changing temperature for five hours each were set. In combination, every cycle lasted twelve hours.

The adjusted temperature range was used for a faster artificial ageing. There was no data available to prove which temperature may be expected inside a marine glazing unit. However, it was assumed that in the area of the edge sealant system temperatures can result in the range of +80°C and -20°C, because of the black colour of the used sealants and the ceramic coatings. It was further assumed that this temperature is realistic for a marine glazing during their lifetime.

3. Results and Conclusions

3.1. Test Process

The specimens were produced by the company "Polartherm Flachglas GmbH" close to the location of the examination at the beginning of March 2015. The type E with polyurethane as secondary sealant had to be produced by "Schollglas" also close to Dresden. After the insulating glass units were delivered, the conditioning of the specimens at laboratory conditions (23°C, 50 % r.h.) was started. The artificial ageing started after 2 weeks of conditioning and ended after eight weeks running. Figure 7 shows the recorded condition in the IGU. Partially the temperature remained unchanged in the cycles and over a period of the two weeks with a constant temperature of +72 °C. This was detected after the analysis of the data loggers. The results pointed on a temporary defect of the climatic chamber. Additionally, some wireless data loggers failed. Therefore, we removed the respective data from further analysis. The results were used for a first subjective evaluation of the penetrating humidity.

After the artificial ageing, the specimens were removed from the climatic chamber and were stored in the laboratory, while the data loggers and the desiccant were extracted and examined.

3.2. Absorption of Humidity

Figure 7 shows the results of the data loggers. One can see the temperature profile inside the insulating glass units from the day of production to the end of the artificial ageing (black line). The data shows that the temperature affects the relative humidity. The diagram shows only the relative humidity measured at a temperature between 22 and 23 °C for comparison.

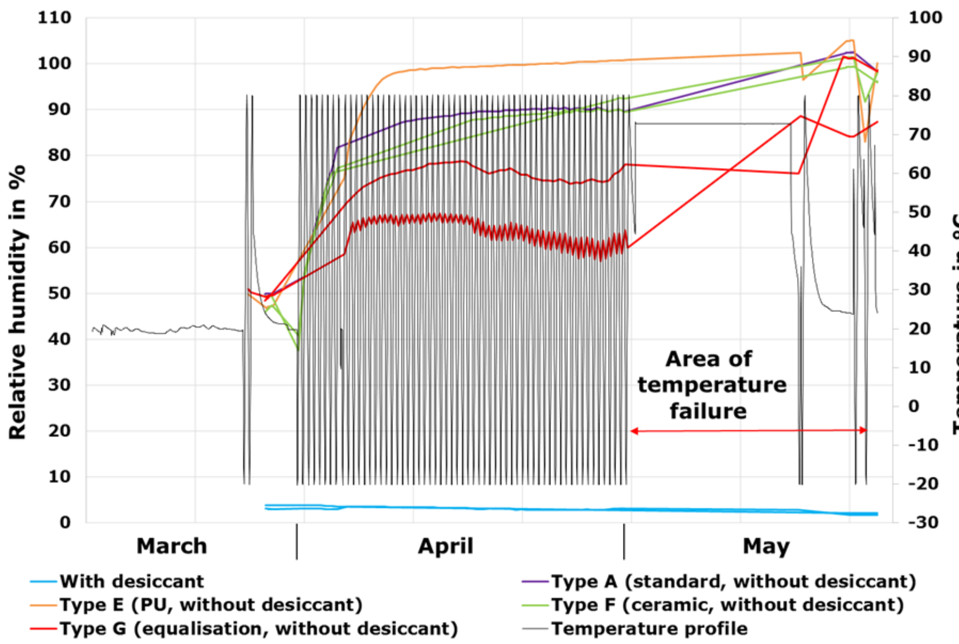


Fig. 7 Relative humidity and temperature in selected insulating glass units

First, the blue lines shows two specimens with desiccant in the spacer. The relative humidity inside the closed cavity was constant at a low level and never exceeded 4 % relative humidity. This fact shows that the desiccant took all the penetrating humidity immediately and it was not possible that the inner site of the glass panes fogged up.

Next, the coloured lines of the edge sealant systems type A, E and F without a pressure equalisation showed a rapid rise of the relative humidity in the first weeks to reach a level of balance with a relative humidity over 70 %. All of these specimens showed condensation moisture on the inside of the glass panes after the artificial ageing. The consequence of this observation is the knowledge that these insulating glass units are prone to penetrating moisture. Their desiccant in a real-life structure will be saturated quickly. Thus, they will have to been replaced after a limited lifetime.

Interesting is the progress of the type G specimens with the possibility of pressure equalisation (red lines associated with two specimen in figure. 7. This option showed the smallest increase of the relative humidity compared with the other specimens. Both specimens of type G showed no condensation moisture on inside of the glass panes. This first impression may lead to the assumption that the pressure equalisation enabled the insulating glass units to resist the impacts of the climatic loads. It adapted approximately the value of the ambient air in the laboratory outside of the climatic chamber. .

Figure 8 shows the moisture content in the insulating glass units before and after the artificial ageing. Thus, the edge sealant systems can be compared and the mechanism of the individual parts of the edge sealant systems can be analysed. The start value indicates the moisture content of the desiccant before the specimens the artificial ageing (type A from table 2). The black line illustrate this start value in the diagram. The mean result of 1,21 % is used for comparison of all specimens.

The seven types A-G of specimens are divided in columns in the diagram. Diamonds as symbols mark the reference specimens, which were stored for the eight weeks without an artificial ageing. These reference specimens enabled the authors to give a statement about the efficiency of the artificial ageing. It can be seen that most of the reference specimens do not show any difference between the start values and the value after the storage over the whole test procedure. As a result, the specimens do not absorb a measureable amount of moisture during constant laboratory conditions. However, there is one exception: both reference specimens of the type E with polyurethane as secondary sealant showed an increased moisture content in the desiccant without any impact from the outside. The presumption was proved that polyurethane is the weak point in the edge sealant system.

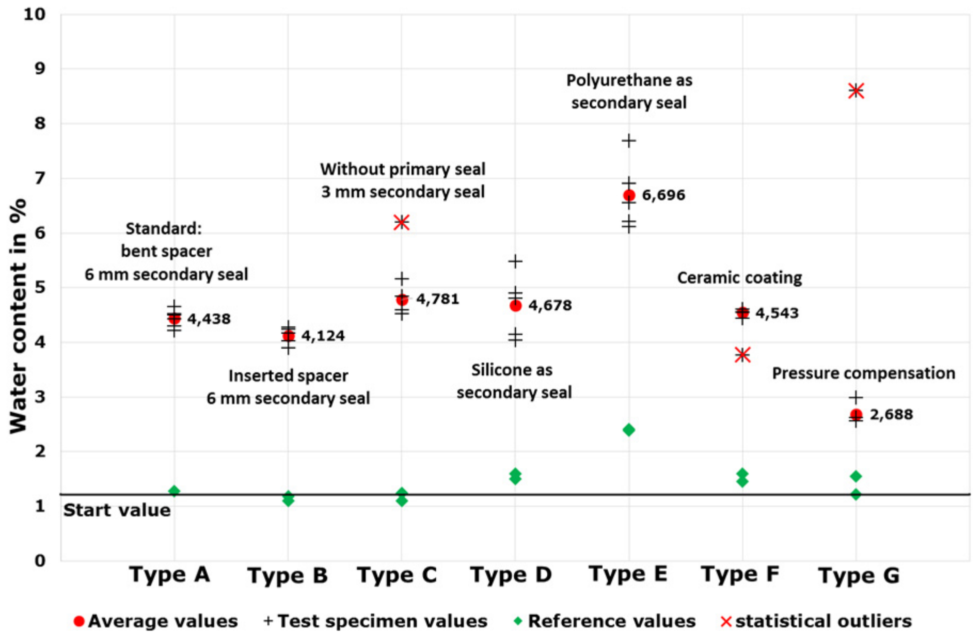


Fig. 8 Moisture content in the desiccant of the insulating glass units after the artificial ageing

The moisture content of the specimens after the artificial ageing is shown in the figure 8 and in the table 4. Values that are crossed out were removed from the examination because these were considered as statistical outliers. The differences between the examined edge sealant systems A, B, C, D and F are insignificant as their mean water content ranges from 4,124% to 4,781% only. The polyurethane version shows the largest increase in moisture content, while the specimens with the pressure compensation systems shows the smallest values.

Table 4: Average moisture content in the desiccant of the insulating glass units after the artificial ageing

Specimen	Start value [%]	Mean moisture content [%]	Moisture increase [%]
A		4,44	3,23
B		4,12	2,91
C		4,78	3,57
D	1,21	4,68	3,47
E		6,70	5,49
F		4,54	3,33
G		2,69	1,48

Comparing type A and type B, it can be seen that there is only a marginal gap between the two groups. It can be viewed as a result that there is no considerable difference between the bent spacer and the spacer that is connected in the corners.

Type C represents an IGU with a failed primary seal. Unexpectedly, the specimens without a primary sealing and less covering secondary sealing did not fail in the examination and did not show a considerable difference compared to the type A reference. That shows that the secondary sealing ensured the gas tightness of the insulating glass units to some extent. Therefore, an increase in thickness of the secondary sealant in marine IGUs is understandable. Further, it is important to produce a secondary sealing without any imperfection in order to reduce penetrating moisture.

The examination of the used secondary sealant materials shows that silicone and polysulfide react equal to the applied loads. Only the specimens with polyurethane take up more moisture than the other edge sealant systems in this study.

Ceramic coatings are normally used in marine insulating glass units because of the increased UV-radiation. It was suspected that the used coating may partially prevent the adhesion of the sealants on the surface of the inner side of the glass edge and thus becoming a weak point in terms of tightness. Comparing type A and type F results, there were no considerable deviations recorded. Thus, we conclude that the ceramic coating can protect the used sealants without influencing the penetration of moisture.

Type G specimens with a tube for the pressure equalisation achieve the best results. The measured results show that the moisture increase is the smallest compared with the other specimens. Thus, the lifetime of insulating glass units in aggressive environments may be expand by using this type of construction. However, the most important factor remains to be a careful production of the insulating glass units. Additionally, the pressure equalisation can also be an imperfection in the edge sealant system. Thus, further studies during artificial ageing and in real-life structures are needed to collect further experience.

The maximum moisture load of the desiccant is 20 % of its dry weight according to manufactures specifications. With this information, it is possible to estimate that most of the specimens reached roughly 25 % of their moisture storage capacity after the two-month artificial ageing program. This value cannot be extrapolated to any marine glazing units, because the moisture storage capacity depends to the amount of the inserted desiccant.

3.3. Functionality of the Pressure Equalisation

The aim of this study was the preliminary prove of the functionality of the pressure compensation and its impact on the duration of the insulating glass units. The following two figures 9 and 10 illustrate a comparison between an exemplary picked reference specimen (type A) and a specimen with a pressure equalisation system (type G).

Figure 9 shows how the pressure inside a specimen without a pressure equalisation changed with the varying temperature in comparison with the measured air pressure at the location of examination. The trend of the red and the max-min values peaks of the green line it roughly the same. However, the pressure within the cavity ranges between 905 mbar and 1037 mbar above and below the ambient pressure outside. This range reflects the alternating stress and its amplitude within the sealant system.

The pressure reduction in the specimen is also linked to the size and the structure of the investigated glazing. The space between the glass panes has an influence to the climatic loads. In the present case this means that the edge sealant system gets loaded with every change between maximum and minimum pressure. Depending on the glass size and thickness, these deflections will be introduced into the edge sealant system and cause a higher rate of penetrating moisture. As the size of every specimen in DIN EN 1279 is equal, the results remain usable for comparison.

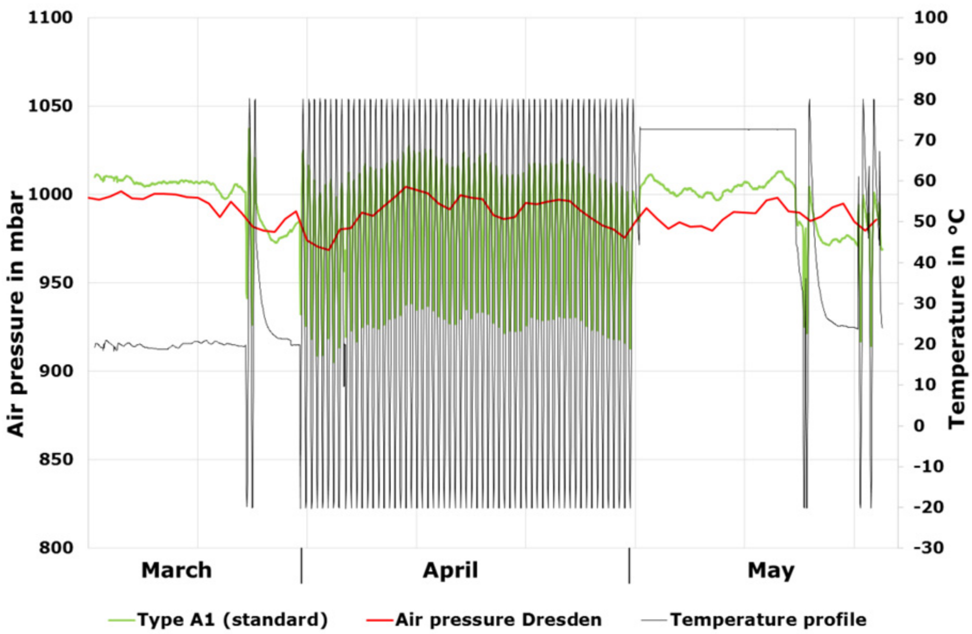


Fig. 9 Barometric and atmospheric pressure in a regular insulating glass unit and local ambient pressure at the location of Friedrich-Siemens-Laboratory, Dresden

Figure 10 shows the pressure inside the specimen G1, the small air tube enables the insulating glass unit to adapt the pressure outside the cavity. The range was between 954 mbar and 1012 mbar was considerably smaller compared with the results depicted in figure 9. Thus, it was concluded that influence of the changing temperature on the alternating stress in the sealant was marginal and the impact on the edge sealant system was insignificant owing to the function of the air tubes. The inner pressure equals the air pressure of the environment that means the glass panes are approximately plane. Based on the result the assumption exists that the edge sealant system almost remains untouched by climatic loads and the lifetime of an insulating glass unit may be extended.

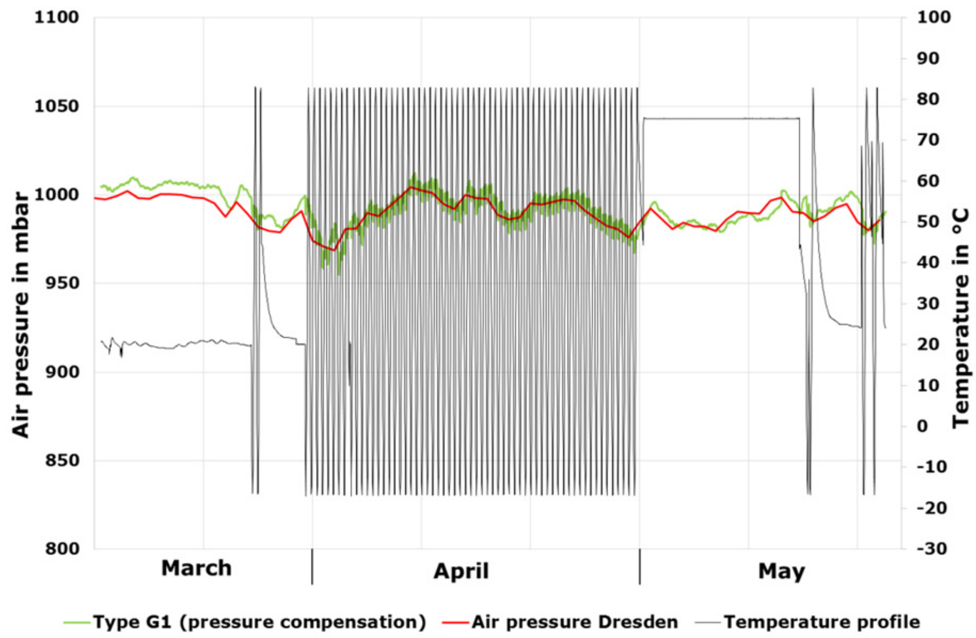


Fig. 10 Barometric and atmospheric pressure in an insulating glass unit with pressure equalisation

The principles of moisture transfer into the cavity were not verified completely by these results. It was proved that it is possible that less moisture penetrates the sealants, because of the pressure equalisation. But a moisture absorption through the air tube is conceivable. Furthermore, there is also the negative aspect that these insulating glass units cannot be filled with inert gas.

4. Summary

Summarising, the research confirms the observation of defect insulating glass units on vessels. Different materials in the edge sealant system seem to have no determining influence to the penetrating moisture rate during artificial ageing.

To accommodate the high impacts on the sea, the stress on the sealant may be reduced with new edge sealant structures: the pressure equalisation reduced the stress range at the edge sealant system. Thus, the lifetime of marine insulating glass units may be extended. However, the transfer mechanism through the used air tubes have to be investigated in future research to separate between the exchange of outside air and inside gas as well as the modalities of moisture transfer separately.

5. Further Research

In this test realisation, only one build-up was equipped with an air tube. Further tests will be conducted to examine the effect of various tube diameters and lengths. Thus, the pressure equalisation will be adjusted to the dimensions of the glass and to the environmental loads.

Furthermore, the permeability of the air tube will be analysed. It is suspected that the system exchanges gas between the open cavity and the ambient air without transporting condensation moisture. In addition to that, the time of reaction of the pressure equalisation will be checked. Climatic loads are a slowly changing impact, but wind loads will stress the insulating glass unit in a short time. There will be an examination how quickly the pressure equalisation can respond to changing impacts.

Finally, the marine impacts to the insulating glass units have to be verified. For that reason marine glazing units will be equipped with the data loggers during a long-term monitoring study. Thus, real climatic loads will be recorded and a marine artificial ageing process will be derivate.

Acknowledgement

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