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ABSTRACT

Between energy-efficient building programs and rising urban temperatures, finding building envelope solutions that could be used to both decrease the operational carbon associated with space conditioning as well as decrease the risk of overheating within the residential sector is of interest. High-performance glazing solutions such as vacuum-insulated glazing (VIG) have emerged as a pivotal advancement in energy-saving technology, offering high center-of-glass thermal resistance, thin profiles, and weight savings as compared to conventional glazing systems. However, without a means of evaluating the minimum service life of any insulated glazing unit (IGU), let alone VIG, subsequent life cycle analysis and maintenance schedules cannot be performed or created, thus limiting our understanding of whether the technology could be considered a low-carbon alternative to conventional window technology. This paper offers a comprehensive overview of current fenestration evaluation standards, test procedures, and equipment essential for measuring performance metrics required for the development of an appropriate accelerated ageing protocol to evaluate the durability, long-term performance, and service life of high-performance glazing systems post-initial certification. In addition, this paper proposes a series of tests that will be evaluated for their potential to estimate the service life of VIG as compared to double and triple-glazed IGU. The outcome of this work could lead to a better understanding of how both comfort parameters and performance metrics associated with our choice of glazing technology may change over their service life, potentially providing the necessary catalyst for the uptake and adoption of high-performance glazing technology going forward.

INTRODUCTION

Monolithic VIG consists of two lites of glass separated by an array of support pillars, where a hermetic edge seal along the glass perimeter is used to maintain a negative pressure or vacuum within the cavity space as seen in Figure 1. One of two types of glass, regular (annealed) or tempered float glass is selected for the manufacturing process. Both types of glass have their advantages and disadvantages, where the type of glass selected can affect both the mechanical and thermal performance of the VIG system as well as influence the overall manufacturing process. The manufacturing process starts with two lites of glass which are baked out in an oven to off-gas any potential residual gases adsorbed within the glass sheets. An array of support pillars is then placed onto one of the lites before the two are brought together. One of two assembly techniques is then used to create a hermetic edge seal using proprietary edge sealing materials. In the first technique, an edge seal is created during the baking process, where after cooling, a vacuum is drawn through a pump-out port. The pump-out port is then sealed and the VIG is ready to be used. In the second manufacturing process, all the components of a VIG are placed within a vacuum chamber and baked to off-gas residual contaminants before a vacuum is drawn around the materials. An edge seal is created as the two lites of glass are brought together under vacuum and high temperature. The chamber is then re-pressurized and the VIG is ready for service.

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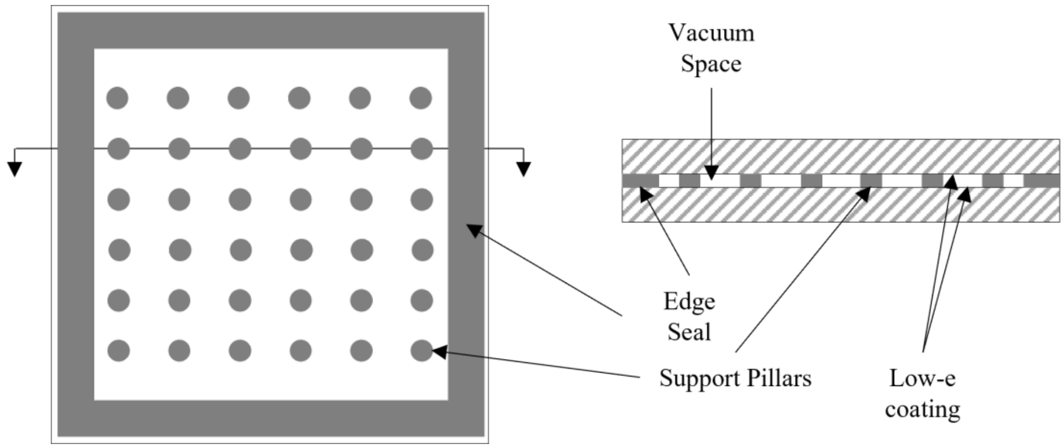

Figure 1 Schematic diagram of vacuum glazing.

During the manufacturing process, the temperature at which bake-out occurs is dependent on the type of glass, low emissivity (low-e) coating, and edge seal material selected for use in the assembly. Annealed glass can support a high baking temperature, which is good for both off-gassing residual contaminants and is required to enable the use of durable edge sealant materials such as solder glass which requires working temperatures around 450 – 500°C (842 – 932°F) (Miao, Shan, Zhang, Sun, & Wang, 2015). However, due to the lower tensile strength of annealed glass compared to tempered glass, VIG manufactured with annealed glass requires a greater number of support pillars to prevent the formation of stress fractures in the glass above the pillar array (Collins & Simko, 1998), leading to greater conductive heat transfer compared to VIG with less support pillars. Tempered glass is two to four times stronger than annealed glass, requiring less support pillar area to maintain the vacuum cavity, but can lose its strength characteristics if exposed to high enough temperatures during the manufacturing process (Koebel, Manz, Mayerhofer, & Keller, 2010) (Memon, Farukh, Eames, & Silberschmidt, 2015). In addition, the temperatures used in the manufacturing process limit the type of low-e coatings that can be used. Pyrolytic or hard coatings (e = 0.10 to e = 0.20) are able to withstand higher baking temperatures (Minaai, Kumagai, Nara, & Tanemura, 2005) compared to soft low-e coatings (e = 0.02 to e = 0.10), which have been found to degrade at temperatures greater than 460°C (860°F) (Fang Y. , et al., 2007). The use of soft low-e coatings is preferable when designing a VIG to decrease the amount of radiative heat transfer gained or lost from a conditioned space. As a result of the thermal and structural trade-offs found in the manufacturing process of VIG, two types or styles of VIG emerge; those manufactured with annealed glass versus those that are manufactured with tempered.

Compared to conventional IGUs that use an inert gas between the two panes of glass, VIG rely on the vacuum within the cavity for their insulating performance. The internal vacuum works to eliminate both the gaseous convection and conduction that would otherwise occur within the gas held between the two sheets of glass (Koebel, Manz, Mayerhofer, & Keller, 2010). The remaining sources of heat transfer through the system are radiation across the cavity and conduction through the support pillars and edge seals. Despite the relatively straightforward concept of VIGs, their insulating performance is dependent on maintaining the internal vacuum within the cavity. Therefore, understanding the mechanisms that lead to an increase in internal pressure and evaluating the impact of this pressure on thermal transmittance are important to determining the service life of VIG.

THERMAL PERFORMANCE OF GLAZING SYSTEMS

The insulating performance of glazing systems is often reported by their center-of-glass (COG) thermal transmittance or "U-value", where fenestration systems are an assembly of both frame and insulated glazing unit. The National Fenestration Rating Council (NFRC) "ANSI/NFRC 100-2020 Procedure for determining fenestration product U-factors" outlines a combination of computer simulations and/or experimental measurements that can be used to determine performance ratings for fenestration systems including thermal transmittance, solar heat gain coefficient (SHGC) and visible transmittance (VT) (National Fenestration Rating Council, 2013). SHGC is defined as the ratio of the solar heat entering the space through the fenestration product relative to the solar radiation incident on the surface, expressed as a dimensionless number from 0 to 1.0, and VT, is the ratio of visible radiation entering the space through the glazing unit to the incident visible radiation.

NFRC outlines two methods for determining the COG and total U-value of glazing systems. The first method uses ISO 15099 approved software to calculate both the COG and total U-value of both the IGU and glazing system. Examples of approved software include WINDOW (U.S. Department of Energy LBNL, 2020) and THERM (U.S. Department of Energy Lawrence Berkeley National Laboratory, 2020). The second method outlines test procedure to determine the standardized thermal transmittance (UST) of a fenestration system or glazing unit at well-defined environmental conditions using hot box methods following ASTM C1199-14. By reporting an UST value, measured results can be compared to the results from laboratories with vastly different hot box configurations and to the results obtained from computer simulations.

Another standard for evaluating the thermal transmittance of glazing system is ISO 19916-1:2017, which outlines two experimental procedures to evaluate center-of-glass U-factors for VIG (ISO 19916, 2017). The two options for determining thermal transmittance are the heat flow meter method in accordance with ISO 8301 or the guarded hot plate method following ISO 8302. The use of buffer plates is recommended in both cases to create uniform contact between the metering surfaces of the instrument and the exterior surfaces of the VIG. In the case of a VIG manufactured with protruding evacuation ports, the buffer plates can be used to protect the evacuation port from damage. The material selected for the buffer plates must not change in thickness due to compression inflicted during testing, and the thermal conductivity of the material cannot be influenced by absorbed moisture. Following the calculation procedure, the thermal transmittance of the sample can be determined by subtracting the known thermal resistance of the buffer plates off of the total thermal transmittance of the buffer plates plus sample. By following either ASTM or ISO standards, the insulating performance of VIG can be evaluated. In order to determine how the insulating performance of VIG may change over time, a review of durability standards for glazing systems and durability studies of VIG has been performed.

DURABILITY STANDARDS AND GUIDELINES FOR GLAZING SYSTEMS

As specified by the Fenestration and Glazing Industry Alliance (FGIA), windows that are to be used within North America are to be constructed with IGUs that meet the requirements of either CAN/CGSB 12.8 or ASTM E2190. Both standards were developed to assess the quality of construction of an IGU's hermetic seal, and its resistance to fogging as a result of the volatility of components within the unit. ASTM E2190 requires that six samples from a baseline set achieve a frost/dew point no higher than -40°C (-40°F) after being tested to high humidity conditions and weather cycling as specified in ASTM E2188 and two to four specimens show no signs of fogging after being tested to ASTM E2189. Both standards rely on qualitative visual inspections throughout the process to assess the performance of an IGU's hermetic seal, quality of construction, and its resistance to fogging; the results of which cannot be used to quantify service life nor long-term performance.

In addition to outlining a procedure for evaluating the thermal performance of a glazing unit, ISO 19916-1:2017 also outlines a process to assess the quality of construction of an IGU's hermetic seal. Where CAN/CGSB 12.8 and ASTM E2190 were developed to assess the performance of double or triple-glazed IGU, ISO 19916-1 was developed specifically to assess the durability of VIG. A detailed flow chart at the start of the standard outlines each step of the process, the number of samples to be tested and when in the process the samples are to be exposed to accelerated climate conditions. Samples tested to this standard are exposed to one of the three climate protocols. The pass/fail criteria for the standard goes beyond a visual assessment, requiring that, the U-value for all specimens tested change by no more than 10.0% from its original value.

The National Renewable Energy Laboratory (NREL) of the United States has released a guideline for evaluating the durability of IGUs and VIGs (Watts, Shah, & Tenent, 2022). In an attempt to cause as little disruption to the glazing industry as possible, the guideline has modified the stress factors that are presently used within the existing industry protocol of ASTM E2190. By increasing the temperature exposure range and increasing the temperature ramp rates, the guideline aims to test glazing systems under climate extremes that may be present in the future as a result of climate change. Going beyond the current ASTM E2190 protocol, the proposed NREL guideline also looks to quantify any change that may result from the durability assessment by measuring the thermal conductance of the samples, where the thermal conductance of a sample shall not change more than 5% when tested in accordance with the ASTM C518 Test Method.

Despite both the NREL guideline and the ISO standard setting a threshold performance value for degradation levels at which a sample is still considered durable, neither are specifically designed to assess how the long-term thermal performance of a fenestration unit may change over time (Likins-White, Tenent, & Zhai, 2023). Therefore, the service life for any window, including VIG, cannot be determined from these rating systems as they are currently written.

IMPACT OF BAKE OUT TEMPERATURE ON INTERNAL VACUUM PRESSURE OF VIG

Since the vacuum within the cavity of a VIG provides the main source of insulation, maintaining its characteristic low pressure is crucial for achieving a long service life. Studies have been conducted to determine how the internal pressure and subsequent thermal transmittance of a VIG system may be affected, as well as the mechanisms that contribute to a decrease in its insulating performance.

Lenzen and Collins conducted a long-term field test of vacuum glazing (Lenzen & Collins, 1997). In their study, VIG samples were integrated into well-insulated boxes, where one side was exposed to outdoor climatic conditions for over a year. The inside of the box was painted flat black and the interior box conditions were free running but influenced by solar heat gains and conduction through the edge seal of the VIG. The sample size of VIG tested was 500 mm x 500 mm x 8.1 mm (19.6” x 19.6” x 0.32”), comprised of two sheets of 4 mm (0.15”) thick soda lime glass and with solder glass edge seal. The VIG experienced temperature differences up to 60°C (108°F) across the glazing with the warm side experiencing temperatures up to 90°C (194°F). The thermal conductivity of the VIG was measured using a Guarded Hot Plate apparatus throughout the study. The author’s intent was to analyze both the thermal performance and mechanical stability of VIG manufactured under a range of bakeout temperatures exposed to natural thermal cycling events. The VIGs that were manufactured at low bakeout temperatures of less than 200°C (392°F) during the evacuation process experienced increase in internal pressure compared to VIGs manufactured using higher bakeout temperatures. The authors concluded that the increase in internal pressure was the result of the high temperature exposure as opposed to the thermal cycling, as there were no crushed pillars or newly grown cracks detected. They also found that the amount of outgassing could be linked to the bakeout temperature during evacuation.

Ng, et. al., (2005), studied the evolution of gas within the cavity of VIG baked at different temperatures during the manufacturing process (Ng, Collins, & So, 2005) (Ng, Collins, & So, 2003). In the study, VIGs were exposed to elevated temperatures or sunlight to induce degradation within the samples. The authors used a spinning rotor gauge to measure the internal vacuum pressure through an external evacuation port. The spinning rotor gauge was able to detect pressure increases in sealed samples of vacuum glazing that are at least two orders of magnitude smaller than those detectable with heat flow measurements. For the samples that were baked at lower temperatures of approximately 150°C (302°F), the internal pressure experienced partial recovery after thermal cycling but did not recover after removal from sunlight, compared to samples baked at higher temperatures around 350°C (662°F) during manufacturing which showed little to no pressure increase throughout the testing. During high-temperature exposure, water vapour was observed to cause the increase in the internal pressure within a VIG (Ng, Collins, & So, 2005), where the degradation of vacuum glazing under optical illumination primarily occurs due to photodegradation of the gases in vacuum glazing. This optical degradation is primarily related to the gas molecules that persist on the internal surfaces of glass panes after the bakeout process, rather than those entering the internal evacuated space during the tip-off process. These molecules are carbon oxides either CO or CO_2, or radicals that release CO and CO_2 through photochemical and/or photo-stimulated processes (Ng, Collins, & So, 2003). The authors suggested that the difference in the evolved gas in these two different ageing conditions explains why optically exposed VIGs show a permanent pressure increase, unlike thermally stored ones, and that VIG manufactured at lower temperatures showed greater internal pressure increases when exposed to sunlight and high temperatures, versus systems baked at higher temperatures.

A study by Fang, et. al., (2009), was conducted to determine if the internal pressure and subsequent thermal transmittance of a VIG system could be affected by extreme thermal cycling (Fang, Hyde, Eames, & Hewitt, 2009). In their testing the VIGs were subjected to cycles of -30 to 50°C (-22 to 122°F) to determine the systems durability. After climate ageing, a guarded hot box calorimeter determined that the thermal conductivity of the samples had increased by approximately 10 percent. Using results from a study conducted by Ng, Collins, & So, (2005), Fang, et. al., (2009) concluded that the increase in internal pressure must have resulted from the evolution of water vapour, as the VIG were subjected to thermal conditions rather than sunlight or external energy excitation. This suggests that climate cycles can alter the thermal performance of VIG.

A 2010 study by Koebel et al. was conducted to determine the mechanisms that may contribute to an increase in the internal pressure and subsequent decrease in thermal performance of a VIG. Four sources of possible pressure increase were examined, including permeation of gaseous molecules through the glass sheets, leakage of the edge seals, thermal and optical desorption of organic compounds from the inner glass surfaces and photofragmentation of large adsorbate molecules. Their findings suggest that,

- A negligible increase in internal pressure is anticipated from the permeation of atmospheric gases through the glass,
- Outgassing can be reduced if edge sealing is completed under a vacuum and high temperature environment,
- Photofragmentation can be reduced by means of proper surface cleaning.

The findings from these studies suggest that the temperatures used during the bake-out, and manufacturing process of VIG can potentially contribute to an increase in internal pressure and a subsequent decrease in thermal transmittance. Since the manufacturing process of VIG directly influences the temperatures used, a test protocol is being proposed to determine if the type of VIG (annealed versus tempered) impacts its degradation and the mechanisms by which it degrades.

PROPOSED TEST PROTOCOL

In order to investigate how VIG may degrade over time, a testing protocol is being proposed based on a review of durability studies and industry standards for glazing systems. The main components of this protocol include, performing accelerated ageing tests, quantifying any changes in performance, and gathering information from field exposure testing.

Throughout the study, two types of VIG (with annealed glass versus tempered one) in two sample sizes will be compared to investigate if potential manufacturing differences have any effect on the degradation of the samples during testing. Two sample sizes will be evaluated to quantify any differences between devices used to measure thermal transmittance and results predicted from computer simulations. ASTM Practice E1423 specifies standard test specimen sizes to be used in the measurement of thermal transmittance in accordance with Test Method C1199. However, as outlined in the practice, other sizes and conditions can be used for research purposes. The test protocol will start by establishing a baseline frost/dew point and thermal transmittance for all glazing samples.

The small samples will follow the testing procedure outlined in Figure 2. The baseline center-of-glass thermal transmittance will be evaluated using a heat flow meter, and the frost/dew point will be assessed. Several mean sample temperatures will be tested to determine the temperature-dependent thermal transmittance of VIG. After the baseline testing, the small VIG samples will be placed in a climate chamber for the first of two high humidity exposure periods. Following this exposure, the frost/dew point of all the samples will be evaluated and visual observations will be made. The samples will then be divided into two parallel paths where half the samples will be subject to an accelerated weathering cycle and the other half will be subject to UV exposure. This split in the testing will be used to determine how different external loads affect the insulating performance of the samples. After this round of testing, both the frost/dew point and thermal transmittance of the samples will be evaluated. The information gained may help adapt testing procedures for future accelerated tests based on the type of VIG being assessed. All the samples will then undergo a second high temperature, high humidity exposure before final thermal transmittance and frost/dew point assessments are taken. Once the final measurements are made, any drop in performance will be normalized relative to the baseline value and reported as a percent reduction.

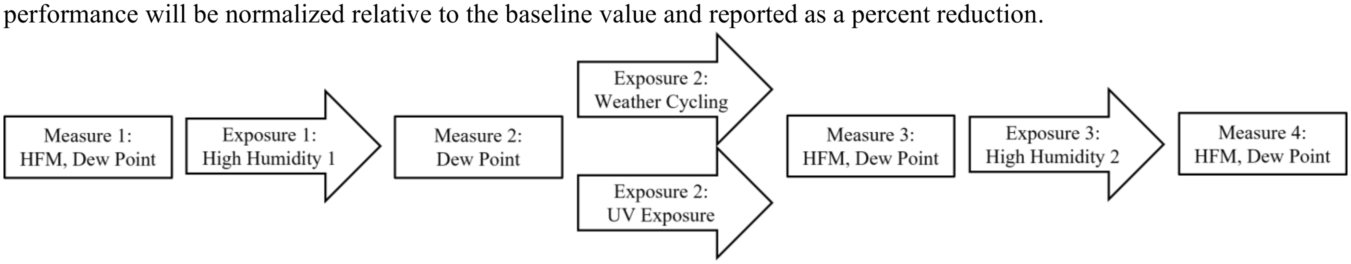

Figure 2 Proposed test procedure for small VIG samples

The large samples will follow the testing procedure outlined in Figure 3, where the baseline center-of-glass thermal transmittance and the total thermal transmittance will be evaluated using a heat flow meter and guarded hot box apparatus, respectively. In addition, the baseline frost/dew point will be evaluated. After the baseline testing, the larger samples will be installed into a field exposure testing facility where interior environmental conditions will be controlled and exterior climate parameters will be recorded. A weather station on site will be used to record the solar irradiance, ambient exterior temperature, relative humidity, atmospheric pressure as well as wind speed and direction. Instrumentation will also be installed on the glazing surface, frame, and glass frame interface to measure the temperature profiles that may result from exposure testing, which will be used to validate computer predictions for surface temperatures. The measured environmental parameters will be used to evaluate how the exposure conditions and duration under the accelerated ageing relate in-situ conditions. The project intends to leave the samples in the exposure facility for a minimum of three heating and cooling seasons. After removal from the field study, the final thermal transmittance and frost/dew points will be evaluated to capture any degradation experienced as a result of climate ageing. Upon completion of the field study, rates of degradation will be calculated for the glazing units, which when combined with the results from accelerated ageing, estimates for service life will be made.

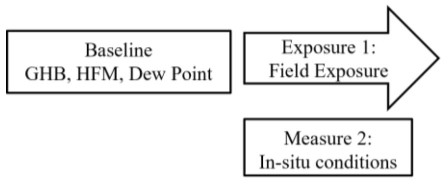

Figure 3 Proposed test procedure for large VIG samples

The project was formulated around understanding the service life of VIG which appears to have the greatest potential of impacting the operational energy use for windows. However, in order to truly quantify the difference between VIG and conventional glazing systems, the same testing protocol will be performed in parallel on conventional double and triple glazed IGUs in two sample sizes.

CONCLUSIONS AND FUTURE WORK

Despite the relatively straightforward concept of VIGs, their insulating performance is dependent on maintaining the internal vacuum within the cavity. Studies on the durability of VIGs have found that those which are manufactured at low bakeout temperatures during the evacuation process may experience an increase in internal pressure compared to VIGs manufactured at higher bakeout temperatures. The temperature used during the manufacturing process may be influenced by the type of glass, edge seal, and low-e coatings selected.

Durability standards such as ASTM E2190 and CAN/CGSB 12.8 were developed to assess the quality of construction of an IGU's hermetic seal, and its resistance to fogging as a result of the volatility of components within the unit but result in a qualitative pass-fail assessment. Both the NREL guideline and the ISO 19916 standard attempt to go beyond a qualitative assessment, by setting a threshold performance value for the degradation levels that would still be considered durable. However, as currently written, they cannot be used to assess how the thermal performance of a fenestration unit may change over time. Without a means of evaluating the minimum service life of any IGU, let alone VIG, subsequent life cycle analysis, and maintenance schedules cannot be created or performed, thus limiting our understanding of whether VIG technology could be considered a low-carbon alternative to conventional window technology. Therefore, the proposed test protocol described in this paper seeks to determine if the type of VIG (annealed versus tempered) has any impact on degradation and the mechanisms that may cause VIG degradation.

This paper offers a comprehensive overview of current glazing systems' evaluation standards, test procedures and equipment essential for measuring performance metrics required for the development of an appropriate accelerated ageing protocol to evaluate the durability, long-term performance, and service life of high-performance glazing systems post-initial certification. In addition, this paper proposes a series of tests that will be evaluated for their potential to estimate the service life of VIG as compared to double and triple-glazed IGU. Going forward, changes in other performance parameters, such as Solar Heat Gain Coefficient (SHGC) and Visible Transmittance (VT), may be measured, as both are also pertinent for certification and thermal comfort.

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