Durability Evaluation of Advanced Fenestration Technologies

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ABSTRACT

In the U.S., more than 40% of primary energy and 70% of electricity is consumed in residential and commercial buildings, resulting in annual energy costs of more than $430 billion. Approximately 35% of this consumption can be attributed to losses through the building envelope, of which windows are currently the weakest link. Multiple technologies are under development to improve this performance. This includes dynamic and photovoltaic glazing as well as emerging highly insulating technologies including vacuum insulating glass (VIG), aerogels and thin-glass based multi-pane configurations. While windows are specified based on expected performance as installed, the energy savings realized by high performance windows are delivered over time. This makes it critical to understand and maximize the durability of high-performance windows to ensure those projected energy savings are delivered. Present methods for evaluating durability are based on existing technologies. These methods may not apply or be adequate for newer emerging technologies which often present novel failure mechanisms that need to be understood and evaluated differently.

In this presentation, we will discuss our efforts to define appropriate methods to improve the evaluation of many existing technologies as well as evaluate the durability of emerging window technologies. This work results from the combination of an extensive review of various international standards as well as existing scientific literature. In addition, input was gathered from multiple industry stakeholders regarding present practice as well as feedback on proposed improvements to existing methods. Here we will share these findings and present proposed improvements to developing and existing durability evaluation protocols.

INTRODUCTION

In the U.S., more than 40% of primary energy and 70% of electricity is consumed in buildings, resulting in annual energy costs of more than $430 billion. Approximately 35% buildings energy use can be attributed to losses through the building envelope, of which windows are, performance-wise, considered the weakest link. Improving window performance is vital to reducing building energy use as well as associated greenhouse emissions and several advanced technologies are currently under development. These technologies represent a significant investment for the consumer and to maximize return on investment (ROI) as well as energy savings windows must deliver the promised performance over time. Therefore, it is crucial to understand and maximize the durability of fenestration products in particular for advanced technologies.

Two key factors are driving a need for the re-examination of present industry practice in durability evaluation. The first is the increase of erratic and extreme weather conditions driven by on-going climate change. The second is that many advanced technologies are subject to novel failure modes that must be accounted for and may not be under present practice. How the durability of fenestration products is evaluated must be reconsidered and modified, both for advanced as well as existing market technologies. Here we discuss how climactic changes may impact the durability of fenestration technologies as well as novel failure modes of some advance technologies. Based on this discussion as well as extensive review of global standards and present industry practice, we propose modification to present durability assessment protocols.

DURABILITY CONSIDERATIONS FOR FENESTRATION

Windows consist of multiple components including glass, or glazing, as well as framing systems. Currently most windows use multi-pane insulated glass units (IGU) which are responsible for ~80% of energy gains and losses in windows as compared to framing components. IGU failures can result in dramatic performance reduction and have substantial impact on building energy use. An IGU is comprised of two or more glass panes held apart by a "spacer" and edge seal assembly, **Figure 1**. The glass panes may have a wide variety of coatings depending on the desired energy performance and building aesthetics. The internal volume of the IGU can be filled with air or inert gases which are more thermally insulating than air, such as argon or krypton to minimize thermal heat transmittance (U-Factor). Glass LowE coatings impact the radiative exchange between surfaces and influence U-Factor as well as solar gain (SHGC) .

Long term energy performance of the IGU is dependent on the edge seal maintaining a suitable environment within the internal cavity. Loss of insulating gas leads to decreased thermal performance. Ingress of moisture and/or oxygen can lead to chemical degradation of coatings as well as visible condensation in the unit.[1] Desiccants are commonly used in spacer systems to mitigate moisture transport through the edge seal and prevent condensation inside the IGU cavity. It is important that the holding capacity of desiccant used, exceeds the humidity ingress over the life time of the unit. Typically the amount of holding capacity consumed by an individual IGU is determined by the moisture penetration index and should not exceed 25%. While a variety of processes and materials have been used in the edge sealing of IGUs historically, the predominant market technology is based on organic polymers.[2] These sealants are applied using a solvent that can be released to the IGU gas gap and lead to condensation and "fogging". Durability of present market IGU rests, largely, on the ability of the edge seals to retain fill gases and prevent moisture ingress. Presently "failure" of an insulated glass unit is defined as when moisture enters the gas cavity and condenses on the interior surface of the glass lites. While this metric is driven by the high value placed on aesthetics, it is important to note that it is not clear that the thermal performance of an IGU is directly proportional to moisture content.

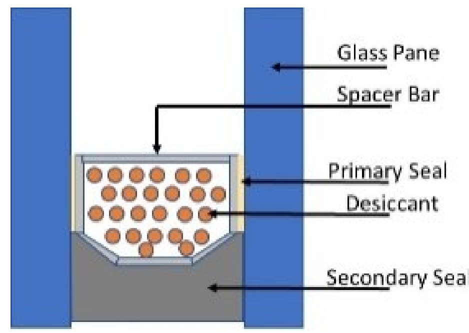

Figure 1 Schematic of a Typical Edge Seal in and Insulating Glass Unit (IGU).

In recent years, industry has made rapid progress in developing innovative IGU's to drive improved performance and increase functionality. Some examples include dynamic control of optical properties (electrochromic/thermochromic), development of exceptionally high thermal performance (vacuum insulating glass, VIG, and transparent aerogels) and integration of energy generation (photovoltaic glazing). Many of these technologies leverage existing IGU fabrication processes and edge seal structures. However, new technologies may stress these edge seals in ways that present technologies do not. In addition, some emerging technologies are expected to present novel failure modes that must be considered. In this work, we will briefly discuss potential modifications to existing industry durability assessment practice for VIG as well as dynamic fenestration products based on their present emergence in the market. Future work will also examine the needs for both photovoltaic as well as aerogel-based products.

Summary of Current Practice

Multiple international standards exist for assessing the durability of IGU products.[3] Relevant US and ISO standards are summarized in **Table 1**. These protocols stress IGU's in a three-step process that consists of an initial high temperature and high humidity exposure followed by a weathering cycle and a second high temp/high humidity phase.

Table 1 Summary of Present ASTM and ISO Methods for Durability of Insulating Glass Units

	USA	**International**
Reference Standard	**ASTM E-2188, E-2189, E-2190 E 2190**	**ISO 20492**
Sample Requirements		

# of Specimens	Double-glazed - 12 Specimens Triple Glaze - 14 Specimens	15 Specimens
Sample Size	355 mm by 505mm (14 in. by 20 in.)	355 mm by 505mm (14 in. by 20 in.)
High Humidity Phase 1		
Temperature	60+/-3 C	60+/-3 C
%RH	95% +/-5%	95% +/-5%
Total time	42 days (14 days + 28 days)	42 days (14 days + 28 days)
Weather Cycle test		
high temp	60+/- 3 C	60C +/- 3C
low temp	-29+/-3 C	95% +/- 5%
UV output	20 to 60 W/m^2	Greater than 10 W/m^2
Moisture exposure	30 min. water spray	
Time per thermal cycle	6 hr.	6 hr.
# of cycles	252	252
Total time **High Humidity Phase 2**	63 days	63 days
Temperature	60+/-3 C	60+/-3 C
%RH	95% +/-5%	95% +/-5%
Total time	42 days	42 days

The temperature at which condensation occurs inside the unit is tested using the ASTM E546 method at varying points throughout the test. Gas content is also monitored before and after testing using the ASTM E2649 or E2270 methods. Condensation must not occur above -40C and 80% of the gas fill must be retained for a unit to pass the method. Further testing is performed to assess the potential of volatile compounds leaving the edge seal and condensing inside the unit using the ASTM E2189 method with a pass/fail criterion of “no observed fog”.

FACTORS AFFECTING IGU DURABILITY AND IMPACT OF CLIMATE CHANGE

IGUs are exposed to a variety of factors in the field including temperature and pressure fluctuations, wind loads, sunlight, water (liquid and vapor) and potentially harmful chemical components (pollutants). The lifetime of an IGU depends on the ability to withstand these factors and varying combinations of them that may act in a synergistic fashion.[4] Here we give a brief discussion of each of these stress factors and how they may impact fenestration products.

Temperature

Changes in temperature can impact the edge seal in multiple ways. Thermal expansion and contraction of component materials can induce mechanical stress and materials fatigue at multiple points. IGU cavity pressure is also affected by temperature. The internal pressure of an IGU increases with cavity temperature causing the IGU to bulge, while low temperature causes the pressure to decrease causing the IGU gap to collapse, as shown schematically in **Figure 2**. This bulging and collapsing induces stress on the edge seal and occurs regularly and repeatedly for installed products. Increased temperature can also lead to increased permeability of edge seal materials to water and oxygen as well as to structural instability potentially leading to separation of the seal from the glass. Present industry practice does take variations in thermal stress into account, however, expected increases in temperature extremes may warrant testing under a broader temperature range going forward.

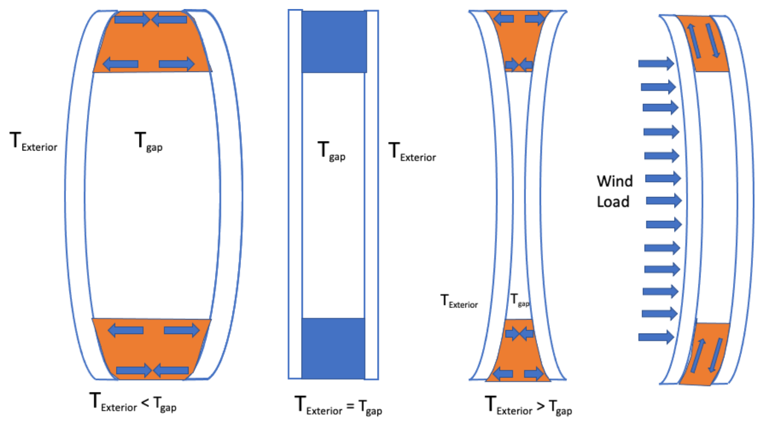

Figure 2 Schematic representations of IGU distortions and associated stresses occurring due to thermal stress as well as wind loads.

Atmospheric and Wind Pressure

Variations in atmospheric as well as wind pressure can also produce stresses on the IGU like those shown in **Figure 2** with similar consequences. Wind loads will likely become a more significant stress factor moving forward due to increased frequency as well as intensity of extreme weather events driven by climate change. In addition, rapid changes in atmospheric pressure have also been seen (polar vortex excursions) and may become more significant. While present designs are based on expected maximum wind speeds, those speeds likely represent relatively rare excursions and would likely be quite extreme to include as a regular factor in long term durability evaluation. We hypothesize that average wind speeds may be more relevant for determining appropriate stress factors for evaluation of long-term durability, as these wind speeds will be more regularly seen in day-to-day use and varied conditions. Cities within the continental U.S. with the highest average wind speeds are shown in **Table 2**. Note that while some large coastal cities are mentioned, (Boston and New York), most of these locations are in the central U.S. This indicates that wind load impact is not exclusive to coastal regions that may already require testing for hurricane conditions. While the data shown here are average values, central US locations can also often suffer from more localized storms that are well known to cause issues in this portion of the country. Based on this, the impact of wind speed and the associated applied pressure must be evaluated to ensure maintained high performance in all regions of the U.S

Table 2: Average Wind Speeds for Various US Cities:

City	Average Wind Speed (mph)	City	Average Wind Speed (mph)	City	Average Wind Speed (mph)
Dodge City, KS	13.1	Lubbock, TX	12.0	Oklahoma City, OK	11.3
Amarillo, TX	12.9	Casper, WY	12.0	Wichita Falls, TX	11.2
Cheyenne, WY	12.3	Corpus Christie, TX	11.7	Grand Island, NE	11.2
Goodland, KS	12.1	Wichita, KS	11.5	Fargo, ND	11.1
Rochester, MN	12.1	Boston, MA	11.5	Galveston, TX	11.1
Clayton, NM	12.1	Great Falls, MT	11.4	Concordia, KS	11.0
		New York, NY	11.3		

- Source NOAA's (National Centers for Environmental Information)

Note: Windows in multi story and high rise buildings are exposed to higher wind pressure as wind velocities are higher at elevated levels. Furthermore, window replacement costs in multi-story/high rise construction are typically quite high which places more emphasis on the need for pressure cycling studies to simulate wind loads.

Wind pressure will subject the glass to deflections. The amount of deflection observed is partly dependent on both glass pane size as well as glass thickness. As an example, the present practice of testing 14” by 20” IGU samples **(Table 1)** is designed specifically to avoid deflection of the glass when under test and is believed to thereby impart maximum stress on the edge seal since stress cannot be relaxed due to glass deflection. That having been said, the lack of deflection means that the edge seals are not exposed to shear stresses that are discussed above and can be detrimental to long term edge seal performance.

While standards exist for assessing structural performance of windows under varied loads, this is not currently considered in durability assessment of the edge seal and associated IGU performance. We believe that inclusion of this mechanical stress alongside more commonly used IGU stress factors is required in an enhanced durability evaluation.

Solar

Solar exposure, especially ultra-violet (UV) light, may have a serious effect on IGU durability. Exposure to UV light is known to be a key factor in the degradation of organic materials, including polymers. Furthermore, a number of organic sealants have been proven to lose adhesion to glass under solar exposure. Solar exposure also leads to an increase in temperature inside the glass unit which can lead to an effective increase in internal gas pressure causing further mechanical stress on edge seals. The present assessment methods focus on the use of UV lamps to simulate solar exposure. Most chemical damage to the edge seal comes from UV driven reactions within the polymers or between the polymers and contaminants. Existing UV exposure protocols are focused on the known chemical degradation of the organic edge seals. However, for advanced technologies, use of the full solar spectrum exposure should be considered. Emerging advanced IGU's incorporate materials which can be more absorptive, e.g., PV modules or electrochromic coatings in the tinted state, that tends to elevate the glass pane and gap temperatures. Simulated exposure to the full solar spectrum would help determine if advanced IGU's components degrade under these conditions which are more like those found in the field.

Water and water vapor

Water in both liquid and vapor form can drive performance degradation of IGU edge seals. Water absorbed into the edge seal can lead to swelling that induces stress. This failure can commonly occur due to the presence of liquid water in the glazing pocket due to improper drainage. As mentioned earlier, water absorbed into the edge seal can also be transferred into the IGU gas gap leading to condensation as well as low-e degradation. In addition, the presence of water either in the liquid state or absorbed into the edge sealant materials can lead to chemical degradation of the seal through hydrolysis driven with combined UV exposure. Present durability assessment methods include water spray and varies relative humidity. Therefore, we do not recommend changes to these protocols currently. It should be noted that testing that allows the edge seal material to be stressed while in constant contact with liquid water would represent a more substantial evaluation.

Gas/Moisture Permeability

The permeability of the edge seal materials to both moisture ingress as well as gas release/uptake is also a key factor in determining IGU durability. The permeability performance is complex and can depend on the inherent properties of the polymer-based sealant materials, properties of the permeating gas, temperature of the sealant material and partial pressure of gases both interior and exterior to the gas gap. The issue of permeability and the various factors that drive it are considered acceptably by current durability evaluation protocols, so further exploration of stressors in this area is not warranted at this time.

Atmospheric Contaminants

Atmospheric contaminants and cleaning agents can have an impact on edge seal durability and IGU performance.[5] Especially, in high rise buildings with glass facades exposed to atmospheric contaminants which can degrade the SHGC and VT of the glazing system. Exposure to atmospheric contaminants can also degrade edge seal materials through chemical attack allowing gas release and moisture uptake. Atmospheric contaminants can also lead to vapor exposure that is more acidic in nature and that attacks sealants. Currently the IGU's are not tested for such exposure. However, existing ASTM standards (ASTM D7897) for assessing soiling of roofing materials could be leveraged to test the impact of atmospheric contaminants on edge seal/IGU performance. We believe that this method should be considered as part of an enhanced durability evaluation.

NREL GUIDELINE FOR ENHANCED IGU DURABILITY ASSESSMENT

Here we present a proposed guideline for enhanced durability assessment of IGU products that takes into account earlier discussions related to stress factors and climate change impact as well as current industry practice. The method is intended to allow multiple manufacturers who are known to be using enhanced durability assessment methods to have this verified by external third parties. This guideline is also intended to define necessary areas for research to support further improvements to the method by NREL as well as others.The proposed protocol is designed to create a minimal disruption from present practice while improving the stringency of the test method. This was done to try and minimize the need for major changes at existing testing houses and research centers.

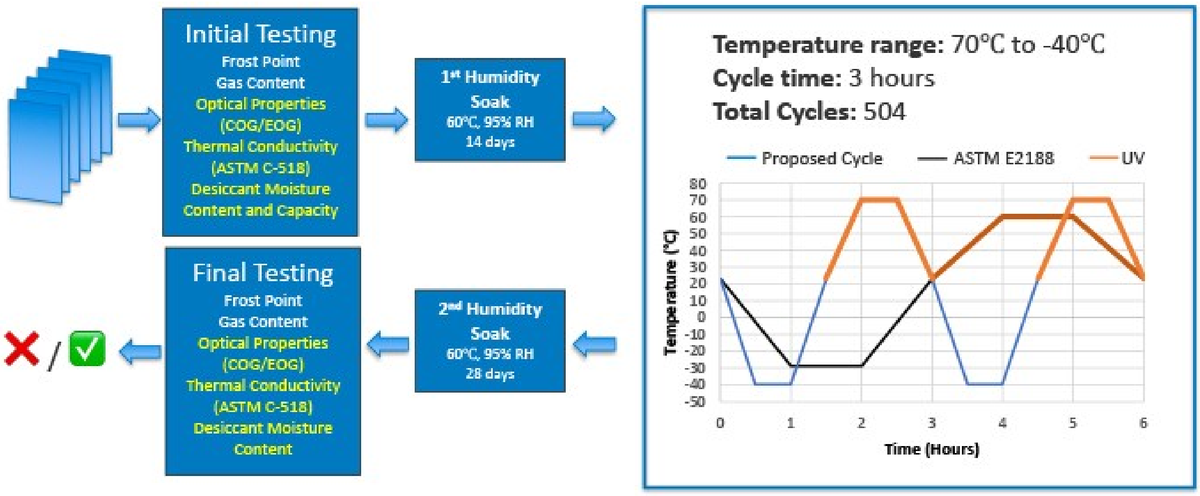

Figure 3. Schematic Representation of the Proposed NREL Guideline for Enhanced Assessment of Durability of IGUs

An overview of the method is presented in **Figure 4**. The process flow, nominally, remains the same as existing practice with initial evaluation of specimens followed by high temperature and humidity, weather cycling, a second humidity/temperature soak and final evaluation. Key changes over the methods outlined in Table 1 include an increase to the temperature extremes that samples are cycled to. This is largely driven by concerns over emerging climate change driven phenomena such as extreme heat as well as rapid and extreme excursions to low temperature (polar vortex). We also propose, optionally, increasing the temperature ramp rates during cycling as well as doubling the number of cycles conducted under the present test. The increased ramp rate is based, in part, on rapid temperature (and associated pressure changes) that have recently led to field failures such as the polar vortex excursions. Increasing the ramp rate also allows us to increase the number of thermal cycles conducted while minimizing impact on the length of time the test requires thereby attempting to prevent negative impacts on current industry practice. Increasing the number of thermal cycles is consistent with many current industrial partner practices who often conduct multiple "rounds" of present methods using the same units in an attempt to project a longer lifetime with some partners touting "double or triple pass" of traditional standards as a differentiator in the market.

We also propose the addition of further metrics to judge failure of the IGU beyond the present frost point and gas retention methods. This is driven by multiple considerations. While condensation is an obvious failure point for aesthetic reasons, the relevant energy efficiency value of the technology is more directly tied to thermal conductivity. Based on this, we propose adoption of an ASTM C-518 test of thermal performance before and after exposure to varied weathering cycles. We also propose more thorough evaluation of performance of desiccant materials in the edge seal at both the start and end of testing. Methods for this work have already been demonstrated and can be incorporated, however, we are also conducting further research in this area presently. This is intended to provide more than just a pass/fail criterion to the test. This allows determination of "how close I was to failure" and can also provide added benefit of eliminating needless and, potentially, expensive over-engineering of products. We also suggest a more thorough characterization of optical properties of IGUs before and after testing. This brings the benefit of understanding the impact on product aesthetics and also on the degradation of Low-e properties.

Optional Inclusion of Pressure Cycling:

While standards exist for assessing structural performance of windows under varied loads, this is not currently considered in durability assessment of the edge seal and associated IGU performance. Addition of pressure as a stress factor for IGU durability assessment is presently an active area of research and, hence we currently suggest this as an optional additional method for assessment. We believe that inclusion of this mechanical stress alongside more commonly used IGU stress factors is required in an enhanced durability evaluation. Currently,12-14 samples sized 20 inch by 14 inch are collected from a manufacturing plant by certification/auditing agencies for durability testing, it is recommended that in addition to these samples *at least one 1m by 1m (*which would represent residential double hung or horizontal window IGU's*)* sample is collected to perform a cyclic pressure test for simulating wind driven IGU failure. The number of cycles and the applied pressure should represent wind pressure, including extremes such as gusts, experienced by the IGU in the field. Data from this test will determine if more samples of larger sizes should be collected to better test the pressure impact. Further work is presently underway on integration of pressure into a test with other concurrent IGU stress factors. This will inform future enhanced durability assessment guidance, however, at this time, to minimize disruption to present industry practice and accelerate adoption of this guidance pressure testing remains separate and exploratory in nature.

Advanced Fenestration: VIG

Vacuum insulating glass (VIG) is like traditional IGU with the key differentiator being the lack of any gas between the two glass lites. This leads to exceptional thermal performance, however vacuum loss due to seal failure, or gas permeability in vacuum insulated glass (VIG) will have high impact on energy performance. Technical approaches to the fabrication of VIG units focus on either rigid or flexible sealing materials. When a temperature differential is placed across a VIG unit the hot glass lite expands relative to the size of the cold glass lite. In the case of a static (non-flexible) edge seal for large temperature differences between the exterior and interior glazing, the linear stress due to thermal expansion is extremely large. This leads to deflection of the VIG unit and places a large stress on the edge seal. Flexible edge seals are being developed specifically to deal with this challenge. Therefore, it is likely critical to test VIG samples at a larger size then the current ASTM E2188/2189/2190 testing standard to simulate field conditions and failures. It is recommended to test samples of at least 1m by 1m size which would represent residential double hung or horizontal window IGU's. For flexible seal technologies in VIG it is critical for the IGU to be able to undergo thermal differential cyclic exposure to simulate linear thermal expansion and contraction experienced in the field and exercise the flexing properties of the edge seal. Furthermore, the seal should be tested for gas permeability before and after weathering exposure to determine any loss of vacuum due to air infiltration.

Advanced Fenestration: Dynamic IGU (Electrochromic and Thermochromic)

Present dynamic glazing products change their optical properties based on external conditions. There are two classes of dynamic glazing presently on the market. Electrochromic technologies that change properties based on the application of a small voltage currently dominate this market. Thermochromic technologies change properties based on temperature and greatly simplify installation without the need for electrical connections. Both technologies achieve their function through the addition of various coating layers that are applied to the glass, often on the interior side of the outboard glass lite. The materials that form these device layers need to be stressed differently than present IGU structures. ASTM durability assessment protocols have been developed to determine long term performance of both electrochromic (ASTM E2141/E2953) and thermochromic or, "environmentally controlled" devices (ASTM E3119/E3120). Such units need to be tested to these methods in addition to tests for standard IGU measurements. Any certification of this class of fenestration to the common ASTM E-2188/2189/2190 protocols should also include certification to the relevant dynamic glazing protocol.

CONCLUSIONS

While windows are a desirable component of any building, they are presently the weak link in building envelope performance. Advanced technologies are currently being developed to address these issues; however, these technologies need to be demonstrated to be durable in the field before any substantial market traction will be gained. Window performance is specified based on "as installed" metrics, however energy savings and associated greenhouse gas emission reductions are only realized if that performance is delivered over time. This work has summarized information gathered related to current practice of durability evaluation of fenestration products as well as shared special circumstances that must be considered for several emerging high-performance technologies. Furthermore, we have outlined a proposed guideline for improved durability evaluation of present IGU technologies. It is our team's hope further research into and adoption of this proposed guideline will help improve the long-term performance of fenestration products and help realize their true potential impact on our environment.

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ASCE: American Society of Civil Engineers (https://www.asce.org/)

NOAA-National Centers for Environmental Information (https://www.ncei.noaa.gov/)

WINDOW: A computer program for calculating total window thermal performance indices (window.lbl.gov)

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