ENTHERMAL

ACCELERATED DURABILITY

The most important factor in the long-term thermal performance of a complete glazing system is the performance and durability of the insulating glass unit (IGU). The IGU comprises the glass panels, edge spacer, desiccants, sealants, gas fill, and coated glass which all must be designed to prevent premature failure. Historically, IGUs have been tested in accordance with the IGCC test standards – ASTM 2188, ASTM 2189, and ASTM 2190, which were developed to validate a metal, foam or silicone spacer with organic-based sealants. Successfully passing the third party, independent test protocol infers the IGU will deliver acceptable lifetime in a glazing application.

Vacuum insulated glass (VIG) is ushering in a new era where u-factor and thermal differential, exterior to interior, performance is a step change from gas-filled IGUs. The test standards used to validate traditional IGU systems are no longer sufficient to fully validate long term durability of VIG. Current ASTM test standards and methods do not properly stress the product design, raw materials, manufacturing processes, and performance of a VIG unit. Since LuxWall's Enthermal VIG outperforms the current test standards by a wide margin, LuxWall has developed an accelerated test protocol to ensure Enthermal units have a minimum 30-year useful life while delivering a 20-year warranty.

This application note details Enthermal test and validation performance for industry standard tests performed at independent test facilities, and LuxWall internal extreme accelerated durability tests. LuxWall's accelerated aging protocol ensures Enthermal products will perform in the built environment for decades to come under adverse weather and end use conditions. Similar to standardized, third-party testing, the LuxWall environmental stressors are intended to accelerate real-world performance requirements and fully validate VIG performance.

The Enthermal units described in this application note were produced per the following configuration: (1) Clear float glass; (2) Low-E coated clear float glass; (3) 50-mm pillar spacing; (4) Enthermal proprietary perimeter seal; (5) Enthermal proprietary evacuation port; (6) 250-um vacuum cavity; (7) Enthermal proprietary getter; and (8) Both glass panes were fully tempered to ASTM standard. Some tests use 5/5-mm or 5/4-mm.

All units described in the report were 14-inches x 20-inches (355.6-mm x 508.0-mm) unless otherwise denoted, and the units were tested as stand-alone VIG units or VIG units installed in an aluminum frame. *Figure 1* details the VIG installed in an aluminum frame.

Figure 1. Enthermal VIG Glazing Cross Section.

STANDARD IGU TEST PROTOCOL (INDEPENDENT VALIDATION)

LuxWall has successfully passed third party testing for all required and critical industry tests.

ASTM E2190: SPECIFICATION FOR INSULATING GLASS UNIT PERFORMANCE AND EVALUATION

ASTM E2190 is a test specification for insulating glass units. A product fully meets ASTM E2190 specifications if it passes the testing parameters defined in ASTM E2188 and ASTM E2189. Upon completing ASTM E2188, the frost and dew points must be -40 °C or colder, and after completing ASTM E2189, the units must have no visible fogging.

ASTM E2188: STANDARD TESTING FOR INSULATING GLASS UNIT PERFORMANCE

ASTM E2188 outlines the standard stress-response protocol for the performance of IGUs covering two phases. The first phase is a heat (60 °C) and humidity (95% RH) soak lasting 14-days. The second phase is a combined stressor cycle using heat (60 °C), humidity (90% RH), 60-minute water spray, fluorescent UV (three hours out of six hours) and thermal cycling from -29 °C to 60 °C on a 6-hour cycle for 63 days. A third phase of heat humidity soak, consisting of 28 days. Upon completion of the stress protocol, a frost/dew point test is conducted with units passing if the frost/dew point is less than or equal to -40 °C. The total exposure time for ASTM E2188 is 15 weeks. LuxWall successfully passed ASTM E2188 at Intertek York, PA per report P7984.01-119-28 R0. Additionally, the independent lab tested u-factor on per ASTM C518 (described below) and the units maintained their original u-factor performance.

ASTM E2189: FOGGING RESISTANCE IN INSULATING GLASS UNITS

ASTM E2189 outlines the stress-response protocol for the fogging resistance performance of IGUs. The protocol is a 7-day test with UV and asymmetric thermal exposure (50 °C and 21 °C). Upon completing the exposure protocol, a fog test is run. LuxWall successfully passed ASTM E2189 at Intertek York, PA per report P7984.01-119-28 R0.

ASTM C518: STEADY-STATE THERMAL TRANSMISSION PROPERTIES

ASTM C518 is a protocol by which the u-factor of a product is tested. For LuxWall Enthermal, C518 tests the center of glass u-factor or R-value. The test is conducted with a heat flow meter that measures the heat flow through a 4-inch by 4-inch metering area in the center of the unit. For internal testing, LuxWall uses a Fox 314 from TA Instruments which, uses a bottom (hot, 21 °C) and top (cold, -18 °C) plate, each equipped with a transducer to measure steady state heat flow. The test is used before and after durability tests to ensure vacuum integrity did not degrade during accelerated testing exposure.

An independent, third-party lab tested Enthermal three product configurations comprising single silver, double silver and triple silver Low-E coated glass with 50-mm pillar spacing. The results are shown in *Table 1.* ASTM C518 testing was performed at Intertek in York, PA per reports Q7578.01-116-25 RO and Q7578.02-116-25 RO.

Low-E Coating	Pillar Spacing	u-Factor (W/m^2K)	u-Factor (BTU/ft^2hrF)	R-Value (ft^2hrF/BTU)
Single-Silver	50-mm	0.477	0.084	12
Double-Silver	50-mm	0.355	0.062	16
Triple-Silver	50-mm	0.315	0.055	18

Table 1. Third-party LuxWall Enthermal Thermal Performance.

ASTM B117: STANDARD PRACTICE FOR OPERATING SALT SPRAY (FOG) APPARATUS

ASTM B117 is designed to create and maintain a salt fog exposure environment for a test specimen. The test chamber maintains an atomized, 5% sodium chloride solution at 35 °C for 2 weeks. LuxWall Enthermal showed no perimeter seal degradation or loss of vacuum quality after salt spray exposure. ASTM B117 testing was performed at Intertek in York, PA per report P7934.01-106-31 R0.

ASTM E2264: DETERMINING EFFECTS OF THERMAL CYCLING ON FENESTRATION PRODUCTS

ASTM E2264 is intended to measure fenestration product performance, when acted upon by asymmetric thermal cycling exposures. The standard simulates seasonal and diurnal temperature conditions on a fenestration product installed in a building with steady interior temperature. The asymmetric thermal cycle consists of two 12-hour cycles per day for 14 days. The Enthermal thermal performance is maintained throughout the cyclic test. ASTM E2264 testing was performed at Intertek in Fridley, MN, per report P8599.01-201-23 RO.

AAMA 1503-09: THERMAL TRANSMITTANCE AND CONDENSATION RESISTANCE OF WINDOWS

AAMA 1503-09 is a test designed to characterize the likelihood of condensation forming on a window or a window frame. The test unit is subjected to -18 °C on the exterior unit surface and 21 °C interior unit temperature. The window system tested comprised a thermally-broken curtainwall frame systems with SSG and EPDM gaskets. In the physical test, thermocouples were placed in pre-set locations around the frame and glazing vision area. Calculations are performed based on measured frame temperatures to calculate a frame-CRF and measured glazing temperatures to calculate a glazing-CRF. Since colder surfaces condense water more readily, the CRF for the system is the lower of the frame-CRF and the glazing-CRF. AAMA 1503-09 testing was performed at Element Material Technology in Saint Paul, MN per report ESP041205P-2.

ASTM E330: UNIFORM STATIC AIR PRESSURE DIFFERENCE FOR WINDOWS

ASTM E330 is designed to determine the structural performance of a glazing system, based on static air pressure differentials. Pressure differentials and deflection are measured at each step of the test. The system passes if it holds the set point pressure (lbs./ft2) for 10 seconds. LuxWall instructed the third-party lab to perform three individual tests. Initially, an Enthermal unit was tested in a 16.75 in x 22.75 in industry standard, non-thermally broken frame. The testing was ceased at 225 psf (DP 225), prior to failure, with a deflection of only 0.25 in. Next, two Enthermal units were tested in 51.125 in x 72.85 in commercially available, thermally broken curtainwall frames. The Enthermal unit in Frame A failed at 70 psf (DP 70 rating) with a COG deflection of 0.784 in while the unit in Frame B failed at 90 psf (90 DP rating) with a COG deflection of 0.892 in. These results demonstrate that LuxWall Enthermal, when properly installed and supported can withstand high wind loads. ASTM E330 testing was performed at Element Material Technology in Des Moines, IA per reports ESP040991P, ESP040037P, and ESP041048P.

LUXWALL ACCELERATED AGING MODELS

Proper aging models are critical for accelerated validation testing. Fenestration products will experience temperature cycling, precipitation, humidity, UV, freeze and thaw cycles, salt atmosphere, and asymmetric thermal stresses. For temperature dependencies, the Arrhenius equation is a foundational model for predicting acceleration factors. LuxWall has developed extreme accelerated aging models for humidity plus, temperature, thermal cycling, and UV exposure to rapidly test raw material, product, and process related performance and to apply test stressors well beyond exposure limits defined in ASTM E2188, ASTM E2189, ASTM E2190, and ASTM E2264.

ACCELERATION FACTORS BASED ON HUMIDITY AND TEMPERATURE

To capture the effect of humidity and temperature cycling, more sophisticated models are needed. The Hallberg & Peck model, shown in *Equation 1*, captures the effect of humidity by an inverse power law in combination with the Arrhenius equation.

$$\mathrm{AF}([\mathrm{T}_0, RH_0], [\mathrm{T}_1, RH_1]) = \exp \underbrace{\left[\frac{Ea}{k}\left(\frac{1}{T_0} - \frac{1}{T_1}\right)\right]}_{\text{Arrhenius}} \cdot \underbrace{\left[\frac{RH_1}{RH_0}\right]^n}_{\text{Humidity}}$$

Equation 1. Hallberg-Peck Acceleration Model for Heat and Humidity.

Where:

- AF is the Acceleration Factor
- T_0 and T_1 are the initial and elevated temperatures
- RH_0 and RH_1 are the initial and elevated relative humidity
- E_a is the activation energy parameter
- k is the Boltzmann constant
- n is the effect parameter of humidity

Where E_a and n are unknown, they can be estimated. LuxWall models use the values E_a = 0.79 eV and n=2.7 based on Peck's paper and a survey of academic resources. These values are on the conservative end of those used for modeling hermetically sealed products.

ACCELERATION FACTORS BASED ON THERMAL CYCLING

Thermal cycling is an important characteristic of long-term Enthermal performance. Regardless of geography, every Enthermal will experience daily and seasonal temperature cycles. To estimate the effect of thermal cycling, LuxWall uses the Coffin-Manson extension of the Arrhenius equation, shown in *Equation 2*.

$$\mathrm{AF}(\mathrm{T}_0, T_1) = \exp \underbrace{\left[\frac{Ea}{k}\left(\frac{1}{T_0} - \frac{1}{T_1}\right)\right]}_{\text{Arrhenius}} \cdot \underbrace{\left[\frac{\Delta T_1}{\Delta T_0}\right]^p}_{\text{Temp Cycle}} \cdot \underbrace{\left[\frac{F_0}{F_1}\right]^q}_{\text{Frequency}}$$

Equation 2. Coffin-Manson Model for Calculating Acceleration based Thermal Cycling.

Where:

- AF is the Acceleration Factor
- ΔT_0 is the base case differences between low and high thermal cycle
- ΔT_1 is the difference between low and high temperatures of accelerated settings
- F_o is the base case cycle frequency
- p and q are the amplitude and frequency factors
- RH_0 and RH_1 are initial and elevated relative humidity
- E_a is activation energy parameter
- k is Boltzmann constant
- n is the effect parameter of humidity

The Coffin-Manson model compares the acceleration factor of a base case thermal cycle to an accelerated one. If, for example, the weather cycles from 3 °C to 19 °C, this would be the base case, ΔT_0 = 16 °C and F_o = 1 day. The accelerated case, LuxWall cycled from -60 °C to 130 °C with 4-hours cycles for a ΔT_1=190 °C and F_1 = 0.17. LuxWall selected conservative values for, p = 1.9 and q = 1/3.

IRRADIANCE FACTORS FOR UV EXPOSURE

Resistance to UV light exposure is critical for long-term VIG performance. UV light can break down hydrocarbon contaminants forming CO and CO_2, release hydrogen from the float glass, and release water vapor from cavity interior surfaces into volatile gas species that degrade vacuum quality. LuxWall measures the spectral irradiance of a bulb and compares the area under the curve to standard daylight, as defined by ASTM G173. Intensity factors are applied based on the total irradiance levels defined in ASTM G173. LuxWall has selected the optimal bulb type, configuration, intensity, and irradiance to mimic sunlight with acceleration factors ranging from 2X up to 32X.

LUXWALL ACCELERATED VIG TEST PROTOCOL

LuxWall has developed its accelerated VIG test protocol to address increasing stress factors:

- Increased temperature exposure based on increasing climate extremes;
- Increased wind pressure due to increased frequency and intensity of storm systems;
- Increased temperature ramps due to rapid environmental changes such as polar vortex systems;
- Decreased u-factor performance resulting in higher asymmetric thermal stress conditions; and
- Decreased u-factor performance leading to increased IGU thermal-induced deflection.

ACCELERATED DURABILITY

LuxWall uses six primary stressors to validate the long-term performance of its Enthermal products: (1) aqueous full immersions in water, pH-3 solution, and pH-10 solution; (2) damp heat; (3) thermal cycling; (4) UV exposure; (5) asymmetric thermal shock; and (6) thermal cycling with water spray and UV. For each of these stressors, the response is u-factor, as measured by C518. The following sections detail the selected test protocol and where applicable, provide the acceleration factor compared to relevant ASTM standards.

The stress-response protocol LuxWall uses are designed to meet two goals - accelerate beyond the ASTM test standards and target specific features of the Enthermal product design and manufacturing build confidence to ensure a minimum 30-year performance with a 20-year warranty.

LUXWALL ACCELERATED TESTS AND STRESSOR COMBINATIONS

LuxWall has thoroughly tested Enthermal products through individual tests utilizing the following stressors: aqueous immersion(s), thermal cycling, damp heat, asymmetric thermal shock, UV exposure, cold-climate rapid cycling, hot-climate rapid cycling, thermal cycle with water spray, and humidity freeze. In addition, LuxWall utilizes sequential combinational tests simulating multiple environmental exposures comprising water immersion, damp heat, thermal cycling, and asymmetric thermal shock.

AQUEOUS IMMERSIONS

When performing validation and accelerated aging testing, the first test LuxWall conducts is full immersion in deionized (DI) or reverse osmosis (RO) water at 65 °C, for 10-days. The warm water causes the perimeter and evacuation port seals to differentially expand relative to the glass substrates. This differential expansion induces stresses on the glass-to-seal interface, which can be a VIG failure point. Any seal defects or water uptake by the sealing materials will result in unit failure and loss of vacuum. No ASTM test standards expose the VIG units to these extreme test conditions. Enthermal units do not lose thermal performance, u-factor, after complete immersion in 65 °C DI or RO water for 10-days. LuxWall also employs two other full unit immersion protocols, pH 3.5 (HCl) and pH 10.0 (NaOH). These immersions are intended to simulate muriatic acid brick wash or alkaline glass cleaners that settle into the sash of a window after installation in the building. The VIG units are exposed to acidic and basic solutions for 10-days at room temperature (25 °C +/- 5 °C). Enthermal units do not lose thermal performance, u-factor, when fully immersed in HCl at pH 3.5 or NaOH at pH 10.0 for 10-days.

THERMAL CYCLING

Thermal cycling is a strong indicator of perimeter seal strength and glass-to-pillar stability. LuxWall's thermal cycling protocol is a round-trip cycle from -60 °C to 130 °C every 4 hours for two weeks. With each expansion and contraction cycle, the perimeter seal is tested for hermetic durability and glass-to-pillar strength and deformation. LuxWall's thermal cycling protocol is significantly more severe than ASTM E2188, which runs from -29 °C to 60 °C on 6-hour cycles. When using the Coffin-Manson calculation, ASTM E2188 has an acceleration factor of 556. Due to the extreme delta temperature (dT) and accelerated ramp rate, LuxWall's protocol has an acceleration factor of 100,000. LuxWall's thermal cycling test is one order of magnitude more severe than ASTM E2188. Enthermal units do not lose thermal performance, u-factor, when subjected to -60 °C to 130 °C thermal cycles 6 times per day for two weeks.

DAMP HEAT

Extreme temperature with high humidity is a severe stressor on a VIG perimeter seal. If the perimeter seal has a defect or exterior to interior migration path, steam moisture would permeate through the seal resulting in vacuum cavity fogging and loss of thermal performance. LuxWall's protocol for damp heat consists of 85 °C environment with 85% relative humidity for four weeks. ASTM E2188 has a damp heat stressor component in its protocol, 60 °C and 95% RH for six weeks. Using Halberg-Peck, the ASTM E2188 acceleration factor is 48. LuxWall's thermal cycling acceleration factor is 289, which translates to a 6-times higher acceleration factor than ASTM E2188. Enthermal units do not lose thermal performance, u-factor, when subjected to 85 °C and 85% RH for four weeks.

ASYMMETRIC THERMAL SHOCK

Due to the high thermal performance, low u-factors, Enthermal VIG units experience high stress conditions at the perimeter seal-to-glass interface and the glass-to-pillar interface. For

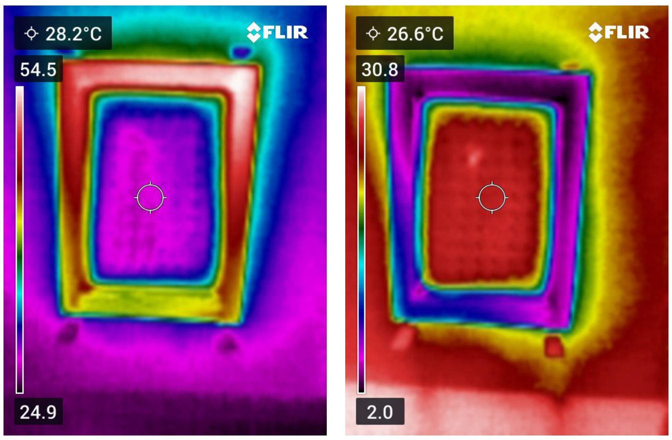

Figure 4. Asymmetric Thermal Shock: +110 °C (left image) and -70 °C (right image).

extreme cold weather conditions, the outdoor glass pane contracts and the Enthermal unit deflects toward interior of the building. LuxWall's asymmetric thermal shock exposes the VIG unit to +/- 90 °C thermal differential conditions. The Enthermal unit is mounted vertically in a non-thermally broken frame. The temperature of the test chamber is increased (decreased) in 5 °C intervals every 30 minutes to the 90-degree differential. The maximum asymmetric hot protocol ranges from +20 °C to +110 °C and the cold protocol goes from +20 °C to -70 °C. *Figure 4* shows Enthermal units of Enthermal when the chamber is at 110 °C and -70 °C, respectively. LuxWall Enthermal products do not break or lose thermal performance, u-factor, when subjected to extreme +/- 90 °C asymmetric thermal conditions.

UV EXPOSURE

Every window will be exposed to UV light. UV light can break down hydrocarbon contaminants forming CO and CO_2, release hydrogen from the float glass, and release water vapor from cavity interior surfaces into volatile gas species that degrade vacuum quality. LuxWall has executed two UV test protocols – 2X UV exposure and 32X UV exposure.

ASTM E2188 UV exposure levels are 0.8X sunlight intensity using a fluorescent UV light source having a dominant wavelength of 365-nm. The units are tested for 63 days with 3 hours of sunlight followed by 3 hours of darkness per cycle; there are four cycles per day resulting in 12 hours of UV exposure per test day. ASTM E2188's cumulative UV exposure is 756 hours. LuxWall's fluorescent UV test protocol uses 2X sunlight intensity with a dominant wavelength of 340-nm, continuous UV exposure (24-hours per day), and 114-day test duration. LuxWall uses a more aggressive dominant wavelength than ASTM E2188 to increase the acceleration factor. LuxWall's cumulative 2X fluorescent UV exposure is 2,736 hours, which is 3.6 times greater than the ASTM E2188 protocol. Enthermal units have passed the 2X UV protocol for 114-days without degradation in thermal performance.

LuxWall's metal halide test protocol uses 32X sunlight intensity with continuous UV exposure (24-hours per day), 100 °C ambient temperature, and 114-day test duration. LuxWall's cumulative 32X fluorescent UV exposure is 2,736 hours, which is 3.6 times greater than the ASTM E2188 protocol. The combination of 32X UV, 100 °C ambient temperature, and 114-days results in an acceleration factor of 100 compared to ASTM E2188 UV exposure. Enthermal units have passed the 32X UV protocol for 114-days without degradation in thermal performance.

RAPID CYCLE EXPOSURE

LuxWall rapid cycle exposure protocols are designed to simulate daily temperature cycles experienced by a real-life window. The goal is to expose units to 5,000 temperature cycles using accelerated aging methods. The rapid cycle protocol completes one cycle of high-to-low-to-high exposure in approximately 30 minutes. One week of exposure equates to one year of thermal and humidity cycles. Grand Forks, ND and Miami, FL were chosen as model cities based on 30-years of extreme temperatures and high heat/humidity respectively. The North Dakota protocol tests extreme temperature fluctuations and the Miami protocol tests a narrower temperature range with high humidity effects.

For each city, historical 30-year averages were analyzed and set points selected form record high temperatures, low temperatures, and average daily temperature change. For January through March and October through December, the target temperatures were calculated from the record low. For April through September, the target temperatures were calculated from the record high. For Miami, the average monthly dew point was used as a set point for relative humidity during the simulated summer months. Enthermal units have passed 7,300 North Dakota cycles and 7,300 Florida cycles with no degradation in thermal performance. In twenty years the product will experience 7,300 daily temperature cycles.

THERMAL CYCLING WITH WATER SPRAY

LuxWall thermal cycling with water spray protocol is designed to expose Enthermal units to extreme temperature ranges with three water phase changes. The protocol uses a 5-hour cycle with ambient temperature ranging from -30 °C to 70 °C. When the chamber is above 20 °C, a water spray, room temperature water, is applied to the Enthermal units. This spray is turned off when the VIG unit is at the maximum temperature, allowing the units to dry and humidity in the chamber to increase. During the cooling ramp, the chamber is reduced to -30° C, allowing water to condense, then freeze. The heating ramp allows the water to melt and then evaporate. Enthermal units have passed 17-weeks with no degradation in thermal performance.

HUMIDITY FREEZE

LuxWall-designed humidity freeze test protocol exposes Enthermal units to extreme temperature ranges, together with three water phase changes. This protocol uses a 5-hour cycle with temperatures from -30 °C to 70 °C. During heat up, when the chamber is above 20 °C, the air is saturated with water vapor (steam generation) to 95+% humidity, remaining so through the 70 °C dwell. This allows water vapor the opportunity to expose any potential weak spots in the vacuum seal. During the cooling ramp, the chamber is reduced to -30 °C, allowing water to condense, then freeze before melting and eventually evaporating during the subsequent

ACCELERATED DURABILITY

heat up. Water phase changes test the units mechanical and environmental reliability. Enthermal units have passed 8-weeks with no degradation in thermal performance.

SEQUENTIAL COMBINATIONAL STRESSORS

LuxWall has developed sequential combination stressors to ensure product durability when the same Enthermal unit is exposed to multiple accelerated aging stressors. LuxWall utilizes sequential combinational testing comprising five days 65 °C full water immersion, 4-weeks with 85 °C and 85% RH damp heat, 4-weeks -60 °C to 130 °C thermal cycling, and +/- 70 °C asymmetric thermal shock. LuxWall utilizes the following combinational test sequences (1) water immersion then thermal cycling then damp heat then asymmetric thermal shock; (2) damp heat then thermal cycling then water immersion then asymmetric thermal shock; and (3) thermal cycling then damp heat then water immersion then asymmetric thermal shock. Enthermal units have passed all three sequential stressor combinations with no degradation in thermal performance.

LUXWALL ENTHERMAL ACCELERATED DURABILITY

Enthermal has successfully passed the following Independent Tests:

- ASTM 2188/2189/2190
- ASTM C518
- ASTM B117
- ASTM E2264
- AAMA 1503-09
- ASTM E330
- AAMA 920

And LuxWall's Accelerated Stressor Test Protocol:

- Accelerated UV Exposure
- Aqueous Full Immersion
- Asymmetric Thermal Shock
- Damp Heat
- Humidity Freeze
- Rapid Cycle Exposure - North Dakota
- Rapid Cycle Exposure - Florida
- Sequential Combination Stressors
- Thermal Cycling
- Thermal Cycling with H20 Spray