THERMAL AND OPTICAL PERFORMANCE OF GRANULAR AEROGEL GLAZING AFTER ACCELERATED AGEING

By

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ABSTRACT

Thermal and Optical Performance of Granular Aerogel Glazing after Accelerated Ageing
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The glazing portion of a window has dual but conflicting functions where it is required to provide views to the outside, but also have good thermal resistance. Glazing is usually one of the weak points in the thermal envelope and tends to age quicker and to a higher severity. The combination of granular aerogel inside a glazing cavity is still relatively new product, but could offer both great thermal and optical performance. Currently available durability data for granular aerogel glazing is scarce. Accelerated ageing was used to generate real life equivalent stresses of 13.5-74 years by exposing a set of samples to several climatic conditions. The center of glass U-value increased by a maximum of 4% after accelerated ageing in the oven and the temperature cycling machine. A maximum reduction of 211% was measured in the visible transmittance after accelerated ageing climatic and humidity chambers.

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1 INTRODUCTION

Global warming can be considered as one of the biggest challenges of the twenty first century which manifests itself in warmer temperatures of the oceans and earth's atmosphere. An increase of an average of 0.8°C of the earth's surface temperature has occurred primarily in the last three decades. Two main reasons for global warming can be attributed to human based activities of burning of fossil fuels and deforestation. During the 21st century, climate model projections indicate a 1.1-2.9°C and 2.4-6.4°C increase for the global surface temperature for best and worst case scenarios respectively.

Based on these prediction, some places around the world have started to adopt a low carbon strategies by taking the appropriate measures (Koebel, Rigacci, & Achard, 2012). Increasing public awareness on carbon footprint has grown in the last several years to show the correlation between CO_2 concentrations and global climate. Stabilizing the atmospheric CO_2 concentration below the 500ppm has been outlined as a point of great importance in many instances.

Increased international political efforts continually act as a strong stimulus for research on high performance insulating materials and systems to meet the ever increasing energy standards. The primary goals for the research is to examine the thermal performance of up and coming materials while improving conventional ones. Improving the energy management of buildings through the coupling of high performance envelopes with renewables would be the method to help stabilize greenhouse gases concentrations in the atmosphere. At the end of the 20th century, the European Union has accepted the Kyoto-Protocol which mandated the decrease of emissions by 20% by the year 2020 compared to the emissions level of 1990, and although this a great start, a low carbon economy through net-zero/positive building is the way of the future.

1.1 Background

As the 21st century rolled in, there was an undeniable necessity for the world to check its energy consumption distribution by sector. In 1999, the total consumption of energy in Europe was reported at 1780 million tons of oil equivalent of which 35% was consumed by the commercial and residential sectors (Cuce, Cuce, Wood , & Riffat , 2014). Buildings have a major impact on greenhouse gas (GHG) emissions in developed countries being responsible for more than 30% of the GHG emission in 2005 (Baetens, Jelle, Gustavsen, & Grynning, 2010) (Baetens, Jelle, & Gustavsen, 2011).

In order to minimize the energy consumption, adding insulation (or more of it) to the building envelope can yield savings in energy consumption which directly reduces emissions. Conventional insulation materials have to be used in multiple and/or thicker layers to achieve the prescribed levels which results in heavier construction, more complex building details and reduced area of inhabitable living space (Aegerter, Leventis, & Koebel, 2011). There is also the notion that using air as an insulator has reached its limit (Cuce et al., 2014). With each passing year, the need to have a high performance insulation material which meet the energy requirements is becoming greater and greater.

There are currently several materials/products in the market which aim to meet the growing demand for high performance insulation. Although aerogel was first discovered in the 1930's (Kistler, 1931) (Kistler & Caldwell, 1932) it has undergone great progress in the last two decades. Aerogel attracted many sectors due to its wide range of applications some of which include construction, automotive, electronics, aerospace, marine, oil & gas and clothing among others. Due to its exceptional physical and chemical properties aerogel has generated a lot of interest for energy efficient retrofitting and high performance buildings.

The market share of aerogels tripled to $83 million in 2008 and reached USD $352.6 million in 2014 (Grand View Research, 2016a). Since aerogel's beginnings, the super insulator (materials with thermal conductivity <0.02 W/mK) has become a significant player in the USD $44.46 billion (as of 2015) global insulation market (Grand View Research, 2016b). Commercializing aerogel is still difficult due to manufacturing process but research and development continues to reduce cost, create new types of aerogel and enhance the performance.

1.2 Objective and Research Motivation

Although aerogel has been already extensively researched and has very attractive performance characteristics, there is still work remaining to be done in terms of reducing the production cost of the material to make it more commercially viable. Regardless of when this breakthrough will come, and whether it will be sudden or gradual, like with any new product seeking to enter the construction industry, its durability must be proven in order to gain and maintain widespread application. Producing aerogel on a commercial scale is a business with a desire to earn a profit, and using an un-tested product would be risky, so in order for it to be more marketable to the construction industry, it needs to show its reliability and durability via accelerated climate ageing.

The issue of durability is always a concern for all parties involved in construction and operation of a building. Even if the product has superior qualities on paper, if it performs worse in low temperatures when compared to conventional batt insulation, it would be difficult to convince owners to use it. In the case of insulated glazing units (IGUs), even the best performing window is worthless when the IGU is unable to perform well after a few years of service (e.g. fogging or freezing during cold weather).

Aerogel has many applications in the construction industry. Ageing aerogel inside IGUs, as a replacement for the gas fill, would allow for a better understanding on how aerogel based glazing would perform in 15-20 years from now by evaluating its thermal and optical performance. This will either help prove its durability or will expose the weak points which will require modification to the design. It is important to get a better understanding on how an aerogel filled IGU would perform in the future from a thermal and optical point of view to either provide guidance for current and future product manufacturers or to halt the entire notion of using aerogel in IGUs.

The following questions can be derived from the research objective:

- How do the prototype granular aerogel filled glazing units perform in terms of thermal conductance and visible transmittance after accelerated climatic ageing?

- Which accelerated climatic ageing mechanisms are the most damaging for granular aerogel inside glazing units?

1.3 Scope of Work and Limitations

The scope of the research is to determine how ageing effects granular aerogel inside a glazing cavity. The experiments and data collection have been carried out within the constraints of the building science laboratory and time tables. It also important to note that testing of the aged aerogel was focused on thermal and optical performance while other aspects such as sound dampening and moisture management were not tested.

The assembly conditions were monitored and held within the recommended range but could not be perfectly controlled due to the allocation of the given assembly area. The created specimen were dependent on the availability of the base components; spacer, glass, sealant and aerogel as well as the ability to assemble them with relative success. The assembled IGUs may not represent best practices in terms of assembly technique or materials selection but rather an effective method to contain the granular aerogel within an IGU assembly to allow for accelerated ageing.

2 BACKGROUND AND LITERATURE REVIEW

2.1 Overview

High performance insulation or superinsulation is a term used to describe materials which have a thermal conductivity lower than 0.020 W/mK. Thermal conductivity (λ) is an inherent property of a material which allows it to conduct heat (Dorcheh & Abbasi, 2008). Metal are known to be very good conductors as can be seen in their application in electronics with their λ being tens to hundreds of W/mK. Glass, sand and other minerals have single digit thermal conductivities. Common insulation materials such as glass wool, mineral wool, expanded and extruded polystyrene have conductivities in the range of 0.030-0.040 W/mk. Polyurethane and phenolic raisins are considered as transition materials between superinsulation and conventional insulation (Aegerter, Leventis, & Koebel, 2011).

Some of the current superinsulation materials include aerogels, vacuum insulation panels (VIPs) and vacuum glazing all offer very low thermal conductivities. There are three types of aerogels, silica, carbon and alumina. Among the three, silica is the most common, with most research and biggest adaptation. In the recent years, research is focused on cost reduction and the creation of new aerogels (Cuce et al., 2014).

2.2 What is Aerogel?

Aerogels were first discovered in 1931 by Samuel Stephens Kistler (Kistler, 1931) (Kistler & Caldwell, 1932) and have been in constant development ever since. The term aerogel comes from the fact that it is manufactured from gels. At the same time, the term aerogel might be misleading since it is dry and rigid in its final form (also known as the solid air). One of the main characteristics that makes aerogel so extraordinary is the combination of extremely high porosity (80-99.8%) and translucent structure (Hüsing & Schubert, 1998) (Gaponik, Herrmann, & Eychmüller, 2012).

Aerogels are essentially the solid framework isolated from it its liquid medium. It consists of cross-linked internal structure of silica chains with large number of air filled pores (Baetens, Jelle, & Gustavsen, 2011). This can be achieved by replacing the liquid in the pores with a gas using supercritical drying (now possible under ambient drying conditions) with little shrinkage (<15%). Xerogels are similar to aerogels and are dried by evaporation but experience extreme shrinkage (>90%). Cryogel® is a commercialized name of a product developed by Aspen Aerogel. It is a flexible composite aerogel blanket (with a built in vapour retarder) used for insulating in low temperature environments, ranging from ambient to cryogenic. Aerogel is the generic umbrella name similar to rock wool and fiberglass insulations.

2.3 Synthesis

The synthesis of silica aerogel can be divided into three main stages; the preparation of the gel (sol-gel process), ageing of the aerogel and drying the gel under a specific set of conditions. In material science the sol-gel process is known as the method which is used to produce a solid material from small molecules. This method is used to fabricate metal oxides, especially from silicon and titanium. This process covers the conversion of monomers into a colloidal solution (sol) which acts as the precursor for an integrated network (gel).

2.3.1 Gel preparation (sol-gel process)

The gel preparation, also called the sol-gel process is the procedure where solid nanoparticles dispersed in a liquid agglomerate to form a continuous three dimensional network throughout the liquid. This process is outlined in great detail by (Brinker & Scherer, 1990). In silica aerogels, the nanoparticles are grown directly in the liquid. Precursors are the starting substances which are used in the growth of the aerogel within the liquid solution.

Some of the more common precursors for silica aerogels are silicon alkoxides which include the following: Tetramethoxysilane $Si(OCH_3)_4$ also known as TMOS, tetraethoxysilane $Si(OC_2H_5)_4$ also known as TEOS and polyethoxydisiloxane or PEDS-P_x. PEDS-P_x can be obtained by reacting TEOS with substoichiometric quantity of water in an acidic alcoholic medium.

From a thermal insulation point of view, the aerogel monoliths created with PEDS and TMOS have lower thermal conductivities than that of TEOS monoliths (Wagh et al., 1999) but TEOS could potentially have better optical properties (Tewari, Lofftus, & Hunt, 1986). Too much water in the solution will yield low porosity gels which requires the use of solvents such as ethanol.

The hydrolysis of silicon alkoxides is done with a catalyst, either acid, base catalysis or two-step catalysis (Venkateswara Rao & Bhagat, 2004). In order for the sol to become gel, the solid nanoparticles in the liquid need to collide with one another. For some types of nanoparticles this is done more easily since they contain reactive surface grounds that allow them to stick together after colliding by electrostatic forces or bonding while other types require additional additive. Using acid for hydrolysis and condensation results in linear (or weak) chains and a microporous structure in silica sols but with long gelation periods (Kirkbir, Meyers, Murata, & Sarkar, 1996). On the other hand, using a base (e.g. NH_4OH) allows for the creation of a more uniform particles which lead to a broader distribution of large pores which is less desirable for thermal insulation materials (Siouffi, 2003).

One of the main precursors for silica aerogels is alkoxides which are described as expensive and hazardous substances (can cause blindness with TMOS) which would prohibit mass production. One solution is to use water glass or sodium silicate as a cheaper raw material for the silica (Schwertfeger, Frank, & Schmidt, 1998). It is currently used as a precursor for commercial aerogel synthesis. This is done by acidification of the aqueous sodium silicate solution with HCI or H_2SO_4 to create silica hydrogel (United States Patent No. 5811031 - Method for the subcritical drying of aerogels , 1998) (United States Patent No. 5647962 - Process for the preparation of xerogels , 1997).

2.3.2 Ageing of the gel

When sol reaches the gel point, the silica network is occupying the entire container, but the delicate structure still contains unreacted alkoxide groups. In order to strengthen the silica network, a sufficient amount of time must be given for hydrolysis and condensation to continue. This process can be enhanced by controlling the pH levels, concentration and the solution (Hæreid, Einarsrud, Lima, & Dahle, 1995) (Hæreid, Nilsen, & Einarsrud, 1996) (Palantavida, et al., 2006).

Two different mechanisms could affect the structure of the gel, dissolution of small particles into larger ones and transport of materials to the neck region. One of the common ageing procedures utilizes an ethanol-siloxane mixture which adds new monomers to the solid silicon monoxide network, increasing the degree of cross linking (Hæreid et al., 1996). The resulting gel has higher strength and stiffness. This ageing process is controlled and although the transport of the material is unaffected by mixing or convection due to the solid network, the diffusion on the other hand is affected. This means that the thicker the gel, the longer each process step will take which limits the practical production of aerogels.

After ageing and before drying, the liquid inside the pores needs to be removed. This can be done with relative ease by washing the gel with ethanol and heptanes (Hæreid et al., 1996). Any leftover liquid would not be removed by supercritical drying which would lead to a very dense and opaque aerogel.

2.3.3 Drying of the gel

The final and most critical step is drying the gel. Due to the size of the pores, the drying process is dominated by capillary pressure (except in supercritical drying and freeze drying) which causes shrinking and potential fractures. The drying process can be sorted into two types; ambient pressure drying (APD) where the capillary tension is present and supercritical drying (SCD) where the liquid in the pores is removed above the critical temperature and pressure to elude capillary tension. This step in aerogel production is where a lot of cost of the aerogel comes from and has potential for cost reduction. Also, the shrinking of the aerogel plays a role in the production cost since with less shrinking the aerogel slabs would be better suited for glazing applications.

2.3.3.1 Supercritical Drying (SCD)

For silica aerogels, the supercritical drying (SCD) is the most commonly used method. Under SCD there are two common methods; high temperature supercritical drying (HTSCD) (Kistler, 1932) and low temperature drying incorporating carbon dioxide (LTSCD) also known as the Hunt Process (Tewari, Lofftus, & Hunt, 1985). HTSCD is not relevant as a method for drying aerogels for building applications but is mentioned for completeness.

The first step for HTSCD is placing the aged gel into in an autoclave which is filled with a solvent. The device is closed and heated slowly to reach past the solvent's critical temperature and pressure (Lide, 1996). For the second step, the resulting fluid is isothermally depressurized at ambient pressure to reach room temperature. For silica aerogels, methanol is commonly used as the solvent liquid for HTSCD (Lide,

1996) which makes the aerogel partially hydrophobic and generally produces higher quality silica aerogels.

For LTSCD the aged gel is placed in the autoclave and is filled with the saver (non-flammable liquid carbon dioxide). Once the solvent in the pores is replaced, the autoclave is heated to 313K. Next the fluid is isothermally depressurized until it reaches ambient pressure at which point the autoclave is cooled to room temperature. Aerogel dried using this method experiences shrinkage due to the replacement of the original solvent with CO_2. HTSCD was found to be the best method to minimize the shrinkage of the gel during the drying process (Baetens, Jelle, & Gustavsen, 2011). It should be noted that the chemical durability of aerogel decreases when liquid CO_2 is used as a solvent in LTSCD (Brinker & Scherer, 1990).

2.3.3.2 Ambient Pressure Drying (APD)

Drying the gel in ambient pressure is of high interest due to the possibility of simplifying the process thus reducing the cost and making aerogel more commercially viable. Ambient Pressure Drying (APD) is carried out in two steps. The first step is silylation of all the OH groups takes place in order to prevent the absorption of water which results from the formation of the hydrophobic aerogel. This is done by replacing the present solvent with a water-free solvent along with a silylating agent which allows the H from the OH group to be replaced with an alkyl (Kricheldorf, 1996).

For the second stage, the drying is carried out by ambient pressure evaporation (Brinker & Scherer, 1990) and consists of three parts. At first there is an initial warming period followed by the second part which is the first drying cycle. This is characterized by the balance of the volume loss of the gel and that of the evaporated liquid all the while free water continuously moves to the exterior surface via capillary forces. The third part is the second drying cycle (also known as the falling rate period) which is dominated by diffusive vapour transport allowing the liquid to escape slowly to the exterior.

2.3.3.3 Freeze Drying

Using this method allows the frozen (solid) pore liquid to change directly into vapour in vacuum (Mathieu, et al., 1997) (Klvana, Chaouki, Repellin-Lacroix, & Pajonk, 1989) (Pajonk, 1989). One of the drawbacks of this method is the long ageing period that is needed in order to stabilize the gel network. In addition to that, the solvent must be replaced with a different one that has a lower expansion coefficient and high sublimation pressure.

2.4 Material Properties

The reason why silica aerogels have high potential is due to their unusual solid material properties. The almost skeletal in nature cross-linked internal structure of silicon dioxide chains has a large number of air filled cavities. The pores in aerogel are very small and range from 10-100 nm (Zeng, Hunt, Greif, & Cao, 1994) for pure aerogel and 5-70 nm for silica aerogels depending on the purity and fabrication method (van Bommel, van Miltenburg, & den Engelsen, 1997). These pores can take up anywhere from 85 to 99.8% of the total aerogel volume (Baetens, Jelle, & Gustavsen, 2011).

The high porosity is a direct result from the extraordinary pore sizes which allows the aerogel to achieve its outstanding physical, thermal, acoustic and optical properties in combination with a very low mechanical strength. Aerogels are some of the lightest solid materials known at this time with a bulk density of 3 kg/m^3 while the skeleton's density is 2200 kg/m^3 (density of air is 1.2 kg/m^3) (Hunt, Cao, & Jantzen, 1991). Aerogels for building applications have a bulk density around 70-150 kg/m^3 (Baetens, Jelle, & Gustavsen, 2011). Apparent or bulk density is the mass of many particles of the given material divided by the total volume they occupy. This volume includes the internal pore volume, inter-particle void volume and the particle volume itself.

Silica aerogels also exhibit high compression strength (up to 300 kPa), but have very low tensile strength which makes it brittle. The aerogel has to undergo a process in order to be made hydrophobic as to prevent collapse of structure when in contact with water due to surface tension in the pores (Jensen, Schultz, & Kristiansen, 2004). A very effective combination is the combination of aerogel in a vacuum which reduces the thermal conductivity even further and also limited the ingress of moisture. The weak tensile strength can be alleviated by incorporating fiber matrix until a better solution is found.

2.4.1 Thermal Properties

Aerogels have very low thermal conductivity (Kistler & Caldwell, 1932) which results from low conductivity through the silica skeleton, low gaseous conductivity through the pores and low radiative infrared transmission (Ramakrishnan, et al., 2007). Finding the total thermal conductivity using the summation of the individual ones is not appropriate since they are heavily interconnected, e.g. changes in the infrared absorbance will also change the solid skeleton conductivity.

Thermal conductivity of the solid silica is quite high but it only accounts for small portion in aerogels. In addition, the skeletal structure has many dead ends which results in a tortuous path for thermal transport. The low gaseous thermal conductivity of aerogels can be explained by the Knudsen effect where the gaseous conduction is expressed as function of the air pressure and the pore size (Kennard, 1938). Aerogels have low pore size and high porosity and as a result, the gaseous thermal conductivity will have a large influence on the overall conductivity.

At ambient conditions, the Knudsen effect is responsible for the low thermal conductivity. The gaseous thermal conductivity can be further reduced by filling the aerogel with a noble gas (has lower conductivity and commonly used in IGU construction), keeping the aerogel in a vacuum or reducing the maximum pore size. Applying a pressure of 5 kPa or less without any other alteration can yield an overall thermal conductivity as low as 0.008 W/mK (Hunt, Cao, & Jantzen, 1991) (Smith, Maskara, & Boes, 1998) (Wong, Perera, & Eames, 2007).

Silica aerogels are reasonably transparent in the infrared spectrum (Baetens R. , Jelle, Gustavsen, & Grynning, 2010). Heat gain via radiation would become a dominant factor in high temperatures (i.e. 200°C) but is not a cause for concern at low temperatures. The effects of radiative transfer can be reduced by adding an additional component such as carbon black (can be done before or after the drying) which can either absorb or scatter infrared radiation. Using this method the thermal conductivity can reach 0.0135 W/mK at ambient pressure or 0.004 W/mK at 5 kPa (Baetens, Jelle, & Gustavsen, 2011). State-of-the-art commercially available aerogel insulation for building application has a thermal conductivity in the range of 0.0131-0.0136 W/mK at ambient temperature with very little increase until 200°C.

2.4.1.1 Aerogel Variations

There are other types/variations of aerogels that are manufactured from different materials with potentially attractive properties. The feasibility of creating polyisocyanurate (PIR) and polyurethane (PUR) based aerogel was investigated by (Biesmans, Randall, Francais, & Perrut, 1998). These aerogels had a density of 80-400 kg/m^3 and were analyzed as a function of pressure. The produced samples showed that it was possible to produce aerogels with a thermal conductivity of 0.007 W/mK below pressure of 1 kPa and an air filled value of 0.022 W/mK with a density of 150 kg/m^3 (typical bulk density between 70-150 kg/m^3 for building applications).

Another type of aerogel which was based on polyurea had thermal conductivities measured at various conditions, ranging from ambient pressure to 0.13 kPa and from room temperature to -120°C (under pressure of 1.07 kPa) (Lee, Gould, & Rhine, 2009). The polyurea aerogel samples had high porosities, low thermal conductivity values, hydrophobicity, somewhat high thermal decomposition temperature (≈270°C), low degassing and produced less dust than silica aerogels. It is interesting to note that this aerogel excelled in low temperatures with the conductivity decreasing from 0.005 W/mK at 20°C to 0.002 W/mK at -120°C which would be useful for industrial applications but also for cold climates.

2.4.2 Optical Properties

Aerogels are not fully transparent like glass is but they allow light through diffusion which gives them the flexibility to be used in glazing applications. Aerogels have high transmittance of radiation in the visible light spectrum (radiation with wavelength of 380-780nm). Monolithic aerogel has much better light transmittance with solar transmittance of T_{SOL}=0.88 (Reim, et al., 2004). Heat treating of aerogels can yield an increase in their transparency up to 6% (Jensen, Schultz, & Kristiansen, 2004). If the best optical properties are desired, it is possible to select the most optimal synthesis parameters during the sol-gel process (Ramakrishnan, et al., 2007).

The light transmitted through aerogel appears to be slightly red while reflected light has a bluish tint. These observations can be explained by bulk (or Rayleigh) scattering and by exterior surface scattering (Baetens, Jelle, & Gustavsen, 2011). Rayleigh scattering is caused by the interaction of light with inhomogeneities in gases, liquids or solids. A good example of these particles is dust in the atmosphere and they become more effective when their size is closer to that of the wavelength of the incident light. The presence of the pores in aerogels acts as scattering centers and the efficiency of the scattering is depends on the size as well as the wavelength of the radiation since different wavelengths will scatter with different magnitudes.

In addition to transparency in the visible range, aerogels also have high transparency in the infrared spectrum (T_{IR}=0.85) (Baetens, Jelle, & Gustavsen, 2011). At higher temperatures, this transparency increases the overall thermal conductivity of silica aerogels. If transparency is not desired (e.g. aerogel that goes into insulation blankets or plaster), the transmission in the visible range can be reduced by 50% by adding a little isopropanol percent by volume or other similar opacifiers (Reichenauer, Manara, Fricke, & Henkel, 2004).

2.4.3 Fire and Safety Properties

Silica aerogels consist of SiO_2 with a $-CH_3$ treated surface giving it hydrophobic nature. These materials are generally non-flammable and non-reactive. Silica aerogels have a very high melting point of 1200°C. Commercial products that contain silica aerogels share the same properties. In some instances, aerogel insulation is used as fire retarding material and if PET fibers were used as reinforcement then they would be replaced.

2.4.4 Health Implications

Aerogel insulation sheets produce dust. Most of the commercially available aerogel insulation products consist of complete amorphous (0% crystalline) silica. Exposure limits sets by the US OSHA are in the range of 5 mg/m^3 for respirable dust. Synthetic amorphous silica is not classified a cancerogen (group 3) to humans by the Agency for Research on Cancer (IARC). Studies on various animals have found that amorphous silica can be completely removed from the lungs (Brüning, et al., 2002) (Warheit, 2001). In addition to that, epidemiological studies of works with long term exposures to synthetic silica found no evidence of silicosis.

Some pollutants are released into the indoor environment which include chloride from tap water, NO_x and SO_x from incomplete burning of gas, formalin from furniture and paints and VOCs from organic solvents. Some allergies and respiratory problems such as asthma, intensify with airborne contaminants. The conversion of these contaminants into non-toxic compounds is an effective method for their removal (Riffat & Qiu, 2013). Some aerogel products such as Pristina have been utilized for the removal of indoor air contaminants and for outdoor environment clean up (Pristina™ Aerogel Materials, n.d.).

2.5 Building Applications of Aerogel

Although aerogel is still expensive, research and development continues to find cheaper variations that maintain the performance but make it more economically attractive to use in the construction industry. Aerogel can be broken down into two main categories; transparent monolithic aerogel and granular aerogel based insulation (translucent or opaque). Aerogel can be used in buildings in the form of insulation blankets as well as filling of the cavity in glazing assemblies. The usage of aerogel in glazing is primarily used for daylighting (e.g. skylights) control. Simple payback calculations indicate that the payback period for aerogel ranged from 5-8 years for a discount rate of 10% (Wong, Perera, & Eames, 2007).

2.5.1 Translucent Insulation Applications

Glazing can be considered as the most important part of most fenestrations partially due to the fact that it generally has the biggest area of the constituent parts but it also serves contradicting functions. Windows are responsible for up to 60% of the total energy loss in a building especially in highly glazed ones (Buratti, Moretti, & Zinzi, 2017) (Gustavsen, Jelle, Arasteh, & Kohler, 2007). When calculating U-value for windows, it is important to mention which method was used since there could be up to a 3% difference between the North American (ASHRAE) and European (ISO) methods (Blanusa, et al., 2007).

The application of aerogels in glazing offers a potential to revolutionize windows allowing great thermal performance combined with high light transmittance (Wong, Perera, & Eames, 2007). There has been a substantial amount of conducted and ongoing research regarding the application of monolithic and granular aerogel in high performance glazing. An important note to make is that when aerogel is exposed to direct sunlight, scattering becomes very visible which could limit the application of aerogel glazing to skylights or north facing windows. Aerogel based glazing systems have started to appear at the marketplace around 2005 (Schultz & Jensen, 2008) (Rigacci, et al., 2004).

Granular based aerogel window was developed by *ZAE Bayern* (Germany) (Reim, et al., 2002) (Reim, et al., 2004) (Reim, et al., 2005) (Wong, Perera, & Eames, 2007). Two types of granular were used in the prototype windows; semitransparent spheres with solar transmittance of T_{SOL}=0.53 (for 10mm thickness) and highly translucent granulates with T_{SOL}=0.88. The granules were packed in a 16mm wide polymethylmethacrylate (PMMA) double skin sheet between two air gaps (12 or 16mm), filled with krypton or argon with glass on each side essentially created a triple glazed type configuration.

Several granular based aerogel prototype windows were created by (Buratti, Moretti, & Zinzi, 2017) with two types of granular sizes to test thermal and optical performance and incorporate into building energy simulations. The thermal transmittance was found to be between 1.0-1.1 W/m^{2}K with 15mm cavity size which is a 63% reduction in the U-value when compared to conventional windows along with a 30% reduction in light transmittance. When low-e glass was used the U-value reduction was lower (31%) and a more moderate reduction in light transmittance (10%) was observed with the larger granules. These types of windows could be considered for new builds as well as retrofits but with marginal annual heating energy savings (4%) and similar performance for cooling loads.

The HILIT$^+$ project of the European Union developed a monolithic based aerogel window. The prototype window used the aerogel with a high performance spacer and vacuum (0.1-1 kPa) to achieve an overall heat loss coefficient U_{window}=0.66 W/m^{2}K and T_{SOL}=0.85+ for 13.5mm thickness. The noise reduction was measured at 33dB (Jensen & Schultz, 2007). Increasing the thickness of the aerogel from 13.5 to 20mm would increase the U-value to 0.5 W/m^{2}K with the solar transmittance staying about 0.75 (Schultz & Jensen, 2008). Replacing the triple glazed, argon filled windows with the prototype 13.5 and 20mm windows, in a house built according to the Danish standard or the Passive House Standard in the Danish climate found energy savings of 19% and 34% respectively. By changing the triple glazed, argon filled windows with aerogel glazing in a typical new built, detached single family house in climatic conditions of Denmark, energy savings of 1180 kWh/year (19%) were observed (Schultz & Jensen, 2008).

Ambient drying process was developed in order to synthesize window glazing coated with silica aerogel film (Kim & Hyun, 2003). The aerogel films were synthesized at the temperature 270°C and atmospheric pressure. The transmittance of the glazing was over 90% which is 12% higher than that of an uncoated glass slide. The thicker the layer of aerogel, the smaller the thermal conductivity became. Several combination of aerogel and glass were used and all samples showed high solar and light transmittance. As expected, due to the aerogel, the light was scattered which resulted in reduced optical quality.

At the University of Perugia, Buratti and Moretti have done some research pertaining to aerogel glazing systems (Buratti & Moretti, 2012a) (Buratti & Moretti, 2012b) (Buratti & Moretti, 2011). The emphasis of their work was focused on investigating the optical and thermal properties of aerogel based glazing systems to determine their viability in building applications to produce energy savings. Both monolithic and granular system were analyzed with the monolithic coming out on top with better light transmittance of $\tau=0.62$ (granular was $\tau=0.27$) and a low U-value=0.60 W/m^{2}K (in evacuated double glazing). The granular systems had a 60% light reduction compared to the base double glazing with low-e coating and a U-value=1 W/m^{2}K for the same thickness (Buratti & Moretti, 2012b). The monolithic aerogel glazing system allowed to obtain a thin system with U-values below 0.50 W/m^{2}K (Duer & Svendsen, 1998) without diminishing the solar factor or considerably reducing daylight transmittance.

The best thermal characteristic for aerogel configuration across multiple climate zones was found to be the following assembly: 4mm outer clear glass, 15mm aerogel layer, 4mm inner clear glass (Wang, Wu, Ding, Feng, & Wang, 2015). The study looked at five different climate zones in China (Harbin, Beijing, Shanghai, Guangzhou and Kunming). The heat transfer coefficient for assembly #5 (mentioned above) was 0.72 W/m^{2}K and a shading coefficient of 0.59.

2.5.2 Opaque Insulation Applications

An example of aerogel based insulation blanket was developed by *Aspen Aerogels, Inc.* (Northborough, MA USA) called spaceloft®. It is a flexible aerogel imbedded blanket available in 10mm thickness and has a thermal conductivity of 0.013 W/mK at 0°C which is 2-2.5 times lower than traditional insulation materials. The preparation process is quite interesting where the aerogel composite is prepared by adding fibers or fibrous matrix to a pre-gel mixture which contains the gel precursors, after which the gel is dried. Application for this type of product can be as continuous insulation for stud frame construction and might be especially desirable for historic building that are being renovated since the material is very thin and would save space (Kosny, Petrie, Yarbrough, & Childs, 2007).

This specific product is no longer in production but curiously can be bought online from various online sellers (e.g. ebay) roughly between \$255.55-322.8/m^2 (\$23-30/sf) as of late December 2016. The cost of a conventional material for the same thermal resistance is about 10 times less. It is important to note that the blankets are made from amorphous silica as opposed to crystalline silica reducing possible health due to exposure.

Another material developed for pipe insulation called Nanogel® Compression Pack™ by *Cabot Aerogel* (Massachusettes, USA) with thermal conductivity of 0.014 W/mK. The product gets "activated" at which point it will expand to fill all the gaps. This product is aimed at deep water pipe-in pipe tieback installations. Cabot Aerogel also offers bulk particles (P100/P200/P300) that can be mixed to create boards, blankets and plasters.

2.5.3 Comparison to other High Performance Materials and Systems

The direct competitor to aerogel windows are the triple (multilayer) glazed high performance windows currently available on the market. The triple glazed windows are heavier, and require bigger and more robust frames to support the thicker glazing assembly. A variation of the triple glazed windows which has similar performance incorporates Suspended Coated Films (SCF) which replace the intermediate glass panes with films. The usage of films allows for thinner frames with comparable U-value which reduces the need for stronger frames as well as opening the door for retrofit projects. One of the drawbacks of the suspended film glazing is a significant reduction in the Visible Transmittance (VT or T_{vis}).

In gas filled IGUs, the increased thermal performance which is achieved through the use of coating and films is tradeoff to the visible transmittance. There is no magic glazing which is able to provide both high T_{vis}, low U-value and low solar heat gain. This idea is also carries through to granular aerogel glazing where bigger granular size let in more light while smaller granular has better thermal performance. The allure of the monolithic aerogel glazing is that it could have both great thermal and optical properties and do it in a light and slim format. Table 1 shows the U-value for selected high performance triple glazed and suspended film glazing products as well as prototype aerogel windows.

Manufacturer	**Product**	**Glazing U-Value (W/m^2K)**	**Visible Transmittance T_{vis}**	**Configuration**
Aerogel				
Cabot Corporation	Nanogel® (granular) Aerogel	1.38	0.80	Double glazed, 10mm cavity.
		0.78	0.62	Double glazed, 20mm cavity.
		0.42	0.39	Double glazed, 40mm cavity.
		0.25	0.19	Double glazed, 70mm cavity.
Okalux	Okagel	0.6	≤0.59	Double glazed, 4/30/6 mm.
		0.3	≤0.45	Double glazed, 4/60/6 mm.
Advanced Glazing Ltd.	Solera+Nanogel	0.31	0.07-0.32	Double glazed, 76.2mm cavity.
Multilayer				
AGC Glass UK	Top N^+	0.50	0.70	Glazing configuration 4/12/4/12/4 mm with Krypton fill.
GUARDIAN Flachglas GmbH	ClimaGuard N^3	0.49	0.72	
	ClimaGuard N	0.50	0.71	
INTERPANE Glas Industrie AG	iplus 3CE	0.49	0.71	
	iplus 3CL	0.53	0.72	

All Weather Windows	Tri	0.31	0.74	Clear glass and argon fill.
All Weather Windows	HS2-C180	0.18	0.73	Low-E with argon fill.
All Weather Windows	HS3-C180	0.13	0.7	Two low-E with argon fill.
Suspended film				
Serious Materials	1125 Picture Window (SeriousGlass™ 20)	0.28	0.23	Dual pane, 3 low SHG films, Xenon fill.
Visionwall Solutions Inc.	Series 204: 4 element glazing system	0.62	0.50	Dual pane, 2 films with air fill; 6/26/*/20/*/26/6 mm.
Vacuum				
Pilkington/NSG	Spacia-21	0.70	0.53	Glazing configuration 3/*/12/3/0.2/3 mm with Krypton fill.
	Spacia	1.1	0.78	Dual pane with 0.5mm vacuum/grid.
Double Glazed				
All Weather Windows	Dual	0.48	0.81	Clear glass and argon fill.
All Weather Windows	HS1-C180	0.26	0.79	Low-E with argon fill.

Table 1 - U-value and Tvis comparison between various high performance glazing systems and aerogel glazing systems (Jelle, et al., 2012)

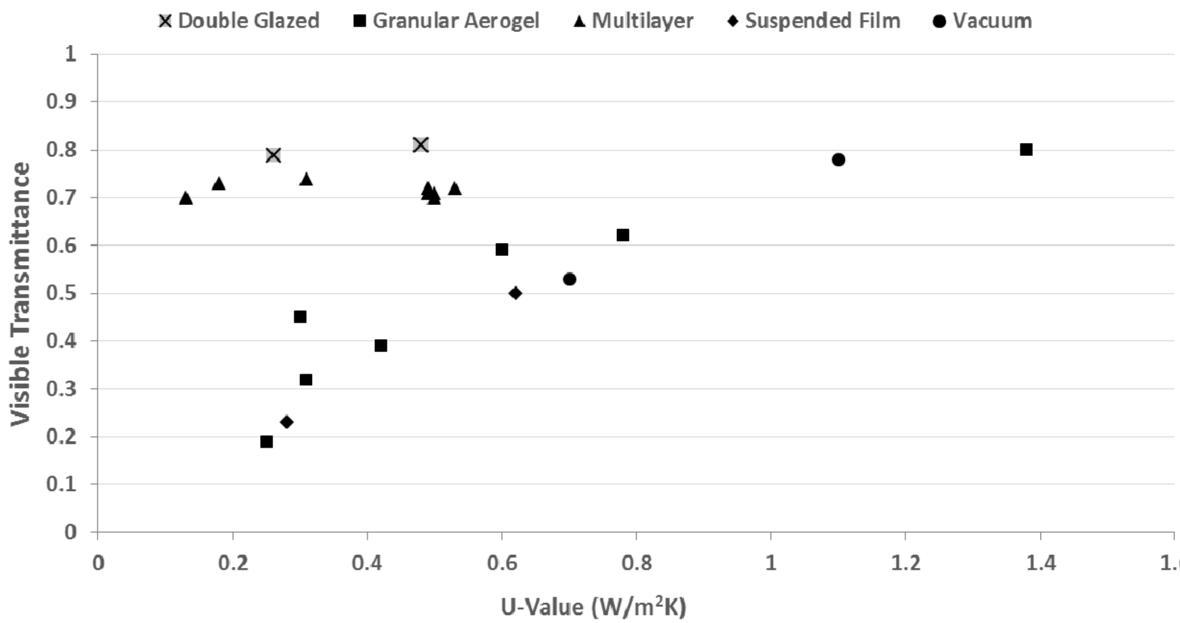


Figure 1 - U-value and Tvis comparison from table 1

Vacuum Insulated Glass (VIG) also known as evacuated glazing is another high performance glazing system which was first conceived in 1913 by Zoller, but was not produced until 1989 (Eames, 2008). This type of glazing consists of two lites of glass separated by an array of support pillars with vacuum in the cavity. One of benefits of the vacuum glazing is the thinness, especially when compared to multilayer glazing.

There are three different categories of smart windows defined by method of color change; liquid crystals, suspended particle devices and (photo-,thermo-, and electro-) chromic windows. They offer high performance solutions through the ability to dynamically control Solar Factor (SF) and transmittance properties depending on exterior conditions and/or interior requirements. Electrochromic windows (ECWs) are the most reliable and promising among the three technologies (Baetens, Jelle, & Gustavsen, 2010). The main advantage of the smart windows is the dynamic solar/transmittance properties by the use of an external voltage control. There is an electrochromic foil that can be applied to existing windows allowing for retrofit applications (ChromoGenics, n.d.). This technology can be combined with suspended film glazing where the interior film is replaced with an electrochromic one for even higher energy savings.

2.6 Accelerated Ageing

Building products and systems have to fulfil many functions during their service life in a building by possessing satisfactory durability with respect to various properties. Unfortunately, it is often that products and systems are unable to satisfy the specified requirements after a relatively short period of time. This results in increased maintenance, health and safety risks, extensive replacement and any other possible consequential building damages throughout the building's lifecycle. Different products have different resistances versus various climate exposure factors. Therefore, it is important to select building products and systems that have a proven and satisfactory long-term durability. This is done with proper documentation by carrying out long-term natural outdoor climate exposure or by using appropriate accelerated ageing in a laboratory.

Natural outdoor climate ageing takes a long period of time which makes it impractical for the majority of building products. The answer to this issue is the use of accelerated ageing which is both faster and more economical. It uses various climatic strains and acceleration factors to test the performance of a given product at various targets. Although the climatic exposure factors can be broken down into categories and tested separately, the total strain from a combination of factors could be substantially larger than the added sum of the single exposure factors (Jelle, Accelerated climate ageing of building materials, components and sturctures in the laboratory, 2012). The most severe strain depends on the product itself as opposed to the climate exposure conditions.

2.6.1 Accelerated ageing of IGUs

Durability of insulated glazing units (IGUs) is critical for building energy performance. Windows are responsible for 30-50% of the thermal transmission losses through the building envelope which makes knowledge about durability important as it directly pertains to energy performance throughout the entire service life of a building (Asphaug, Jelle, Gullbrekken, & Uvsløkk, 2016). There is a range of standards and research that has been carried out that specifically deals with accelerated ageing through the form of durability certification for IGUs.

Glazing units are exposed to a diverse set of environmental factors such as wind and working loads, solar radiation, temperature and atmospheric pressure fluctuations, water and water vapour. The vast majority of contemporary double glazed units have a double seal which is fairly gastight and performers better when compared to single seal. The amount of gas fill can vary in new units but it is usually around 90% in most cases (Olsson-Jonsson, 2005).

For conventional glazing, the durability primarily comes from its ability to prevent gas escape which is almost exclusively determined by the low water vapour permeability of the primary seal (e.g. polyisobutene (PIB)). The second seal's water vapour permeability is minor in comparison, but its tensile and elastic recovery properties are what allows the primary seal to function well (Wolf, 1992) (Wolf & Waters, 1993). Seal failure is the primary cause for loss of gas fill (e.g. argon, krypton or xenon) which reduces the thermal resistance of the glazing unit.

2.6.2 Accelerated ageing of aerogel

Although aerogel is nonflammable and could be considered stable in terms of ageing, water surface tension could damage the nanoporous silica structure, reducing thermal performance (Jensen, Schultz, & Kristiansen, 2004). Although the surface of aerogel is hydrophobic, the degradation could occur if repeated moisture attacks cause breakage. This could be especially prevalent in aerogel glazing where the aerogel is sandwiched between two panes of glass with primary and secondary seals that are designed to prevent moisture migration through the assembly. With time, due to the factors such as UV radiation, pane movement and deterioration in seal adhesion, the cavity could experience humidification and dehumidification cycling. Aerogel's hydrophobic surface (consists mostly of methyl groups) can decompose under exposure to solar irradiation (primarily from short-wavelength 290-370 nm) over time (Ihara, Jelle, Gao, & Gustavsen, 2015).

2.6.3 Degradation Mechanisms and Configuration

The most common degradation mechanisms that are used for IGU accelerated ageing are temperature, humidity and radiation. There are a few standards available that deal with accelerated ageing for building products. One of the European standards used by Asphaug, et al, (Asphaug, Jelle, Gullbrekken, & Uvsløkk, 2016) to test the durability of glazing spacers for airtightness and their impact on energy performance is the Nordtest Method (NT) Build 495. NT Build 495 provides the guidelines for accelerated ageing in a vertical simulator for up to 490 days (490 x 24hr) which is sufficient for the vast majority of accelerated ageing for glazing units.

Within the vertical climate simulator the samples are subjected to four different climatic conditions; Ultraviolet (UV) and infrared (IR) irradiation (black panel temperature of 63°C), water spray (0.015 $m^3/(m^2\ hr)$), freezing (-20°C) and ambient laboratory conditions. The UVA and UVB intensities were averaged to 30 W/m^2 and 3.4 W/m^2. The duration time for each climatic condition is 1 hour. This type of configuration allows to create a cumulative strain on the samples due to combination of ageing factors which would be closest to real life strain.

2.6.3.1 Elevated temperatures

Using high temperature for accelerated ageing is quite common especially for polymers (e.g. sealants and gaskets) which have an accepted safe range of about 60-70°C. The selected temperature should be high as possible to accelerate the temperature degradation as much as possible based on the Arrhenius Equation (provides the exponential temperature dependence of chemical reaction rates) while staying within the safe range. At the same time, the selected temperature should not be as high where it would induce degradation which would not occur during natural ageing. Having higher temperature in combination is an effective way to increase the rate of reaction and reduce ageing time.

2.6.3.2 Temperature cycling

Temperature cycling can cause large degradation due to the freezing-thawing cycle (especially in materials containing water) which would be subject to volume expansion at the macro- and micro-scale. This type of testing is crucial for products that are designed to be installed in colder climates where there freezing-thawing cycles can be frequent as well as large temperature differences between interior and exterior. The temperature range used for freeze-thawing cycles by Asphaug, et al, (Asphaug, Jelle, Gullbrekken, & Uvsløkk, 2016) ranged between -20°C and ambient laboratory conditions. North

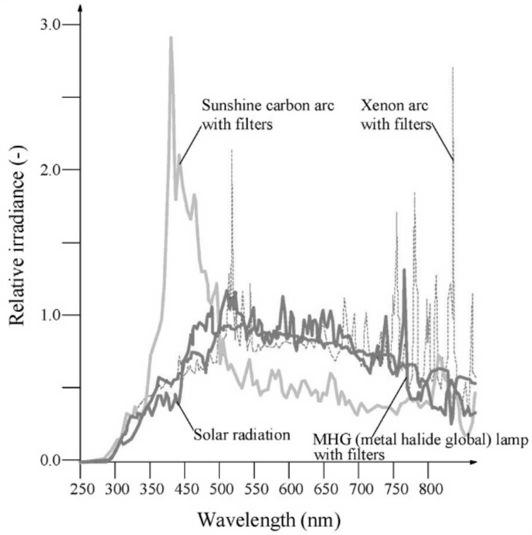
American standards such as ASTM E773 and E774 which are used to test and certify conventional IGUs have a range of -20-60°C as part of their cumulative strain ageing.

2.6.3.3 Solar radiation

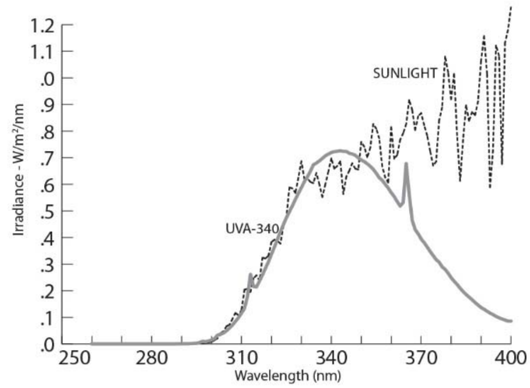
Solar radiation is one of the main degradation mechanisms. The solar radiation at the earth's surface ranges roughly between 280 and 3000nm: ultraviolet (UV) radiation has wavelengths below 400 nm, while visible light (VIS) has a range of 380-780 nm and infrared radiation (NIR) is between 780-3000 nm. The UV radiation range can be further broken down to UVA (315-400 nm), UVB (280-315 nm) and UVC (100-280 nm). Almost half of the energy can be found in the NIR range (Jelle, 2012).

Various building products (especially organic materials) may deteriorate as chemical bonds are broken as a result from collision with higher energy particles (i.e. UV and shortwave VIS). Damage can range from discoloration or loss of mechanical strength. The exact atomic composition and impurities determine the energy needed to break chemical bonds. Generally with building materials it is best to have durable and long-lasting products. One crucial aspect of accelerated ageing in a laboratory is to minimize changes or chemical reactions which would not occur under natural outdoor ageing process.

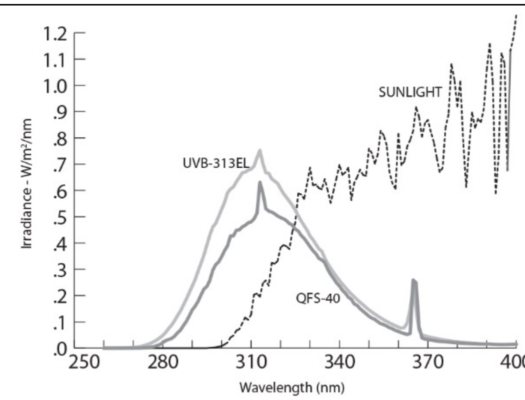
The choice of the light source is important since various lamps have energy peaks shifted to lower or higher wavelengths. The Metal Halide (MH) lamps simulate the most accurate solar spectrum at the earth's surface with Metal Halide Global (MHG) version being the best. Different types of lamps are better suited for different types of ageing such as using xenon or MHG lamps for accelerated ageing of photovoltaic solar cells while UV lamps are not used for this purpose.



Radiation spectra of several ageing lamps (Ihara, Jelle, Gao, & Gustavsen, 2015)



Radiation spectrum of UVA-340 lamp (QUV ACCELERATED WEATHERING TESTER, n.d.)



Radiation spectra of UVA-340 and QFS-40 lamps (QUV ACCELERATED WEATHERING TESTER, n.d.)

Figure 2 – Radiation spectra comparison between sunlight and ageing various lamps

The vertical climatic chamber used by Asphaug, (Asphaug, Jelle, Gullbrekken, & Uvsløkk, 2016) for IGU ageing incorporated ultraviolet (UV) tubes and infrared (IR) irradiation (black panel temperature of 63°C). The UVA and UVB intensities were averaged to 30 W/m^2 and 3.4 W/m^2 respectively for the bulb configuration used in the vertical climate simulator. Canvas samples were aged in the Atlas SC600 MHG Solar Simulator which uses 2500W MHG lamps at an intensity of 1200 W/m^2 but with physical metal grid to reduce it by 50% for an effective irradiance of 600 W/m^2 (Jelle, 2012).

The lamps specified by ASTM E773-88 Seal Durability of Sealed Insulating Glass Units, section 6.2.2.2, specify the use of F72T12BL/HO[4] (85W) lamps with an intensity not less than 10 W/m^2. A long wave ultraviolet meter was used in direct contact with the lamp to measure irradiance. For the fogging test outlined in this standard, it specified a 275W Type RS sunlamp with an intensity of 20 W/m^2, tested every 200 hours (UVA). IEA SHC Task 27 (Elmahdy, 2002) referenced ASTM E773-88 and also specified the use of F72T12BL/HO lamps but no specific irradiance. For the fogging test in the same report, it is specified to use a UVA lamp with an output of 4 W/m^2.

ASTM D7897-15 Laboratory Soiling and Weathering of Roofing Materials to Simulate Effects of Natural Exposure on Solar Reflectance and Thermal Emittance (ASTM D7897-15) mentioned the use of UVA-340 lamps in section 6.3 (if an accelerating apparatus or a climatic chamber is used). ASTM G154-16 outlines multiple configurations of exposure conditions that provide combinations of lamp type, irradiance and cycling. Typical irradiance levels range from 0.49 to 1.55 W/m^2*nm with the UV portion of the cycle lasting between 4 and 8 hours.

Aerogel granule ageing driven by moisture and solar radiation (Ihara, Jelle, Gao, & Gustavsen, 2015) used Atlas SC 600 MHG (metal halide global lamps) with an irradiance of 1200 W/m^2 in wavelength of 200-3000 nm. The solar ageing cycle consisted of two step, 5 hours of radiation at 60°C and 50% relative humidity followed by an hour long water spray at 10°C.

	Typical Irradiance	**Comments**
Nordtest Method (NT) Build 495	UVA 30 W/m^2 and UVB 3.4 W/m^2	
Jelle, 2012	600 W/m^2	2500W MHG at 1200 W/m^2 with physical metal grid reduction of 50%
ASTM E773-88 Seal Durability of Sealed Insulating Glass Units	>10 W/m^2	F72T12BL/HO[4] (85W) lamp
	20 W/m^2	275W Type RS sunlamp
Elmahdy, 2002	4 W/m^2	IGU fogging test
ASTM G154-16 Operating Fluorescent Ultraviolet (UV) Lamp Apparatus for Exposure of Nonmetallic Materials	UVA 527 W/m^2 (@ 340nm)	UVA-340 lamp for 8 hours
	UVA 303 W/m^2 (@ 340nm)	UVA-340 lamp for 8 hours
	UVB 220 W/m^2 (@ 310nm)	UVB-313 lamp for 4 hours
	UVB 152 W/m^2 (@ 310nm)	UVB-313 lamp for 8 hours
Ihara, Jelle, Gao, & Gustavsen, 2015	1200 W/m^2 (200-3000 nm)	Atlas SC 600 MHG

Table 2 - UV radiation exposure conditions

2.6.3.4 High humidity

The fourth method that can be used to age various samples is high relative humidity with or without mist/water (liquid) spray. To evaluate the moisture ageing resistance, Ihara et al, (Ihara, Jelle, Gao, & Gustavsen, 2015) used a thermal chamber (Atlas SC 600 MHG Solar Simulator) to exposure the aerogel to moisture fluctuations. The aerogel was placed in glass trays with spacers to provide equal exposure to each of the trays without lamp radiation. A container held 50 cm^3 of water at bottom of the chamber which was hermetically sealed. The temperature was kept mostly at 65°C except during the warm up and cool off period (slightly over an hour combined) which was 35°C. The aerogel granules were exposed to a constant saturated relative humidity for roughly 300 cycles (3 months). When aerogel granules are exposed to humidity cycling, the granules experience repeated stress due to the surface tension of the water. The accumulated fatigue damage which is defined by Miner's Law can be the main ageing factor.

The climatic chamber used by Asphaug, et al, (Asphaug, Jelle, Gullbrekken, & Uvsløkk, 2016) had a water spray installed which provided 0.015 $m^3/(m^2\ hr)$. It generally recommended to use deionized water to reduce the chance of other contaminants reacting with the material tested. The humidity chamber used for seal edge durability by (Elmahdy, 2002) cycles between 60±3°C and 95±5°C.

2.6.3.5 Cycling and samples

The number of samples needed can vary depending on what is being testing and to what level of accuracy it needs to comply. In the case of Asphaug, et al, (Asphaug, Jelle, Gullbrekken, & Uvsløkk, 2016), 18 samples were divided into three groups with six samples in each group with a different set of ageing mechanisms employed. The first group was placed in the vertical climate simulator for the entire duration, the samples are exposed to each climatic condition for one hour every cycle. The second group was placed also in the vertical climate simulator but only for the first two weeks after which it was moved to a heating chamber. The third group was placed directly into the heating chamber for the entire duration. All IGUs were vertically placed in both the climatic chamber and the heating chamber.

For seal durability testing (Elmahdy, 2002), the testing lasted for 3 months (105 days). Six units are selected and placed in the high humidity chamber for 14 days. The same six units were then placed in the weather cycle chamber for 63 days. The units were mounted with one side exposed to ambient laboratory conditions while the other side is exposed to weather cycles to simulate real life configurations. Each cycle lasted for 6 hours. For the first hour the temperature is decreased to -29±3°C and then it is maintained at that temperature for another 1 hour. In the following 1 hour the heat is turned on allowing the temperature to reach room temperature. Next, the UV lamps are turned on for 1 hour to reach a temperature of 60±3°C. At the beginning of the same time period the water mist is turned on to reach a minimum of 90% RH and turned off at the end of the hour. In the fifth cycle our, both the temperature and UV exposure is maintained. During the last hour of the cycle, the temperature is gradually reduced to room temperature while the UV is on and is only shut off at the end of the cycle.

3 METHODOLOGY

To get a better understanding of the durability for granular aerogel glazing a series of accelerated ageing tests were conducted to simulate equivalent real life strain in a short period of time. Glazing serve multiple roles in building facades by providing view, daylight, thermal resistance and protection from the elements. As such, IGUs are exposed to outdoor conditions that range from extreme cold to high temperatures in combination with fluctuating indoor temperatures as well. The selected apparatuses represent the most common, severe real life stresses on the IGUs.

The oven was used to simulate sustained high temperature while the temperature cycling machine fluctuated from high temperature to very low to create freeze thawing cycles. The humidity chamber created a warm and moist environment to generate high vapor drive. While most of these apparatuses created more isolated ageing conditions, the climatic chamber was used to create a full array of conditions including high relative humidity, UV radiation, high temperature and condensation to simulate the effects of cumulative strain.

The IGU components which were selected had several criteria to meet. The component had to compliment the expected real life performance, meaning that a super spacer with low U-value was selected since aerogel glazing is usually picked for its high performance. Clear, low iron glass was chosen to provide the best optical performance. The ability to assemble the IGU without professional equipment was again facilitated by the easy cutting super spacer as well as the sealant which came in a tube and was used with caulking gun. Two types of granular aerogels were used as the cavity fill to check the extent of accelerated ageing on granular size in relation to performance.

The focus of this research was on the thermal and optical performance of the granular aerogel IGUs. As such, two testing apparatuses were used for testing, the heat flow meter (HFM) and spectrophotometer. The spectrophotometer supports up to 12x12cm unit sizes but using this size inside of the HFM would mean that the center of glass value would be skewed due to the proximity of the sensor (diameter is 10cm) to the edge. Based on this information, two sizes were created to provide more accurate measurements, a smaller size for the spectrophotometer 10x10cm and a larger size for the HFM 30x30cm.

Glazing has contradicting roles which make it a crucial item in a window assembly. Glazing certification and performance tests are similar to accelerated ageing tests designed to evaluate the ability of a design and manufacturing to provide the expected life time durability. Aerogel glazing is relatively new with limited commercial products partially due to its novelty and unfamiliarity. Durability data for aerogel glazing is quite limited since currently the main focus is commercialization via cost reduction and optimization of pristine performance. These aspects are crucial in the widespread adaptation of a new product or system but for long term market share, durability is key.

3.1 Experimental Setup

3.1.1 Glazing Unit Assembly

There are many types of glazing currently on the market. They range from double glazed, triple glazed, quad glazing with films, various low-e coatings and gas fills. In order to isolate the aerogel, other variables in the glazing assembly had to be eliminated or minimized as much as possible. At the most basic level, double glazed unit with low iron clear glass, spacer and double seal would the most suitable. This type of assembly eliminates unnecessary components and complexity allowing the aerogel to be the variable factor (no coatings or gas fills) that impacts the performance the most.

3.1.2 Components Selection

The selected components were chosen to reflect a compatible assembly in terms of expected performance, ease of assembly and to improve performance measurements. Low-iron glass was selected due to its high clarity which gives the ability to evaluate any discoloration of the aerogel if any were to occur after the ageing process as well as maximum light transmission. Two sizes of glass were ordered, 10x10 cm and 30x30cm from CANADA GLASS & MIRROR co. at a thickness of 6mm. A thickness of 3 or 4mm would have been preferable but was not available at the time, and in order to expedite the process the thicker glass was deemed appropriate enough.

An edge spacer separates and provides for a uniform distance to be maintained between two lites of glass. The most common spacer is made from aluminum and is usually filled with desiccant to absorb any moisture that infiltrates inside of the assembly. Aluminum spacers are highly conductive but for the purpose of this testing it would have not been an issue, but they do require special tools to cut them to size as well as additional corner pieces.

Super Spacer® by Edgetech (Quanex) is a flexible, high performance warm edge spacer with a thermal conductivity of 0.159 W/mK (C . R. Laurence of Canada, n.d.). It is made from structural silicone foam, filled with desiccant (47% by weight) with pre-applied side adhesives. It comes in roles of 20.1m (66ft) and can be cut to size with either a hand notcher or any sharp knife (Figure 11). This allows for custom sizes and easy assembly even for layperson without prior knowledge of IGU assembly. The selected size is a gray 13mm (0.5") with a 6.4mm (1/4") thickness. The combination of this spacer and two lites of 6mm glass formed an IGU with 25mm (1") thickness (for both sizes).

This type of spacer has a low U-value (0.2 W/m^2K) which helps maintain the high performance nature of the IGU around the edge where in the past it has suffered from highly conductive aluminum spacers, thus poor performance. Commercially available granular aerogel glazing systems also incorporate the use of high performance spacer making the selection in line with industry standard. Aside from the ease of use and great thermal performance, this spacer is also very durable with good resistance to UV radiation and temperature performance (-40 to 121°C). These two properties indicate that the likelihood of the spacer failing during the accelerated ageing would be low, making the IGUs sturdy and durable for the duration of the ageing and testing. The spacer also features a vapour retarding backing, together with the acrylic adhesive forming the primary seal.

The spacer is designed to be used in conjunction with conventional IGU sealants such as hot melt butyl which is used in glazing assembly facilities. The alternative to these sealants that can be used in smaller quantities of glazing that are not assembled in a factory is silicone foam sealant (C. R. Laurence of

Canada, n.d.), together with the spacer is distributed by C. R. Laurence of Canada. The sealant comes in standard 305 ml tubes that fits into a 10 oz. caulking gun. This sealant is a single component urethane sealant that has a special low-solvent formulation that makes it compatible with Super Spacer® adsorbent and does not require a polyisobutylene primary seal. This sealant has a shelf life of 12 months from the date of manufacturing and should be used roughly within that period to guarantee performance. One sealant tube is good for approximately 2 small (10x10cm) and 2 large units (30x30cm) which is equivalent to linear length of 32cm (12.6").

Figure 3 - Cabot P300 granular aerogel (1.2-4mm particle size)

Figure 4 - Airglass (box 150 SE-24522) granular aerogel

Two types of granular aerogel were used in the assembly of IGUs. The first type of aerogel is manufactured by Cabot Corporation located in Boston, Massachusetts, USA (http://www.cabotcorp.com/solutions/products-plus/aerogel/particles). They specialize in servicing industries such as transportation, infrastructure, environment and consumers with products such as rubber, specialty carbons, cesium formate brines, activated carbon, aerogel, fine cesium chemicals, graphenes and more. The P300 aerogel (Figure 3) is part of a family of similar aerogels with the primary difference being the granular size. The P100 and P200 granules have particles sizes of 0.01-4mm and 0.01-1.2mm respectively. The entire lineup has a pore diameter of 20nm and porosity greater than 90%. The surface area of the granular is in the range of 600-800m^2/g and is hydrophobic in nature. The particle density is between 120-150g/m^3 while bulk density is 65-85kg/m^3 for the P300 line (and 80-100 kg/m^3 for P100 and 75-95 kg/m^3 for P200).

The second type of granular aerogel used is manufactured by Airglass Inc based in Sweden (http://www.designinsite.dk/htmsider/r3300.htm). This is the same company that has manufactured the monolithic aerogel for the European HILIT+ project in the early 2000's. As can be seen from Figure 4, this type of aerogel is akin more to a monolithic slab that was shattered/crushed as opposed to particle type aerogel that Cabot provides. This type of aerogel creates more irregular fills and voids within the IGU cavity which would could vary the thermal and optical properties a little more when compared to Cabot P300.

3.1.3 IGU Assembly

A total of 9 IGUs were assembled in two different sizes, five 10x10cm and four 30x30cm. The glazing units were assembled in groups for efficient use of materials. The first unit to be assembled was a clear 10x10 (unit 1) in order to get familiar with the spacer and application of the sealant. The sealant got quite messy during application process which meant that the following units were masked with tape on the exposed faces in order to prevent the need to use a razor blade to clean it off and risk damaging the surfaces. Tooling the sealant with a concave device is needed, but after creating a mess with no benefit to adhesion or fill consistency caused by unit 1, tooling was not used on the following units. Although tooling is required to ensure proper application of sealant in real life glazing, for the purposes of this research, as long as the aerogel stays sandwiched between the two glass lites, that is sufficient for proper testing.

The next batch of units were unit 2 (Cabot P300 Aerogel 10x10cm), 3 (clear 30x30cm) and 4 (Cabot P300 Aerogel 10x10cm). Unit 2 and 4 were filled horizontally without any compaction so after sealing of the unit, it was noticeable that there was a large air gap (bigger for the 30x30 unit), see Figure 7 and Figure 8. P300 granule ranges in the size of 1.2-4mm in diameter which makes it quite small and must be compacted in order to have properly filled IGU as was also noted in (Gao, Jelle, Ihara, & Gustavsen, 2014). The next set of units (5-9) was done shortly after as single batch.

Unit 5-7 are the smaller 10x10cm size but they are filled with Airglass 150 aerogel as opposed to Cabot P300 (Figure 7). This type of granular aerogel has “chunks” of aerogel of highly varied sizes which creates a slightly less diffused and a little more translucent lighting effect (Figure 9). The remaining units, 8 and 9, were filled with Cabot P300 but this time were compacted in the horizontal position before placing the second glass lite and sealing the IGU (Figure 8). Unit 8 can be considered to have a “perfect” fill while unit 9 has a little too much aerogel. It would have been ideal to have two “perfect” fill units but the overfill in unit 9 is not a major issue since the IGU is still dimensionally stable and the aerogel is contained. The larger units with Cabot P300 aerogel show larger gaps, area percentage, when compared to the small units that are filled with the same aerogel.

Unit Number and Description	**Temperature and Relative Humidity during installation of spacer**	**Temperature and Relative Humidity during secondary sealant installation**	**Comments**
Unit 1 – 10x10cm clear (no aerogel)	18.3°C 40%	19.2°C 42%	• First unit to be assembled. • Some room for trial and error. • 3 bricks (7.948kg total) were used as weights for 30 minutes to compress the two lites for good adhesion. • Cured for more than 48 hours. • Exterior of glass got dirty from the sealant, had to be cleaned after curing.
Unit 2 – 10x10cm with	20.5°C	21.4°C	• 3 bricks (7.948kg total) were used as weights for 30 minutes to

Aerogel (Cabot P300)	36%	49%	compress the two lites for good adhesion. • Protective cover on glass before sealant application. • Cured for more than 48 hours. • Small air gap in aerogel, not enough aerogel was used.
Unit 3 – 30x30cm clear (no aerogel)	20.6°C 36%	21.4°C 49%	• Glass washed with warm water and soap. • Several water bottles (7.5kg total) were used to compress the two lites for good adhesion. • Protective cover on glass before sealant application. • Cured for more than 48 hours.
Unit 4 – 30x30cm with Aerogel (Cabot P300)	21.4°C 46%	21.4°C 49%	• Glass washed with warm water and soap. • Several water bottles (7.5kg total) were used to compress the two lites for good adhesion. • Protective cover on glass before sealant application. • Cured for more than 48 hours. • Medium air gap in aerogel, not enough aerogel was used.
Unit 5 – 10x10 with Aerogel (Airglass Box 150)	22.2°C 40%	22.5°C 41%	• 3 bricks (7.948kg total) were used as weights for 30 minutes to compress the two lites for good adhesion. • Protective cover on glass before sealant application. • Cured for more than 48 hours. • No visible air gap.
Unit 6 – 10x10 with Aerogel (Airglass Box 150)	22.2°C 40%	22.5°C 41%	• 3 bricks (7.948kg total) were used as weights for 30 minutes to compress the two lites for good adhesion. • Protective cover on glass before sealant application. • Cured for more than 48 hours. • No visible air gap.
Unit 7 – 10x10 with Aerogel (Airglass Box 150)	22.2°C 40%	22.5°C 41%	• 3 bricks (7.948kg total) were used as weights for 30 minutes to compress the two lites for good adhesion. • Protective cover on glass before sealant application.

			• Cured for more than 48 hours. • No visible air gap.
Unit 8 – 30x30 with Aerogel (Cabot P300)	22.2°C 40%	22.5°C 41%	• Several water bottles (7.5kg total) were used to compress the two lites for good adhesion. • Protective cover on glass before sealant application. • Cured for more than 48 hours. • “Perfect” aerogel fill.
Unit 9 – 30x30 with Aerogel (Cabot P300)	22.2°C 40%	22.5°C 41%	• Several water bottles (7.5kg total) were used to compress the two lites for good adhesion. • Protective cover on glass before sealant application. • Cured for more than 48 hours. • Small gap in corner between spacer and glass due to slight aerogel overfill.

Table 3 - IGU assembly condition and description

Figure 5 - 10x10cm Cabot P300 aerogel filled IGU Unit 2 (left) and clear IGU (Unit 1, right)

Figure 6 - 30x30cm Cabot P300 aerogel filled IGU Unit 4 (left) and clear IGU (Unit 3, right)

Figure 7 - 10x10cm Airglass 150 aerogel filled IGUs, unit 5, 6, 7 (left to right)

Figure 8 - 30x30cm Cabot P300 aerogel filled IGUs, units 8 (left) and unit 9 (right)

Figure 9 - Comparison of 10x10cm IGUs (left unit 5 with Airglass 150 aerogel, middle unit 2 with Cabot P300 aerogel and unit 1 on the right without aerogel)

The assembly of all the units was done using a makeshift assembly table (Figure 10 and Figure 11). All the units were assembled in ambient room temperature (18-22°C) and relative humidity (36-46%). Once the spacer (and aerogel if it was used) were applied, the second lite was placed and to ensure good adhesion, the IGU was placed under a weight (roughly 8kg) for a minimum period of 30 minutes. After that the units were sealed using the sealant mentioned in section 3.1.2 and left to cure in the same room. The sealant depth for all the IGUs is 4.76mm (3/16") with a height of 12.7mm (1/2") which requires 24hrs to cure at 25°C and 50% RH according to the manufacturer. Since the room conditions did not match to those that the manufacturer used, as well as the daily fluctuation, all the units were left to cure for 48hrs+. The final step was to remove all the masking (painter's masking tape and newspaper) as well as trim the excess sealant for it to be flush with the glass surface.

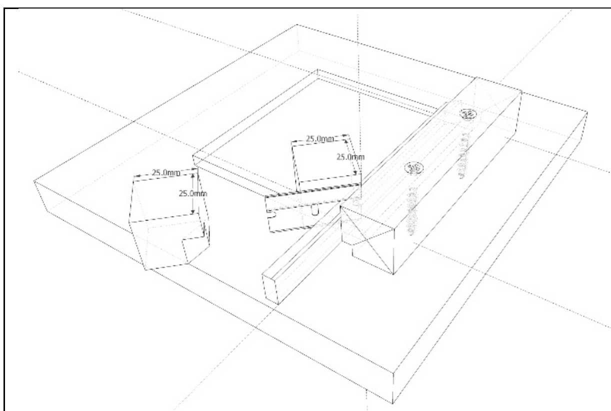


Figure 10 - Diagram sketch of assembly area and notching of the spacer

Figure 11 - Assembly area with glass and notching of the spacer

3.2 Accelerated Ageing

Accelerated ageing is used to test product durability in smaller time frame when compared to natural outdoor testing. This gives the researches or manufacturer the ability to estimate the service life span for a given product and identify the mechanisms that might cause premature failures and either modify the design or application instructions. There are multiple ways to age a product and it predominantly depends on what the end goal is for the given product. During the execution of accelerated ageing it is important to not cause any changes or chemical reactions in materials or products which would not occur during natural outdoor ageing. It is also important to accelerate only the processes which take place during outdoor climate ageing (e.g. too much UVB radiation which would cause chemical reactions that would not occur during regular ageing).

To have an accurate understanding on how various factors may affect the accelerated ageing of aerogel glazing it is ideal to test each condition (strain) separately and then in various combinations. Individual strains can provide a rough understanding to what extent the given specimen is sensitive to. The cumulative strain (i.e. combination of various ageing mechanisms) would be greater than the total sum of the individual strains since some mechanisms are more potent in combination with other factors.

Several types of equipment were used for facilitate the accelerated ageing: the oven, temperature cycling machine, climatic chamber and humidity chambers. Various glazing samples were placed in the equipment for a period of 1 month (≥28 days) at a time after which they were measured using either a spectrophotometer for optical properties or heat flow meter for thermal properties. After each set of measurements, the samples are visually inspected and documented and placed back for the cycle to repeat.

3.2.1 Oven

Elevated temperatures increase the kinetic reaction rates in chemical degradation processes. The mechanical convection oven by Cole-Parmer (RK-52301-30) is microprocessor-controlled which allows for precise control and good uniformity by allowing for easy setup and monitoring functions (Cole-Parmer Microprocessor-Controlled Mechanical Convection Oven, 5.0 cu. ft. 115 VAC, n.d.). Two units were placed in the oven in vertical orientation (with wooden spacers to provide air circulation), unit 3 (30x30cm, no aerogel) and unit 9 (30x30cm, Cabot P300 Aerogel). Vertical orientation is closer to real life application since the majority of glazing units would be installed in that orientation. The set point temperature was set to 70°C which is at the higher end of the normally accepted high-end safe temperature range of 60-70°C for accelerated ageing of polymers (secondary seal). The highest safe temperature was chosen to test the specimens at as high temperature as possible and to accelerate the temperature degradation as much as possible. A relative humidity of 15% was maintained within the chamber during testing.

Unit 3 on the left (clear) and 9 on the right (Cabot P300 aerogel) are placed in vertical orientation in the oven

Figure 12 - Cole-Parmer Microprocessor-Controlled Mechanical Convection Oven RK-52301-30

3.2.2 Temperature Cycling Machine

The next piece of equipment is the temperature cycling machine. This apparatus consists of the freezer which is the main component that houses a few other pieces of equipment that provide it with the ability to have temperature cycling also known as freezing and thawing cycling. The freezer is Salton Upright Freezer CF-2060 (COMPACT FREEZER 3.0 CU. FT. (85 LITRE) , n.d.) which houses the STEGO 100W Fan Heater HVL 031 (Fan Heater Part # 03102.9-00, HVL 031 , n.d.) and Onset HOBO Data Logger (temp/RH) U10-003 (HOBO Temperature Relative Humidity Data Logger, n.d.) at the bottom storage compartment. Temperature cycling is controlled via Intermatic ET1115C 24hr basic electronic control (ET1115C | 24-Hour Basic Electronic Control, n.d.) which is installed on the side of freezer.

The interior volume of the freezer is smaller when compared to the oven thus having less available area for specimen placement. Due to the need to share the machine and the inability to move the shelving, the selected specimen had to be placed horizontally to occupy one of the bays. Unit 8 (30x30cm) which has the “perfect” amount of Cabot P300 aerogel fill was placed horizontally on a wooden tray to prevent contact with the metal shelf. The temperature cycling machine runs on 24 hour cycles as following; 5 hour warm up periods to reach a temperature of 40°C (relative humidity 55% to 40%), the temperature is maintained at 40°C (humidity around 40%) for 7 hours, next it takes 4 hours to cool down to -30°C (relative humidity 25% to 45%) where the temperature is stays constant for 8 hours (relative humidity 45% to 55%) and then the cycle repeats.

	 *Unit 8 (Cabot P300 aerogel) is placed horizontally in the middle shelf*
 *STEGO 100W Fan Heater HVL 031 and Onset HOBO Data Logger (temp/RH) U10-003*	 *Intermatic ET1115C 24hr basic electronic control*

Figure 13 - Salton Upright Freezer CF-2060

3.2.3 Climatic Chamber

UV radiation is responsible for the majority of the photodegradation for materials that are exposed to outdoor conditions. The QAV/se's fluorescent lamps are able to simulate the critical short-wave UV radiation and reproduce the physical damage caused by sunlight. Some of the potential damage to the materials include loss of gloss, cracking, hazing, embrittlement and color change. It is interesting to note that dew, not rain, is responsible for the vast majority of wetness that occurs outdoors. The apparatus is able to simulate dew by purifying tap water through evaporation which is actually the distillation process which removes impurities from the water. The chemical degradation processes started by the UV radiation and condensation will have increased kinetic reaction rates as a result of the increased temperatures.

The next apparatus is the climatic chamber which has a combination of UV radiation, temperature and high humidity. The climatic chamber, Q-LAB Accelerated Weathering Tester QAV/se (QUV ACCELERATED WEATHERING TESTER, n.d.), is compatible with several types of lamps and can support different weathering cycles. The selected cycle is cycle 6 based on ASTM G154-16 standard (ASTM, 2016) with the following schedule; 8 hours of UV radiation at 60°C (±3°C) black panel temperature and 4 hours of condensation (100% RH) at 50°C (±3°C) black panel temperature.

Unit 1 (top left), Unit 5 (top right) and Unit 2 (bottom right) are placed in the machine

Figure 14 - Q-LAB Accelerated Weathering Tester - Model QAV/se

Due to the combination of UV, moisture and heat, it possible that there could be some significant changes in the optical properties of the aerogel glazing. Since the measuring area is quite small, and the measure instrument itself supports only smaller size, the 10x10 units were selected which also allowed for a few of them to be aged simultaneously. Unit 1 (no aerogel), unit 2 (Cabot P300 aerogel) and unit 5 (Airglass aerogel) were placed inside the apparatus. It would have been ideal to include two control IGUs in the ageing apparatus and have a least three replicas for each aerogel type for better statistical evaluation of results but due to materials availability and scope limitation it was not feasible.

3.2.3.1 Lamps

The QAV/se tester supports a variety of ultraviolet lamps which are equivalent to conventional 40W fluorescent lamps in terms of power consumption and physical size. Each lamp is different in the total amount of UV radiation it emits as well as the wavelength spectrum. Fluorescent UV lamps are generally categorized into UVA or UVB lamps depending on the region where most of their output falls. The exposure application defines the need which in turn determines which lamp and cycle should be used.

UVA lamps do not have any radiation output below the wavelength of 295nm so they do not degrade materials as quickly as UVB lamps. They also provide better spectrum accuracy with actual outdoor weathering. UVA-340 lamps provide the best simulation of sunlight in the critical region of short wavelength radiation from 295 to 365nm. The peak emission appears at 340nm, hence the name, and they are especially useful for comparison tests of different configurations. UVA-351 simulates the UV radiation as if filtered through glass window which is not applicable for this research.

UVB has the shortest wavelength radiation of sunlight at the earth's surface. These types of lamps emit unnatural, shortwave radiation below the cutoff of 295nm and can cause anomalous results as such it is common for them to be used for quality control and research and development. The UVB 313EL produces high levels of UV radiation and is generally used for quality control and research and development, particularly for durable materials. It replaces the UVB-313 since it is more stable and provides fast results. The second type of UVB lamp is QFS-40 which is also known as FS-40 or F40 UVB, it was the original lamp for this apparatus. They are predominantly used for automotive coatings and are only available on the QUV/basic model.

Other manufacturers might have similar UV lamps with similar names but can have very different irradiance, spectral power distribution and ageing characteristics, as such it is recommended to use Q-Lab original lamps for best and most consistent results. Mixing different types of bulbs will result in uneven ageing. UVA 340 is the most suitable lamp which provides the most accurate natural UV radiation in the critical wavelength. One of the benefits in the QUV/se model is the ability to control and monitor the irradiance via SOLAR EYE. Even after the lamps have been used for a period of time, the needed intensity level can still be maintained by automatically adjusting the power level.

3.2.3.2 Mounting Considerations

The QUV/se model supports a few types of flat specimen holders. The standard holders support 75x150mm (exposure area 63x95mm) samples which do not fit the 100x100 samples. There are two more types of brackets that support 100x150mm (exposure area 88x95mm) and 150x150mm (exposure area 95x132mm) samples. The other issue is the circular retaining rings which support fairly flat samples. There would have been a need to order thick panel retaining clips which are designed to hold specimen of thicknesses of 6-19mm in the same flat panel holders which would be insufficient for the aerogel glazing units (25mm thickness).

Replacement trays had to be custom made by the fabrication shop using galvanized steel. It is mentioned in ASTM G154-16 that the trays would need to be made from corrosion resistant alloys of aluminum and stainless steel, which were not available to the shop at the time. Theoretically, the galvanized steel would be able to perform well, unless it was cut to expose the untreated material which had to be done in order to create custom openings in the size of 90x90mm. The units occupied 3 openings and were secured using UV and heat resistant zip ties by Arctic Tie (ICE-1180C). Each sample was secured using three ties, two creating an "X" overlap at the bottom to provide gravity support and one more horizontally to prevent samples from tilting. Due to the nature of the thick zip tie plastic (i.e. bending radius), there is a gap on the interior side which does allow UV light to reach areas that are directly behind the ties due to the multiple lamp configuration. The remaining fourth opening was sealed using a galvanized steel plate from the same batch and held in place with aluminum tape. This was done to have proper vapour seal for the condensation phase of the cycling.

Figure 15 - Rear view of custom metal tray for aerogel IGUs

Figure 16 - Front view of custom metal tray for aerogel IGUs

3.2.4 Humidity Chambers

Water in its various states such as wind driven rain, precipitation, free water, water vapour condensation and relative humidity can all factor in the degradation of building components (Jelle, Accelerated climate ageing of building materials, components and sturctures in the laboratory, 2012). Aerogel within IGUs is not exposed to free water or rain due to its protective enclosure which means that the effects of vapour condensation and humidity are the primary focus. Although aerogel undergoes a treatment to become moisture resistant via hydrophobic surface treatment, the silica skeleton structure can be still prone to collapse due to ingress of moisture. Constant moisture pressure could degrade aerogel due to surface tension of the water.

3.2.4.1 Chamber 1

In order to evaluate the effects of accelerated moisture ageing, a custom-built dedicated humidity chamber (1) was used to create a high moisture environment. Temperature and relative humidity set points were set to 40°C and 90% respectively to create high vapour pressure drive. The actual temperature and humidity fluctuated in the range of 43-46°C and 65-85% RH. Unit 6 which is of the smaller variety (10x10cm) with Airglass aerogel was placed inside of this chamber in a free standing vertical position for the duration of the ageing.

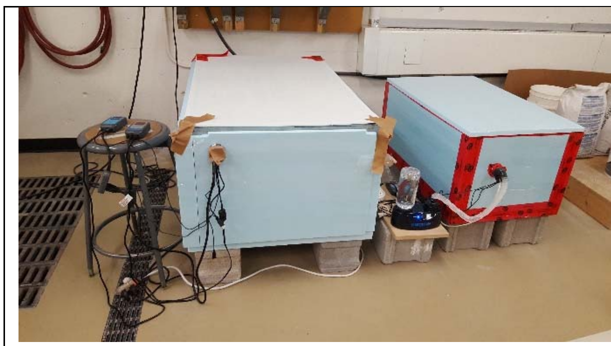
This chamber was built with interior dimensions of 118(l) x 68.5(w) x 45(h) cm using 1cm thick acrylic glass. The acrylic glass box is encased in 50mm rigid XPS insulation (RSI 1.76) to reduce the amount of heat loss to the ambient air within the laboratory. In order to maintain as high air tightness as possible, the removable top (lid) of the chamber was lined with closed cell self-adhesive weatherstrip foam tape (Climaloc CF21002). Raised floor was built out of perforated galvanized metal and raised by using clay bricks. This allows for uniform moisture and temperature distribution throughout the chamber.

A humidity and temperature controller (INKBIRD IHC-230) was used to control a heat lamp (Sylvania 13840, 175w PAR38, red) which was mounted with a porcelain clamp lamp (by Zoo Med) to maintain the air temperature as close to the set point as possible. Portions of the interior surface near the heat lamp were lined with aluminum foil to disperse the heat deeper throughout the chamber. A humidity controller (INKBIRD IHC-200) was used to control a bucket heater (Miller Manufacturing Company 742G) that was kept submerged inside the clear plastic container (20L) filled with distilled water.

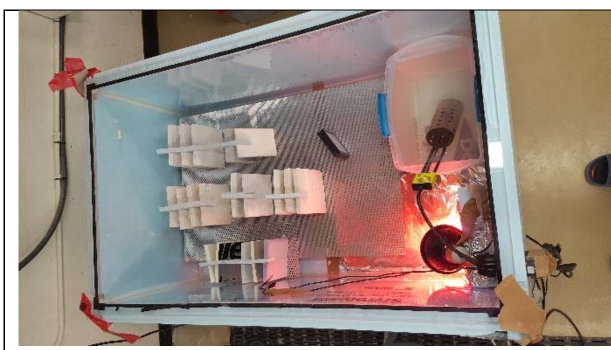
3.2.4.2 Chamber 2

A second chamber (2) was built as well with the primary intention to increase the moisture content of given samples. This chamber was set to a temperature of 23°C and 70% relative humidity. The actual temperature was around 22-24°C while the relative humidity was 65-70%. Although the temperature and relative humidity configuration were not as severe as chamber 1, this chamber serves as good comparison to see how prone a given sample is to ingress of moisture and how much of a performance reduction can be expected. This chamber housed unit 7 which is smaller (10x10cm) with Airglass aerogel in free standing vertical position.

The chamber was built using 50mm XPS rigid insulation boards (RSI 1.76) with sheathing housewrap tape (Tuck Tape) to provide better air tightness as secondary air barrier. The interior dimensions are 90(l) x 50(w) x 37(h) cm that house a clear 104L plastic container (Sterilite ClearView Tote with latch) that acts as the primary air tightness barrier. Raised floor was also incorporated into this chamber using perforated galvanized metal on clay bricks for good distribution of temperature and water vapour. A temperature and humidity controller (INKBIRD IHC-230) was set to control an incandescent bulb (Noma 60W Incandescent Bulb, Transparent Red) inside a clamp on shade (Sunlite E1201) to maintain the temperature. The humidity controller (INKBIRD IHC-200) controlled a humidifier (Zoo Med Repti Fogger™ Terrarium). A portable dehumidifier (22W Homasy Portable Mini Dehumidifier) was also wired independently to make sure the relative humidity does not exceed the set point. Both of the chambers were constructed by two graduate students as part of their research into high performance insulation materials and aerogel.



Custom built humidity chamber 1 (left) and 2 (right)



Open humidity chamber 1 with IGU 6

Open humidity chamber 2 with IGU 7

Figure 17 – Custom built humidity chambers

3.2.5 Acceleration factors

Real life durability data collection is an extended process and is generally not suitable for high tech materials and products but the data is still needed in order to generate market penetration and acquire market share. Aerogel, and specifically aerogel glazing falls into that category, and the most suitable approach to test the durability is via accelerated ageing. This type of ageing exposes the products to various climatic stresses that exceed typical use conditions.

The combination of aerogel fill inside of IGUs has the potential to present a unique set of challenges. Some of the mechanisms that are present and play a role in ageing of aerogel in its standalone state could either be completely ignored or greatly exaggerated when aerogel is incorporated into a multi-layer configuration. On the most fundamental level, an aerogel IGU would be composed of two lites of glass, spacer, sealant and aerogel filled cavity. The components that make up the base of the IGU also serve as the enclosure for the aerogel and in theory are supposed to provide protection thus maintaining its high level of performance in addition to its already high durability.

It is important to understand how the length and intensity of the various degradation mechanisms effects the aerogel when it is configured in an IGU. In order to provide an estimate as to how much equivalent real life time has passed for a given accelerated ageing period, acceleration factors need to be calculated. The accelerated temporal ageing tests included elevated temperatures, temperature cycling, and combination of UV radiation, high temperature and humidity. In order to provide a rough estimate as to how long equivalent real service life each ageing sequence has yielded, a series of equations (Arrhenius relationship, Coffin-Manson equation and Peck model) were employed to serve as the theoretical basis.

3.2.5.1 Elevated temperature

A constant high temperature can be used for accelerated ageing in order to detect potential defects or failure modes in a short period of time. The Arrhenius relationship was originally formulated for accelerated life testing with the acceleration stress selection being thermal. This model relates the exposure time of the experimental temperature to that of the use condition temperature. This formula

$$AF_{Temp} = e^{-\frac{E_A}{k}\times(\frac{1}{T_A}-\frac{1}{T_U})} \qquad (1)$$

Where AF_{Temp} is the acceleration factor due to temperature stressing (Crowe & Feinberg, 2001)(Jelle, 2012), E_A is the activation energy of the failure mechanism, k is the Boltzmann constant (8.617×10^{-5} eV/K), T_A is the accelerated temperature (in Kelvin) and T_U is the use condition temperature (in Kelvin).

The activation energy (E_a) is the minimum required energy that is needed to initiate a chemical reaction and it is a property of the material being tested. From the Aerogel Handbook (Aegerter, Leventis, & Koebel, 2011), aerogel is assumed to be temperature independent and has activation energy of about 70 kJ/mol. The constant use temperature was assumed to be equal to 20°C (293.15K).

Given the conditions in the oven mentioned in section 3.2.1 and the information above, the acceleration factor was calculated to be 65.5. A testing period of 4 months (117 days) is equivalent to 21 years of typical use conditions. It is important to note that the higher the average annual temperature that is plugged as the use condition, the lower the accelerated factor which makes this type of calculation region specific.

Test #	Ageing Dates	Number of days

First month of ageing	Dec. 5 – Jan. 9	35
Second month of ageing	Jan. 16 – Feb. 10	25
Third month of ageing	Feb. 17 – Mar. 13	24
Fourth month of ageing	Mar. 17 – April 19	33
	Total	117

Table 4 - Accelerated ageing durations for oven and temperature cycling machine

3.2.5.2 Temperature cycling (freeze thawing cycles)

Temperature fluctuations are a part of the natural weather cycles with even high temperature differences occurring during the winter season where the indoor temperature is quite warm while outdoor is below freezing. Having a material or product fluctuate between high and low temperatures can cause cumulative stress (thermal shock) that may result in a failure which in turn would compromise the performance. The Coffin-Manson equation (Delserro Enginerring Solutions, 2014) is able to provide a simplified calculation method for an acceleration factor due to freezing and thawing cycles:

$$AF_{Temp\ cycling} = \left(\frac{\Delta T_{test}}{\Delta T_{use}}\right)^{m} \tag{2}$$

Where $AF_{Temp\ cycling}$ is the acceleration factor due to temperature cycling, ΔT_{test} is the temperature difference in the testing chamber (from -30°C to 40°C → ΔT_{test} = 70°C), ΔT_{use} is the temperature difference in natural outdoor climate conditions (assumed 20°C for Toronto) and m is fatigue, or the Coffin-Manson exponent [typically 3 (Delserro Enginerring Solutions, 2014)].

Using the set points outlined in section **Error! Reference source not found.** and above, the acceleration factor was calculated to be 42.88. A total of 117 days (4 months) of accelerated ageing in the temperature cycling machine with freeze thaw cycling is equivalent to 13.5 years of regular outdoor exposure.

3.2.5.3 Elevated temperature, UV radiation and high humidity

The combination of multiple environmental conditions can create severe stress on any given material or product. The alternating combination of heat assisted UV and humidity degradation was aimed to simulate more conditions which would cause a compounded effect on the samples.

The combined acceleration factor for the entire test span (AF_{THUV}) is a strong simplification which is based on Peck Model and the Arrhenius relationship but is specific to the climatic chamber cycling. These models are used in combination with a simple proportion between the total UV energy during ageing (Φ_A) and the natural outdoor ageing process (Φ_U) to find the combined acceleration factor:

$$AF_{THUV} = \frac{1}{3}(AF_{T1} \times AF_{H}) + \frac{2}{3}(AF_{T2} \times AF_{UV}) \tag{3}$$

Where AF_H is the humidity acceleration factor (Crowe & Feinberg, 2001), AF_{T1} is the temperature acceleration factor during the 4hr test cycle where only temperature and humidity are involved, AF_{T2} is the temperature acceleration factor during the 8hr test cycle where only temperature and UV radiation are operational, AF_{UV} (Jelle, 2012) is the UV acceleration factor and AF_{THUV} is the combined acceleration factor for both temperature, humidity and UV radiation. The equation can be then separated into its component pieces:

$$AF_T = e^{-\frac{E_A}{k}\times(\frac{1}{T_A}-\frac{1}{T_U})} \tag{1}$$

$$AF_H = \left(\frac{RH_A}{RH_U}\right)^m \tag{4}$$

$$AF_{UV} = \frac{\Phi_A}{\Phi_U} \tag{5}$$

Where RH_A is the relative humidity of the test, RH_U is the relative humidity in natural outdoor climate conditions, T_A is the temperature in the ageing chamber, T_U is the temperature in natural outdoor climate conditions (average annual temperature for Toronto is 15°C), m is a humidity constant (2.66), E_A is the activation energy (= 0.7 eV).

Φ_U is total energy during natural outdoor ageing [3.67 kWh/m^2/d * 365 days = 1339.55 kWh/m^2 [Toronto International airport (RETScreen 4)]. Φ_A is the total UV energy during accelerated ageing (14935.8 kWh/m^2) which was calculated by averaging the multiplied typical irradiances (1.55 W/m^2*nm) by each wavelength (nm) to find the average intensity in W/m^2 and converting it to kWh/m^2.

Using the information provided above and in section 3.2.3, the acceleration factors were calculated as following; AF_{T1}= 14.36, AF_H= 7.4, AF_{T2}= 31 and AF_{UV}= 11.15. Based on these values, the combined acceleration factor was found to be AF_{THUV}= 265 [AF_{THUV} can range from 5 to 250 (Jelle, 2012)]. A testing period of 102 days (2439 hours) is equivalent to 74 years of natural outdoor exposure conditions.

3.2.5.4 High relative humidity

Extended periods of exposure to water in its liquid and vapour form can cause stress and premature failures in certain materials or products. The high relative humidity generates high vapour drive into a given sample as well as potentially creating condensation on the surface. Exposing a sample to these conditions alone is not enough since without the activation energy from higher temperature, no reactions would take place.

The combined acceleration factor for humidity and elevated temperature (AF_{TH}) is based on the combination of Arrhenius and Peck models and used for estimating the equivalent real life span of a material when both temperature and humidity are accelerated (Crowe & Feinberg, 2001).

$$AF_{TH} = AF_T \times AF_H \tag{6}$$

The equation is then further broken down to its components:

$$AF_T = e^{-\frac{E_A}{k}\times(\frac{1}{T_A}-\frac{1}{T_U})} \tag{1}$$

$$AF_H = \left(\frac{RH_A}{RH_U}\right)^m \tag{4}$$

Where AF_H is the humidity acceleration factor (Crowe & Feinberg, 2001), AF_T is the temperature acceleration factor, AF_{TH} is the combined acceleration factor for both temperature and humidity, RH_A is the relative humidity of the test, RH_U is the relative humidity in natural outdoor climate conditions, T_A is the temperature in the ageing chamber, T_U is the temperature in natural outdoor climate conditions (average annual temperature for Toronto is 15°C), m is a humidity constant (2.66) and E_A is the activation energy (= 0.7 eV).

Test #	Ageing Dates	Number of days
First month of ageing	Mar. 9 – Apr. 7	29
Second month of ageing	Apr. 10 – May 8	28
	Total	57

Table 5 - Accelerated ageing duration for humidity chambers

Using the information provided above and in section 3.2.4.1, the acceleration factor was calculated to be 88 (for chamber 1). A testing period of 2 months (57 days) is equivalent to 13.5 years of natural outdoor exposure conditions. As mentioned previously, due to unresolved technical malfunctions with the heating coil, this calculation should be considered more of an ideal scenario or nominal value but is lower in reality. Also, an acceleration factor is not provided for the second chamber since the conditions were not as severe, thus serving more as control for chamber 1 and to check if there is any moisture accumulation inside of the IGU for the purposes of moisture content measurements.

3.3 Testing

It is would be unfortunate if a high performance product would deteriorate a significant amount over a span of 15-20 years. In order to design a well performing and durable products, durability data, and performance testing after accelerated ageing is crucial. Performance testing can be used to test various properties such as compressive and tensile strength, moisture absorption and retention, colour changes and transparency changes. This research focuses on two important aspects for a glazing, thermal and optical properties.

Glazed components comprise large portions of building facades and in their current state are large source of heat transfer. Minimizing heat transfer through glazed assemblies could be a great increase to energy efficiency. The second, is the glazing's ability to provide daylight and view to the outside. These aspects are related to each other and play a significant role in a person's physical and mental well-being. In addition, having sufficient amount of daylight in interior spaces could reduce the need for artificial lighting which in turn can provide energy savings. The two equipment used to test the thermal and optical properties are the heat flow meter and the spectrophotometer respectively.

3.3.1 Thermal performance measurements

Thermal conductivity is the measure of a given material's ability to conduct heat. In building applications, it is generally desired to have as high thermal resistance as possible. Higher resistance to heat transfer means smaller heat movement over the building envelope which in turn mean less energy is wasted on maintaining comfortable indoor conditions. To measure thermal conductivity, the NETZSCH HFM 436 Lambda Heat Flow Meter was used (HFM 436 Lambda Heat flow meter, n.d.). The large samples (30x30cm) size was specifically chosen to accommodate this machine as to eliminate the need to have foam “housing” to get a better center of glass measurement. A housing or a sleeve would be needed to bring the samples of smaller size to the 30x30cm size for proper testing. Although the actual heat flow instrument is only 10cm in diameter, one would not want heat to move from the sides but rather in a single linear direction, from top to bottom.

For many materials, even insulation materials, the thermal conductivity is a function of temperature. For this reason, it was important to measure the aerogel’s performance in a temperature range to see how it fares when compared to other insulation types (aerogel is used in blankets for exterior applications). The selected (mean) temperatures were as following; -10, 0, 10, 20, 24, 30, 40 and 50°C to reflect a range of exterior conditions across multiple seasons. In order to measure the thermal conductivity, the machine generates a temperature difference across the sample (ΔT). The top plate is warmer one, while the bottom plate is the colder one. The temperature difference is set to 20°C which means 10°C degrees below and above the mean temperature set point.

Sample inside the heat flow meter

Figure 18 - NETZSCH HFM 436 Lambda Heat Flow Meter (right) and Julabo FP50-MA Refrigerated/Heating Circulator (left)

Having a larger temperature difference is beneficial for an even more accurate measurement regardless of the accuracy of the equipment. During the third testing session (after two months ageing), the temperature difference for the first mean temperature (-10°C) was changed from ΔT=20°C to ΔT=10°C to reduce stress on the machine and reduce testing duration with no change to the accuracy. There are four models of HFM 436 Lambda and this particular unit is able to achieve such low test temperatures due to use of Julabo FP50-MA Refrigerated/Heating Circulator (FP50-MA Refrigerated/Heating Circulator, 2017). One measurement cycle takes roughly 10-12 hours to complete all eight points which would make it very time consuming to execute three times for more accurate results.

3.3.2 Optical performance measurements

Optical performance for a glazing units can have multiple measurement criteria such as, solar heat gain, visible transmittance, reflectance and absorbance. In most conventional glazing units there is a balance between the properties above; there is no scenario where one glazing has all the best qualities, generally speaking it is a tradeoff. For aerogel glazing, the size of cavity is what controls the thermal resistance which means that the larger the cavity, the better the thermal performance. Visible transmittance is an important parameter for any glazing unit since it quantifies the amount of light getting to the interior which is predominately what glazing is used for in buildings.

Granular aerogel glazing is different (from monolithic) since it is used for diffused daylighting purposes due to the granules scattering, reflecting and refracting the light significantly thus reducing visual clarity to the outdoors. Although granular aerogel glazing functions more like frosted glass, it still lets light through. Absorbance is the measure of the amount of solar radiation that does not pass through a given material and has an inverse relationship to solar transmittance.

The spectrophotometer by Agilent Technologies – Cary 5000 UV-Vis-Nir Spectrophotometer is able to measure absorbance in the range of 175-3300nm (Cary 5000 UV-Vis-NIR, n.d.). The absorbance was measured in the solar radiation range of 200-2000nm and was converted to transmittance which then can be used for comparison and analysis. The apparatus supports samples for up to 120x120mm in size, so having small set of units allows for easy and quick measuring with each test taking several minutes to conduct.

Sample inside the spectrophotometer

Figure 19 - Agilent Technologies – Cary 5000 UV-Vis-Nir Spectrophotometer

The measurements are done separately with a laser at each wavelength in the range of 200-2000nm using a PbSmart detector. The cross section area of the measurement is quite small which makes it heavily dependent on which granules it passes through. It is preferable to test each sample multiple times with rotation changes but the absorption curve stays the same for same type of aerogel and would varies within 10-15% bracket depending on which configuration of granules it passes through.

The detector measures light that was able to travel mostly in a linear trajectory, all the light that gets scattered and reflected is essentially unaccounted for. Normally this is not an issue if used for transparent samples, but if a translucent material is used (such as frosted glass or granular aerogel), the light would be scattered. This is what gives frosted glass the ability to provide privacy while maintaining light transmittance. Testing with the spectrophotometer without the integrating sphere measures the amount of light that passes through the IGU, which is more akin to what the human eye would experience.

The counter argument point to this is that the transmittance values generated without the sphere would be much lower and potentially misleading as to the actual amount of light passing through. Having an integrating sphere provides the ability to measure all the light that passes through the aerogel glazing, including the light that would not be visible to the human eye due to refraction and reflectance.

An integrating sphere is hollow with the internal white reflective surface (non-selective diffuse reflector) with small entrance and exit ports. The geometry of the sphere is designed to collect the majority of reflected or transmitted light (without directional preference) and directing a cumulative signal to the detector. Integrating sphere are ideal for measuring the transmission of turbid, translucent or almost opaque samples where standard practices are inadequate due to the loss of light from scattering effects.

Figure 20 - Agilent's integrating sphere for the Cary series spectrophotometers (https://www.agilent.com/cs/library/brochures/5990-7786EN_Cary-4000-5000-6000i-UV-Vis-NIR_Brochure.pdf)

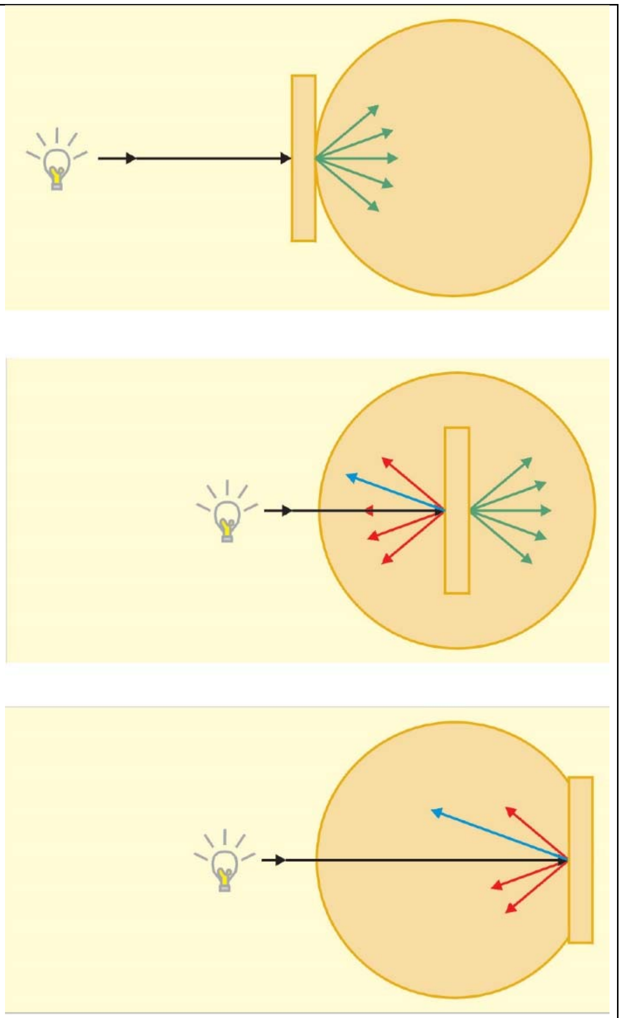


Figure 21 – Integrating sphere diagram showing transmitted (top) and reflected (bottom) light (https://www.agilent.com/cs/library/flyers/public/5991-1717EN_PromoFlyer_UV_DRA.pdf)

4 RESULTS & ANALYSIS

4.1 Thermal Performance

Thermal performance is focused on aspects of heat transfer through the tested assemblies predominately via conduction which is primarily denoted by thermal conductance (W/m^2K), thermal resistance (R-value in m^2K/W) and overall heat transfer coefficient (U-value in W/m^2K). Thermal conductivity is generally used for homogeneous materials but when testing products or assemblies, using thermal conductance is more appropriate to show the overall ability of the heat to move through the product.

The tests were carried out in roughly one month (4-5 weeks) intervals in order to get an understanding if there were any intermediate changes and to make sure the IGUs were not compromised during the ageing. The first test served as the initial benchmark in pristine condition performance which also included unit 4 as control. Unit 4 was kept in room temperature conditions inside a case away from direct daylight. It was measured only twice, test 1 and test 5. This was done to make sure that the aerogel does not "naturally decay" within the IGU.

After each test, the heat flow apparatus provides a set of data (see appendix) which was used to plot graphs (1-3). The thermal conductance values (Y-Axis) were plotted against the mean temperature (°C) (X-Axis) in a XY scatter graph. A constant slope trend line was added with the corresponding formula. It is common practice in the industry to calculate the average thermal conductance at room temperature. The thermal conductance (as outlined by ASTM C168-15) for each IGU was calculated by first inversing the thermal resistances that were provided by the heat flow meter followed by plotting a constant slope trend line which allowed for the calculation of the overall conductance at 24°C.

The Cabot P300 aerogel granules were measured in the heat flow meter (no compaction) in pristine condition at 20°C, 22°C and 24°C with a ΔT of 10°C, 20°C and 10°C respectively. A similar methodology was used with the creation of a trend line and the calculation of the thermal conductivity at 24°C was found to be 0.0425 W/mK.

The focus on glazing only (as opposed to inclusion of window frame) meant that the performance parameters for the IGUs are limited to center of glass measurements/calculations (U-value of glazing or U value center-of-glass) since overall U-value cannot be determined due to two reasons. The first reason being that U-edge cannot be determined since there is no frame and secondly, U-edge is generally simulated as a separate entity due to the nature of air movement in the cavity near the frame, but since in this particular case the cavity is filled with mostly solid material, it is not applicable.

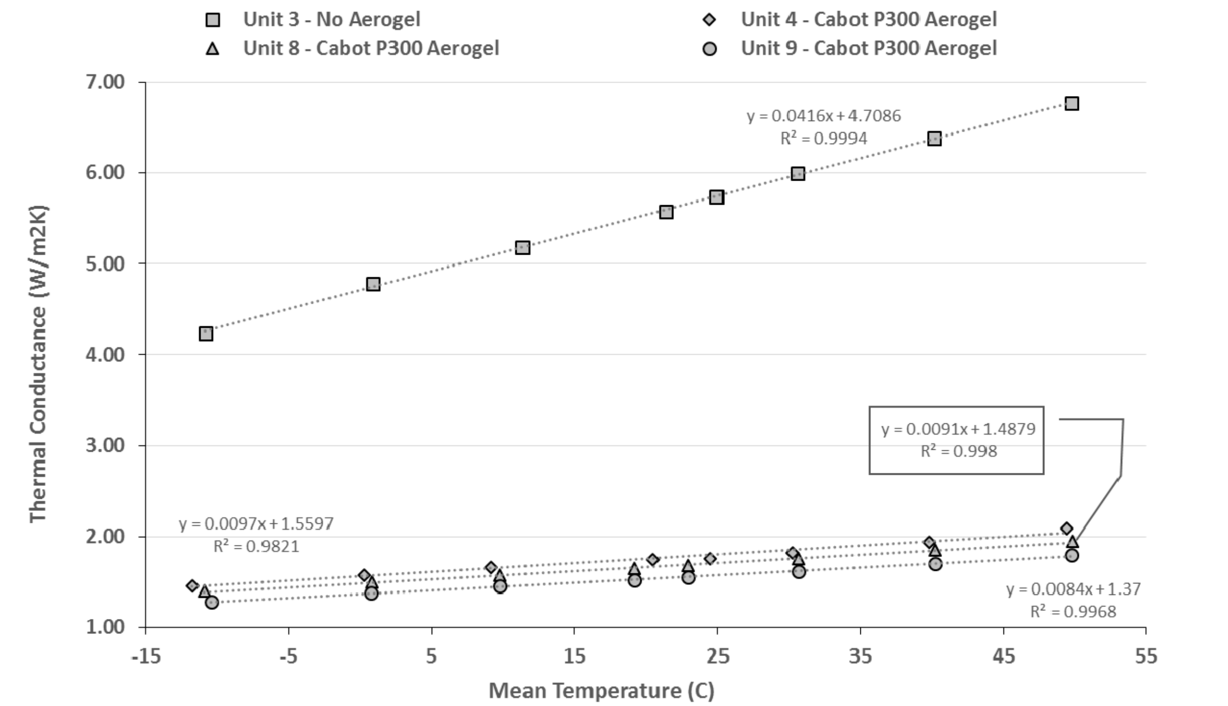


Figure 22 - Thermal Conductivity Test 1: pristine condition

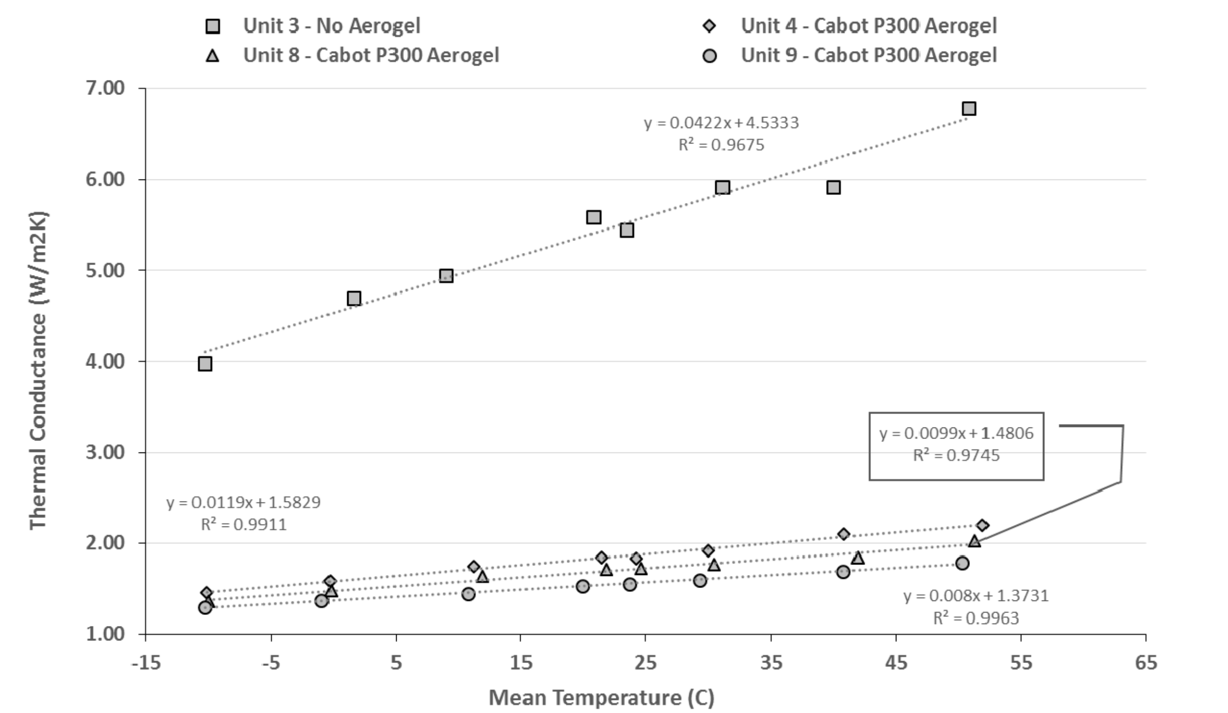


Figure 23 - mal Conductance Test 5: four months of accelerated ageing

Looking at Figures 22 and 23 it is possible to see that the slope of conductance for aerogel is much smaller (3° vs. 15°) than the slope for air conductance. A smaller slope is better from a performance point of view since there will more consistency (less variation) in the thermal resistance across various temperatures. Although argon gas has low thermal conductivity (0.017 W/mK) and if it were to be configured in a similar IGU, the expected (for a cavity thickness of 13mm) R-value would be around 0.76 m^2K/W. While this RSI value is higher than what was achieved by the aerogel (0.53-0.64 m^2K/W), it is a theoretical value and real life concentration of the gas would be less and combining it with the glass could be a little lower i.e. more in line with the aerogel. Furthermore, the slope of the thermal conductivity for the argon (or other gas) would be similar to that of the air, and as the gas escapes over time, the line would move closer and closer to air line while the aerogel, even after ageing, would be very close to its pristine condition having consistent performance over time and over temperature range.

The accelerated ageing processes in the oven and temperature cycling machine have caused a very small change in the thermal performance, with the most significant change being in the control unit (↑4% difference). Unit 3 (no aerogel - oven) and 9 (Cabot P300 aerogel - oven) saw a difference of ↑3% and ↓1% respectively while unit 8 (Cabot P300 aerogel – temperature cycling) had an increase of 1% in conductance. These values are very small and fall within the margin of error (up to 5%) indicating that the ageing had little impact on the aerogel's thermal performance.

	Unit 3 – No Aerogel	Unit 4 – Cabot P300 Aerogel	Unit 8 - Cabot P300 Aerogel	Unit 9 - Cabot P300 Aerogel
	Oven	Control	Temperature cycling	Oven
U-value center of glass (W/m^2K) @ 24°C – Test 1 pristine condition	5.707	1.792	1.706	1.571
U-value center of glass (W/m^2K) @ 24°C – Test 5 (4 months accelerated ageing)	5.546	1.868	1.718	1.565
R-value (m^2K/W) – Test 1 pristine condition	0.175	0.557	0.586	0.636
R-value (m^2K/W) – Test 5 (4 months accelerated ageing)	0.180	0.535	0.582	0.639

Table 6 - Thermal performance of IGUs before and after ageing

The difference in the thermal performance between the pristine condition and after accelerated ageing is quite small (up to 4%) and in some measurements, the thermal conductance has actually decreased as opposed to the expected increase with time and ageing. The biggest increase was seen in the clear IGU which is filled with air and fluctuations in the gas within the cavity could have played a factor. In the aerogel units, the difference is much smaller and practically insignificant, and the biggest conclusion is that the performance of the aerogel is still very close to its pristine condition. This translates into high durability for granular aerogel and great ability to maintain energy performance over time.

Glazing U-values were found to be in the range of 1.5-1.8 W/m^2K for IGUs with Cabot P300 aerogel while the clear IGU (unit 3) ranged 5.5-5.7 W/m^2K, 3.5 times higher than the aerogel. Comparing these values to some of the high performance glazing mentioned in Table 1 shows that this particular set of samples has worse thermal performance (higher U-value). When comparing the best pristine condition of the aerogel IGU (unit 9 – test 1) to Cabot's Nanogel glazing with 10mm cavity which has a glazing U-value of 1.38 W/m^2K, it is 14% lower while the 20mm cavity yielded a glazing U-value of 0.78 W/m^2K which is 51% better.

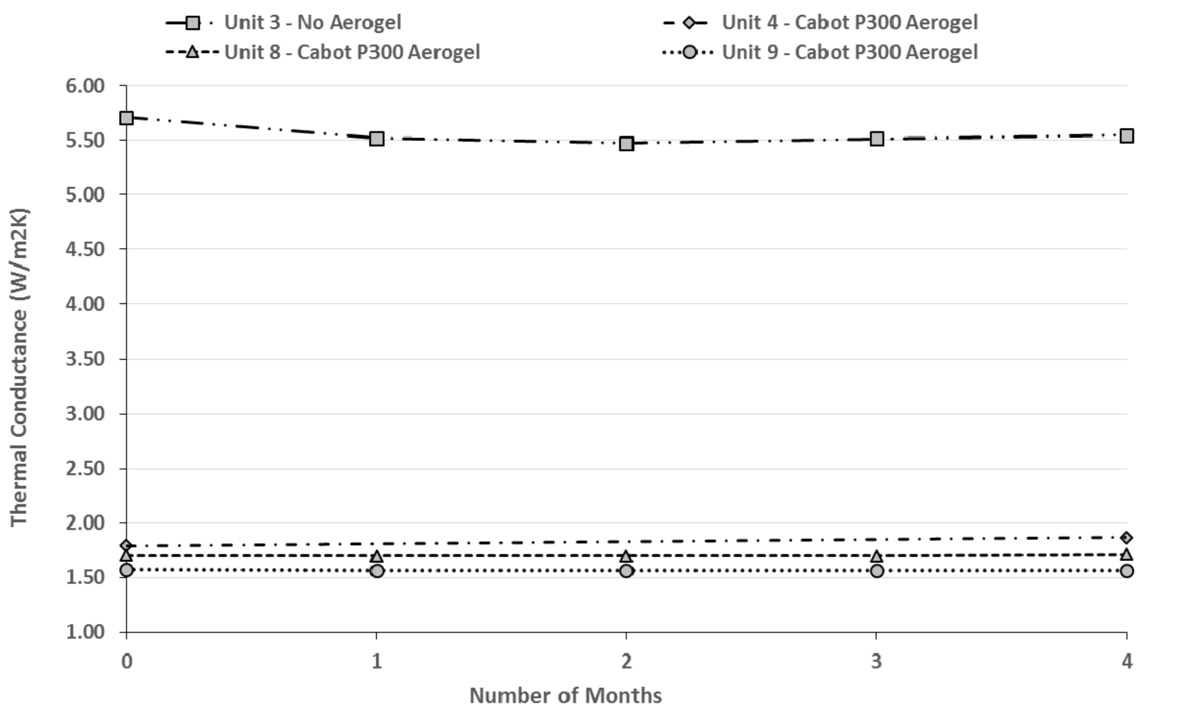


Figure 24 - Thermal conductance of all units after accelerated ageing

4.2 Optical Performance

The second aspect of windows is the transmittance of light for daylighting and visual connection to the outdoors. Glazing in its current configuration is predominantly used to provide view to the outdoors, and any modifications to the glazing (e.g. coatings, gas fills) are encouraged to improve performance but only as long as they do not impede the visual fidelity too much.

The apparatus used for optical performance measurements was the spectrophotometer from the chemistry department in Ryerson University. The apparatus uses an emitter to shoot laser beams at a specimen and measure how many photons make it to the collector on the opposite side at different wavelengths. The resulting absorption data is recorded by the onboard computer and relayed to a workstation computer which then can be converted into Microsoft Excel file or other formats for data analysis. The cross section area of the specimen through which the light passes is quite small and depending on the arrangement of the granular can provide slightly different results with a variation of 5% (see **Error! Reference source not found.**) for the same type of aerogel. The smaller the granules, the more consistent the results would be across various IGUs.

This particular machine does not have an integrating sphere which means that the light which gets refracted and scattered is not accounted for, increasing the perceived absorbance. On the other hand, not including an integrating sphere provides are more accurate representation of what a person might experience when looking through an aerogel glazing, but it does not look attractive to designers.

The absorbance values cannot be used directly in the same fashion as the thermal conductivity or thermal resistance values that are generated by the heat flow meter and require conversion prior to analysis. Depending on the wavelength, some of the absorbance values can appear quite high which required for all values above 2 to be normalized to 2. Next, a derivative of the Beer-Bouguer-Lambert Law was used to convert the absorbance values to transmittance. The Beer-Bouguer-Lambert Law is generally used in chemical analysis measurements to understand the attenuation of light. The original formula is written as:

$$\mathrm{A} = -\log_{10} T \tag{7}$$

Where the A is the absorbance data from the spectrophotometer and T is transmittance. It can be rearranged to solve for T as following:

$$T = 0.1^{A} \tag{8}$$

The reflectance can be calculated by subtracting the transmittance from one.

The range of wavelength testing was set to 200-2000nm with 200nm being the lowest supported wavelength by the apparatus and 2000nm as the upper limit to represent sun’s radiation as it reaches the earth’s surface.

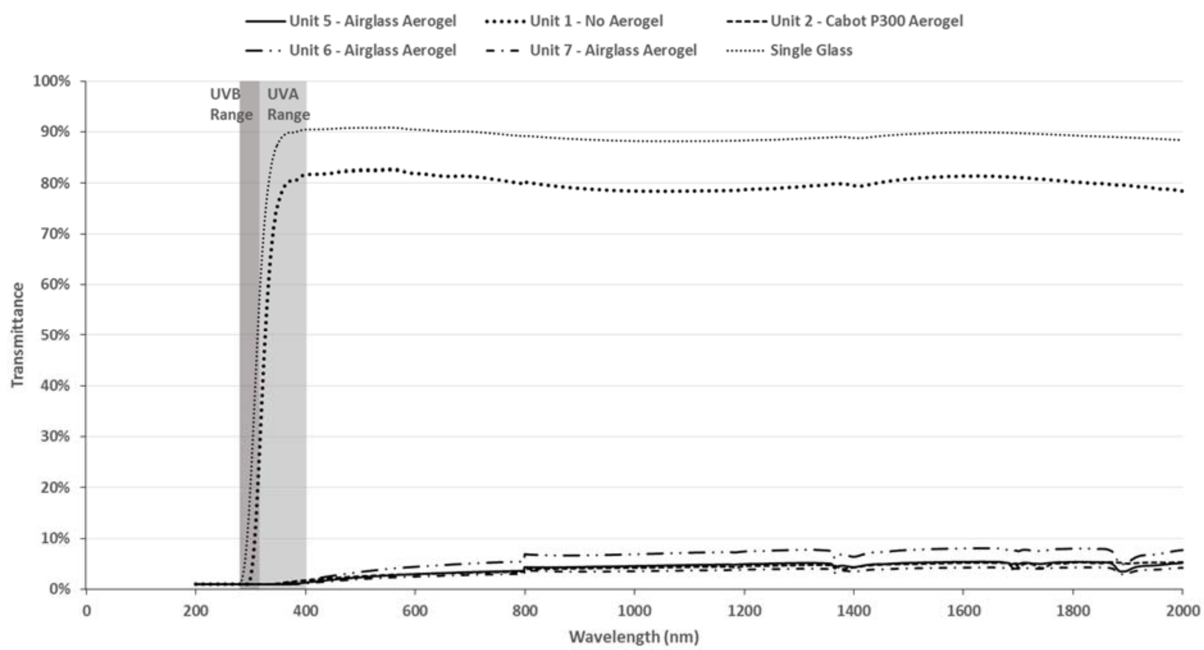


Figure 25 - Optical Transmittance Test 1: pristine condition

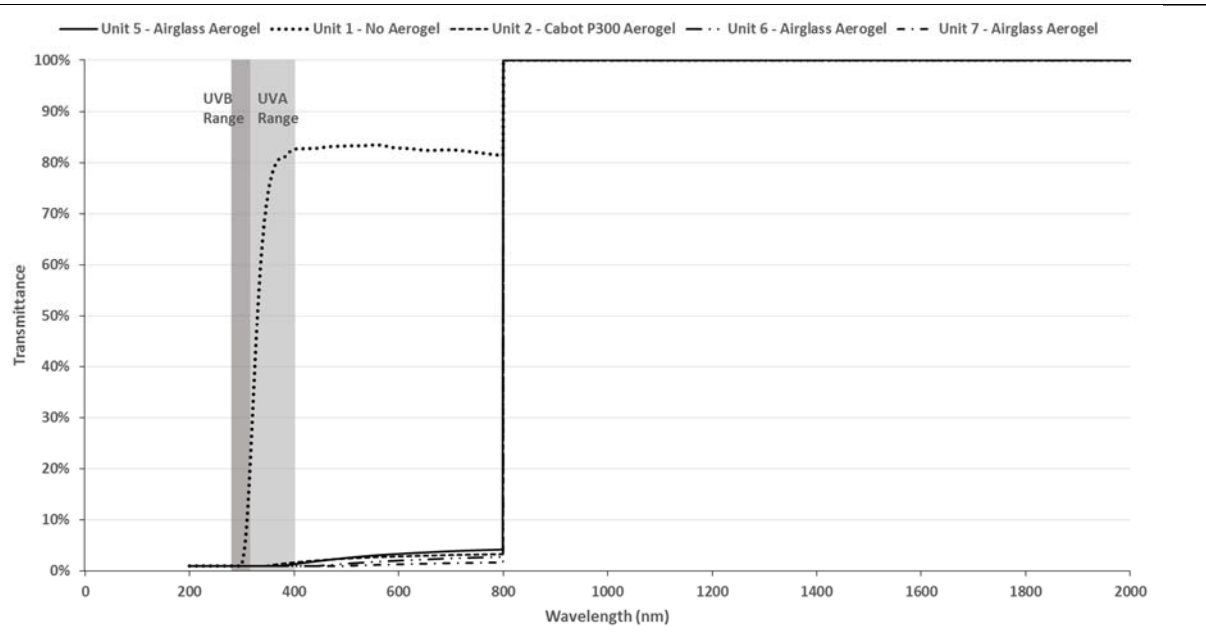


Figure 26 - Optical Transmittance Test 4: 3 months of accelerated ageing (3 months for unit 6 + 7), measured up to 800nm

A clear IGU and a single piece of glass were measured in the first test as part of control group to get understanding what the absorbance is for the base components of the IGUs. The clear IGU was found to have a transmittance of 80% while a single piece of glass has a transmittance of 90% both of which are in line with what was expected. The single glass transmits all of the UVA but only the majority of the

UVB radiation while the clear IGU also transmits all of the UVB but only about 50% of the UVB. Since the single glass transmits most of the UV radiation, it is assumed that the aerogel absorbs the majority of it which is beneficial for accelerated ageing when examining the impact of UV radiation on it.

Unit 1 (no aerogel in climatic chamber) has similar performance in term of light transmittance to its pristine condition to no surprise since glass has great properties and the air inside the cavity does not really impede the passage of light unless there is condensation. Unit 2 (Cabot P300 aerogel in climatic chamber) has very similar average visible transmittance with about a 4% reduction. This reduction is not significant enough and potentially could be the result of the configuration of the aerogel since the units undergo shaking after equalizing. Surprisingly, unit 5 (Airglass aerogel in climatic chamber) has shown 10% higher transmittance which seems counter intuitive and similarly to unit 2 could be the result of light passing through a larger piece of aerogel which is more clear thus creating less scattering and allowing more direct light through.

Unit 6 and 7 (Airglass aerogel) were aged in chamber 1 and 2 respectively and saw the biggest differences in their average visible transmittance. Unit 6 which was aged in chamber 1 under the more severe conditions saw a 211% decrease in the transmittance while unit 7 which was exposed to much more mild, almost ambient room conditions, saw a 75% decrease. These results do appear to be in line with the work of Ihara, et al. (2015) where the aged particles also had altered appearance and increased thermal conductivity due to the degradation of the silica network after accelerated ageing.

4.3 Visual Analysis

4.3.1 Temporary Shrinking of Aerogel Granular

Originally, unit 9 was assembled with a slightly too much aerogel which has caused a slight gap between one of the glass panes and the spacer (at one of the corners). Even after the first ageing period (1 month), the aerogel in unit 9 showed significant shrinkage (Figure 27) which was repeated in the latter measurements as well (about ≈4-5cm gap). The IGU units from the oven were taken out and were allowed to equalize in room temperature before the thermal conductivity measurements the following day (minimum of 24 hours). At which point unit 9 was shaken in order to create a more even distribution of granular before the measurements. Surprisingly, the large air gap that was visible immediately after taking the unit out of the oven has shrunk to ≈1cm gap, meaning that the same aerogel occupied more volume at room temperature after the IGU was shook (Figure 29). Although the compaction of the aerogel is due thermal stress, it is in line with the findings by Gao et al. (2014) that showed the tendency of granular aerogel to shrink.

Another aspect that was noted after the visual inspection is that there were small aerogel particles trapped between the glass and the spacer (Figure 32). This is likely due to the combination of the ageing in the oven in the vertical orientation as well as the shaking of the IGU which forced more particles into the gap that was initially created due to excess aerogel in the cavity. The portions along the spacer where no gap was created, exhibited very little if any trapped aerogel (Figure 31).

Figure 27 - IGU 9 (Test 5 after 4 months of accelerated ageing) before shaking of IGU, vertical ageing

Figure 28 - IGU 9 (after 4.5 months of accelerated ageing) before shaking of IGU, horizontal ageing

Figure 29 - IGU 9 (Test 5 after 4 months of accelerated ageing) after shaking of IGU, vertical ageing

Figure 30 - IGU 9 (after 4.5 months of accelerated ageing) after shaking of IGU, horizontal ageing

Figure 31 - IGU 9 (Test 5 after 4 months of accelerated ageing) top left corner without aerogel on spacer

Figure 32 - IGU 9 (Test 5 after 4 months of accelerated ageing) bottom left corner with aerogel sandwiched between glass and spacer

Unit 9 was placed in the same oven at the same temperature set point but in the horizontal position for one week. Once the unit was taken out and positioned vertically with minor shaking of the IGU, an air gap was created. The gap measured 2-2.5cm. The unit was placed back in the oven to finish the one month ageing period. The unit was taken out two weeks later with the gap size ranging 2-2.5cm (Figure 28). After equalizing overnight, and shaking the IGU, the gap was reduced to its 4 month aged size (≈1cm) (Figure 30). These results imply that heat and not the orientation affects the volume shrinkage of the aerogel.

A piece of monolithic Airglass aerogel (rough dimensions 20 x 25 x 18.5mm) was placed inside the oven for a period of 10 days at the same set point as the ageing (70°C) with the intention to measure expansion of the material. The dimensions were measured once before and after heating with the difference being below 1% (with two of the sides showing smaller values after being heated). The original shape of the piece only had two parallel sides with the other two sets requiring trimming with a knife. The process of cutting did not yield fully parallel sides as well as causing chipping of small pieces from the aerogel due to its brittleness.

4.3.2 Altered Appearance of Aerogel Particles

4.3.2.1 Large IGUs (30x30cm)

During the assembly process of the aerogel IGUs it was noted that a few of the particles (Figure 33) from the Cabot P300 variety were not translucent but were opaque (off white appearance). Although their initial quantity was quite small and essentially insignificant, due to their lack of translucency, they would reduce the optical performance but their biggest negative impact is their visual appearance. The quantity of the particles did not seem to increase in any of the ageing processes except in the elevated temperature one. It would seem that prolong exposure to high temperature (70°C) has created more of this type of particles (Figure 34).

These results are similar to those found by Ihara et al. (2015) but with the difference being humidity ageing versus elevated temperature ageing. A possible cause for this phenomenon was considered to be free water absorption but ruled out since the particles remained white after drying in 105°C heat for 48 or being aged at 70°C and 15% RH, in both cases removing any moisture.

Furthermore, it is mentioned that after ATR-FTIR analysis, the white particles were missing the methyl groups which are responsible for the hydrophobic surface but due to imperfections during the treatment are not present. This would allow for some moisture to penetrate into the silica network (due to water surface tension) and when sufficient mechanical stress is applied, the aerogel would break exposing the non-treated interior. The exposed silica can react to various substances in the environment such as CO_2 and salts (in water) thus creating the altered appearance.

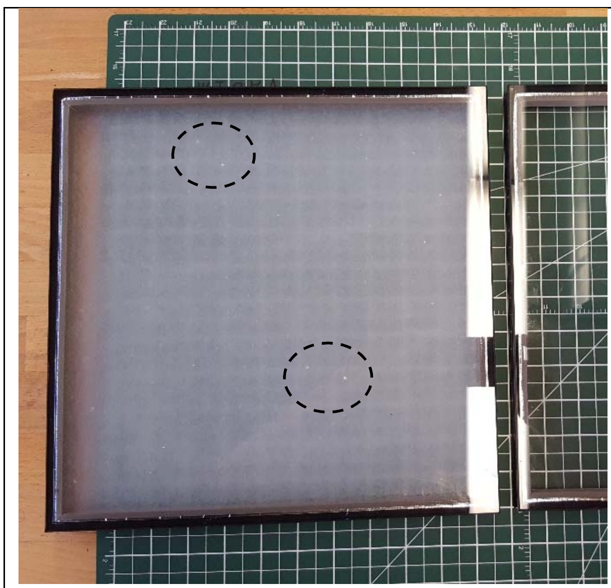


Figure 33 - Unit 9 (Cabot P300 Aerogel) pristine condition

Figure 34 – Unit 9 (after 4 months of accelerated ageing) discoloration of aerogel particles at bottom left corner of IGU

On the other hand, the Airglass aerogel filled units did not include any such particles in both pristine and aged conditions. Airglass aerogel was potentially manufactured as monolithic aerogel and then mechanically stressed to create smaller particles that were treated to give them hydrophobic nature.

The potentially better application of hydrophobic treatment would alleviate stresses from the granular that would have otherwise be caused by water surface tension.

4.3.2.2 Small IGUs (10x10cm)

Similar to the findings for the larger IGUs, the P300 aerogel in unit 2 also has shown a discoloration in the particles specifically around the perimeter. Unit 2 has been aged in the climatic chamber which has several ageing mechanisms such as UV radiation, elevated temperature and high humidity. In the pristine condition, the unit has showed a few spots (Figure 35) where the aerogel particle was white (opaque). After the accelerated ageing, the number of particles did not increase but the opacity/translucency of the particles around the perimeter has modified, appearing more opaque when compared to the pristine condition. This change does not affect the optical performance since the spectrophotometer uses the center of glass for its measurements, but on the other hand, the full IGU light transmittance would suffer as well as potentially creating esthetic discomfort.

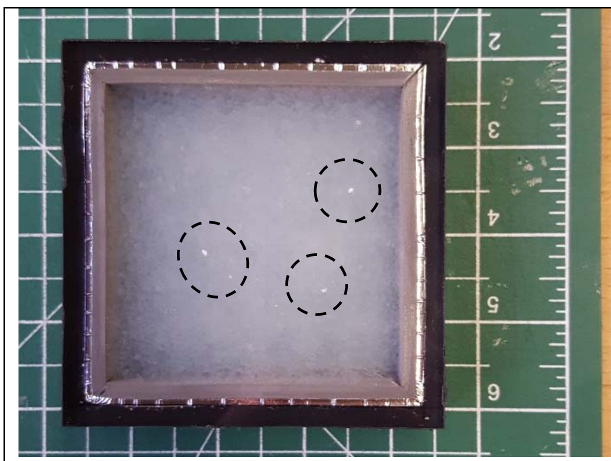


Figure 35 - Unit 2 pristine condition

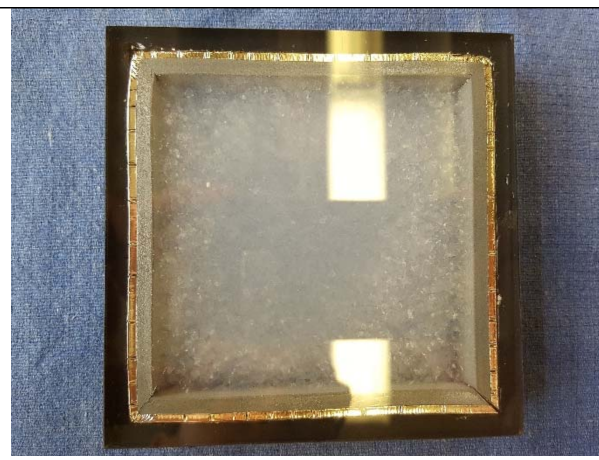


Figure 36 - Unit 2 after 3 months of accelerated ageing showing significant increase in discoloured aerogel particles

The Airglass aerogel IGUs (units 5, 6, 7) have a different type of deterioration as it would seem to be aerogel dust accumulation. All the Airglass aerogel units have shown varied amounts of the addition of these very fine particles trapped within the IGU cavity. The particles in unit 6 (aged in chamber 1 at 40°C and 90% RH) have migrated to the space between the spacer and the glass while the IGU cavity has just the aerogel (Figure 40). It would seem that there was an outward pressure from the inside of the IGU which has driven the particles towards the outside. Units 5 and 7 have smaller quantity of particles near and on their spacers but also have some in the cavity itself (Figure 38). The presence of particles at their current quantities would not pose much of an issue with regards to thermal or optical performance due to their size and density and is mostly an esthetic nuisance.

 Figure 37 - Unit 7 pristine condition	 Figure 38 - Unit 7 after 3 months of accelerated ageing creating fine particles in the aerogel cavity

 Figure 39 - Unit 6 pristine condition	 Figure 40 - Unit 6 after 3 months of accelerated ageing with aerogel particles trapped between the glass and the spacer

4.3.3 Aerogel Granular Compaction

All the units from the small variety (10x10cm) have been accelerated aged using one of the two methods, either in the climatic chamber or high humidity chamber. Unit 2 (Cabot P300 aerogel) and 5 (Airglass aerogel) were both aged in the climatic chamber where they were exposed to a combination of UV radiation, high relative humidity and elevated temperature. After visual inspection and documentation of the units after the ageing, it was noticed that unit 2 has experienced a very mild shrinking of the aerogel volume. The gap was barely visible under the pristine conditions (Figure 41) and has expanded after 3 months of exposure (Figure 43). Unit 5 on the other hand has maintained its volume with the only major difference is the appearance of dust like substance near the spacer on one side and on the glass on the opposite side. The reason why unit 5 did not undergo any significant compaction during the ageing could be attributed to mixture of larger and smaller granule sizes as opposed to Cabot's P300.

Figure 41 - Unit 2 (left) and unit 5 (right) pristine condition

Figure 42 - Unit 6 (left) and unit 7 (right) pristine condition

Figure 43 - Unit 2 (left) and unit 5 (right) after 3 months of accelerated ageing

Figure 44 - Unit 6 (left) and unit 7 (right) after 3 months of accelerated ageing

Unit 6 and 7 (both with Airglass aerogel) have been aged in the humidity chambers with unit 6 experiencing more extreme conditions in its ageing chamber (1) while chamber 2 had much more mild conditions. Both unit 6 and 7 had small (>0.5cm) air gaps in their pristine conditions which increased to roughly ≈0.5cm after the accelerated ageing. It is interesting to note that although both humidity chambers had different moisture loads, the compaction of the aerogel inside both the IGUs seem to be very similar.

Although the compaction of both types of aerogels is the result of stress, it is in line with findings that showed the tendency of granular aerogel to shrink (Gao, Jelle, Ihara, & Gustavsen, 2014). It is possible that certain moisture exposure in terms of intensity or length may have resulted in the deterioration of the aerogel up to a maximum point after which, the extra stress from heat or moisture did not add to the deterioration. The compaction of the aerogel granules created a bigger air gap that would have a negative impact on the thermal conductance of the unit and creates visual esthetic discomfort.

5 DISCUSSION

5.1 Performance benchmarking

The tested units, both in pristine and in aged condition, have very similar performance to one another which indicates great durability. Although this is a highly beneficial property to have, but it is not enough to justify the use of AGUs in buildings, thus must be benchmarked against the competition to prove their viability. Since the aged units were separated into two groups, there are two independent sets of data with the smaller units built for optical testing while the larger ones were used for thermal testing. This configuration was optimized for ease of testing but it also meant that there was no combined set of data (optical and thermal) for any unit.

For purpose of benchmarking, the thermal and optical performance data from the various IGU tests was merged to create theoretical units to reflect the combined performance. Following this methodology, three theoretical units were created to reflect the possible best performance, worst performance and control unit (non-aged units' performance). The U-values were taken from Table 6 while the visible transmittance (T_{VIS}) was calculated by averaging all the values in the range of 380-780nm. The performance for the various benchmarking units was presented by the manufacturer in the most ideal conditions and at times could be slightly skewed in their favour by using a specific methodology.

All of the benchmarked assemblies are commercialized products which were optimized for their category and expected performance. The majority of the units are somewhat following the trend where lower U-value (better thermal performance) comes at the expanse of lower visible transmittance (worse optical performance) and vice versa. There are some outliers to this trend but there could be other parameters that are less than desirable such as increased thickness, increased weight and much higher cost due to assembly complexity.

Looking at the theoretical units which are bunched up on the right hand side of the graph, it is possible to see that they are being outperformed in both categories. As discussed in previous sections, the lack of integrating sphere during the spectrophotometer testing measured visible transmittance values below 10% since it was unable to capture all the light that got reflected and refracted. An obvious solution would have been to retest the units after installing the sphere which was not feasible at the time. An alternative solution would have been to measure a known T_{vis} piece of frosted/privacy glass to see if it too would yield a low visible transmittance values confirming that the low values are indeed due to lack of integrating sphere.

On the thermal side, there was no missing equipment but the center of glass U-values are still not competitive with the rest of the units. The best performing unit has a U-value of 1.57 W/m^2K with 13mm of granular aerogel while the worst performing commercial aerogel glazing with 10mm of Nanogel® is able to reach 1.38 W/m^2K. Although the difference is not large, but in theory, the difference should be much smaller than 14% especially considering the both aerogel types are manufactured by Cabot. Moving to a large cavity size of 20mm, the U-value becomes roughly half at 0.78 W/m^2K, or twice as good, right below the Passive House's U-value-0.8 W/m^2K. Nanogel® is no available and was the predecessor to the Lumira® aerogel particles which is what is currently offered by Cabot for their glazing solutions.

A simple double glazing with 13mm cavity filled with argon would yield a rough U-value of 1.31 W/m^{2}K which is roughly equivalent to the Cabot Nanogel worst performer and 16% better than the best performing tested AGU. The advertised value for aerogel is quite low and in theory would provide even performance than argon gas but looking at granular aerogel, the thermal conductivity value becomes higher in its uncompressed state and come very close to argon when compressed properly. Based on this information it was expected that granular aerogel glazing would perform on part with argon filled IGUs.

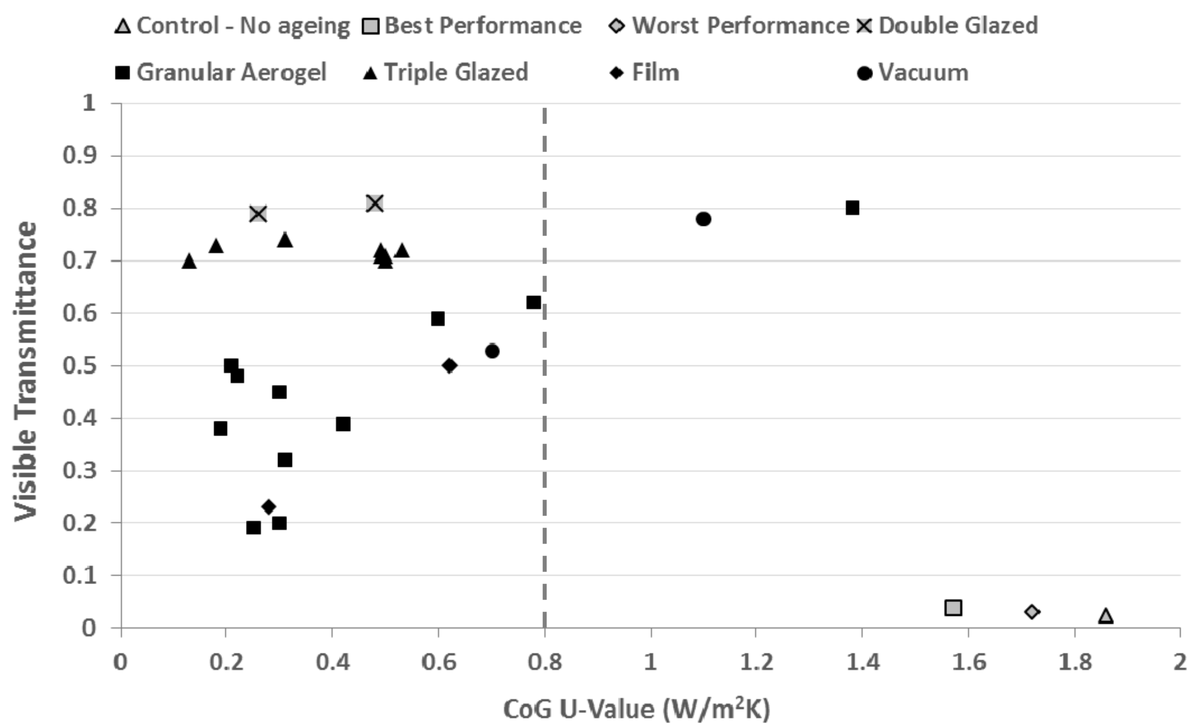


Figure 45 - Comparison of high performance glazing systems with aged samples performance

There could be several factors behind the discrepancy between the AGUs' thermal performances. The compaction level as seen in this research, in Lumira's specification sheet and mentioned by Neugebauer et al. (2014) indicates that there an optimal level of compaction for granular aerogel. The increase in performance from compaction for the assembled AGUs is almost double aligning with Neugebauer's findings. It is possible that Cabot's P300 optimal compaction level for 13mm thickness was not achieved and some performance loss was suffered there. This information is not supplied by Cabot and could be a potential area for future research.

Another factor that could play a significant role in the discrepancy is the selection of the aerogel particles. The P300 particles do not have their thermal or optical properties listed in the specification sheet (potentially due large variation within the product line) and looking just the experimental value shows that they are much worse than Lumira (Table 7) which is specifically designed and targeted for glazing applications. Using aerogel particles that were designed to be used in glazing could help bring the U-value closer inline to what is expected for it to be competitive with argon filled IGUs.

P300	Un-Compacted (experimental)	0.0425 W/mK
Lumira®	Un-Compacted at 65 kg/m^3	0.0230 W/mK
Lumira®	Compacted at 85 kg/m^3	0.0180 W/mK

Table 7 – Thermal conductivity comparison between Cabot's P300 and Lumira aerogel granular

Since the benchmarking was done on commercialized IGUs, the use of optimal glass types and thickness as well coating/films would also create a better performing glazing unit. The tested AGUs were assembled with basic components to isolate the impact of the aerogel on both optical and thermal performance, but in doing so, puts them in a disadvantage in a benchmarking. The selection of the glass and coatings can have a sizable impact on the performance differences.

The selection of the spacer can also have an impact on the thermal performance of the AGU. Using a smaller size IGU for testing in HFM would have meant that the granules would be closer to the edge and more effected by the type of spacer especially if it highly conductive like aluminum. The edge-of-glazing is measured from the frame or divider is considered to be 63.5mm (2.5") so subtracting two edges from 300mm length of the tested AGUs leaves 173mm and with the sensor being 100mm in diameter, the edge condition should not be an issue. In addition to that, the chosen spacer for assembly was Super Spacer® which has a U-value of 0.2 W/m^{2}K well below that of the aerogel for the same thickness.

The maximum increase in CoG U-value for the tested units was 4% while aged double and tripled glazed, argon filled IGUs tested by Asphaug et al. (2016) had increase of 4% and 5% respectively (after 70 weeks of ageing). Given that the IGUs rely on the retention of the gas to maintain their thermal performance, a leak or seal failure could cause the gas to escape causing an increase of 23% and 35% in the U-value for double and triple glazed units while a similar incident for an AGU would have minimal impact.

5.2 Impact on Energy Consumption

The impact of deteriorating envelope components can be quite substantial over time and having high durability for a given product or material is crucial for long term performance. Based on the energy simulation carried out by (Asphaug, Jelle, Gullbrekken, & Uvsløkk, 2016) it is possible to get a sense of what the impact of decreased performance might mean over a span of 20 years. Two building typologies were investigated in the simulation, commercial and residential (single family house), both of which are the target audience for aerogel glazing. Both of the buildings were simulated in the Norwegian climate which is quite cold with significant heating demands.

The office building has a heated floor space of 3500m^2 (@ 20% WWR) and after accelerated ageing for period of 70 weeks which yielded a 4% decrease in the U-value, the building saw an increase of 64.8 MWh due to loss in gas concentration. Four percent is the highest difference that the accelerated testing of the P300 aerogel yielded, meaning that this type of increase could cost the building owners 10,000 CAD (converted from Norwegian Krone) over a span of 20 years or $500 yearly. For an operation of a commercial building, such small decrease in performance is not significant enough to warrant concern. Having said that, 4% decrease in U-value is the maximum for granular aerogel while for IGUs this essentially the minimum value and costs for the same office building can be $1375 and $2690 for 50% and 100% gas loss respectively.

For a single family dwelling with a floor space of 160m^2 (@ 20% WWR) the increase in energy consumption would be 1280 KWh in a span of 20 years by using the maximum of 4% increase in the U-value. This increase is roughly $210 which is insignificant for that length of time but this is assuming current prices and trends. For gas concentrations of 50% and 100% loss the extra cost for 20 years would be $585 ($30/year) and $1140 ($57) respectively which are still quite small amounts. As the weather becomes more severe with climate change and energy prices' continual rise, the difference would increase as well, but it would only start to really matter when there is a yearly difference of a few hundred dollars.

	Office	Single family detached house
Area and WWR	3600 m^2 @ 20% WWR	160 m^2 @ 20% WWR
Pristine (92% concentration)		
4% (85% concentration) increase in glazing U-value	64.8 MWh extra for a span of 20 years is 10,000 CAD ($500 yearly)	1280 kWh extra for a span of 20 years is 210 CAD ($10.5 yearly)
12% (50% concentration) increase in glazing U-value	173 MWh extra for a span of 20 years is 27,500 CAD ($1375 yearly)	3700 kWh extra for a span of 20 years is 585 CAD ($30 yearly)
23% (0% concentration) increase in glazing U-value	340 MWh extra for a span of 20 years is 55,000 CAD ($2750 yearly)	7200 kWh extra for a span of 20 years is 1140 CAD ($57 yearly)

Table 8 – Energy increase after 20 years due to increase in glazing U-value for office building and single family detached house (Asphaug, Jelle, Gullbrekken, & Uvsløkk, 2016)

5.3 Applications of Granular Aerogel Glazing in Buildings

Aerogel glazing, granular based specifically, has been incorporated into several buildings over the years but it was mostly done as an experiment or a novelty item as opposed from a pure superior performance point of view (i.e. superior optical and thermal performance) but it is slowly changing with designers taking advantage of its unique properties. The current market for granular aerogel glazing applications is primarily focused on daylighting and glare control especially in highly glazed facades. Skylights and north facing glazing orientations are the most suitable candidates due to reduced direct sunlight providing soft diffused light but also function very well in other orientations by reducing glare. Two of the more notable projects where granular aerogel was incorporated into the glazing system are Yale University's Sculpture Building (New Haven, Connecticut, USA) and the National Circus School (Montreal, Canada).

The sculpture building is a four story building with almost entirely glass façade that is composed from Kalwall® (curtain wall system) in combination with Cabot's Lumira® aerogel in a configuration. The interior height of the spaces is 4.27m with only mullions dividing the glass occupying the entire height. The entire lower section of the full height glazing is composed out of AGUs (aerogel glazing units) while the upper portion has a mixture of vision and aerogel IGUs. The combination of the granular aerogel in the curtain wall system is able to provide a RSI of 3.52 m^2K/W (U-value 0.28 W/m^2K) and functions as a replacement for the spandrel panels and privacy screens while providing ample daylight with reduced glare.

The circus school is a multi-story building that features a large atrium like space with large glazed areas to provide it with daylight. In this case, the glazing system is the combination of SOLERA® plus Cabot's Lumira® aerogel (25mm thickness) with an RSI of 0.88 m^2K/W (U-value 1.14 W/m^2K). This system was designed to provide diffused sunlight as well as eliminating hot spots and glare as well as having similar thermal performance as triple glazed (gas filled) system at a similar price point.

Another granular aerogel combination system which is getting traction is the use of Pilkington Profilit™ (glass channels) with Lumira® aerogel. The glass channels are already translucent in nature with potentially similar optical properties to that of the granular aerogel. Building 115 in Seattle (by Graham Baba Architects) is prime example of this system in use where a large glazed street facing façade is able to provide both daylight into the spaces while maintaining privacy.

A popular trend seems to emerge among the buildings that do incorporate granular aerogel that pertains to the type of glass which is being used for the enclosure. Although granular aerogel has good durability, it can suffer from discoloration over time. In order to combat that and provide appealing aesthetics regardless of the age of the assembly is use, several of the systems choose to use frosted or translucent glass. Using this methodology allows for the visual aesthetic to be maintained regardless of the condition of the aerogel inside the cavity.

Aside from the selection of the type of glass, the second and equally as important design choice is to have a combination of clear vision glass with the aerogel IGUs. Until monolithic glass with exception clarity and thermal performance becomes common place, alternating between the two types allows the designers to provide views (connection to the outdoors), control glare, improve daylighting and maintain thermal performance. Although granular aerogel is not fragile like monolithic aerogel, it might be good practice to keep the operable portions of the windows with the conventional glazing as opposed of aerogel to prevent premature deterioration. A good example of this practice is the Detroit School of Arts (Midtown Detroit, Michigan, USA).

The decision on the percent coverage or the scheme comes from the designers and can be done in a multitude of ways. For more traditional styles such as the New England style, the individual squares can be configured to be with aerogel while others are clear as was discussed by (Berardi, Development of Glazing Systems with Silica Aerogel, 2015a). For a more contemporary design, an execution such the sculpture building in Yale or Nobel Halls Student Residence & Activity Center at SUNY Stony Brook (New York, USA). Regardless, granular aerogel glazing is versatile and can be incorporated into a multitude of designs to fit the projects' needs.

6 CONCLUSIONS

Silica aerogel is still considered to be in its experimental/trial phase for building applications. Based on existing research, it is suggested that due to the extraordinary properties of silica aerogel it should be widely adopted for building applications. The majority of research to date has been focused on either the improvement of performance or synthesis cost reductions in predominately pristine condition. One of the prerequisites for a material or product to gain wide spread usage in the construction industry aside from raw performance, is the need for a proven track record i.e. good durability. Durability data, or how well the performance is maintained over a given time period can be a long process if done naturally, but by using accelerated ageing, the span of years can be condensed into a few months.

Fenestrations are generally considered the weakest points in the thermal envelope and glazing specifically has a dual function where it has to provide views/daylight and thermal resistance. Aerogel's unique properties with its translucent skeletal structure and low thermal conductivity could be the perfect combination to address both functions. Silica aerogel comes in two formats, monolithic and granular. Monolithic silica being superior in both optical and thermal performance and is the better choice for glazing applications, but it is also very brittle, difficult to manufacture and expensive making it difficult to obtain. As a consequence to this, granular aerogel was used in glazing units to test the optical and thermal performance before and after accelerated ageing in various climatic conditions.

Two sets of IGUs were built and filled with aerogel (Cabot P300 and Airglass), the smaller variety (10x10cm) were used for optical testing in the spectrophotometer (which supports a maximum size of 12x12cm), while the larger ones (30x30cm) were used for thermal testing in the heat flow meter. The larger units were aged in the oven (elevated temperatures) and temperature cycling machine (freeze thaw cycles) for 4 months (equivalent to 21 and 13.5 years respectively). The smaller units were aged in climatic chamber (UV, elevated temperature and high humidity) and humidity chambers for 3 and 2 months (equivalent to 74 and 13.5 years respectively).

The U-value for center of glass (CoG) showed a 1-4% increase after the accelerated ageing with one unit even showing a slight improvement (decrease). This is a very slight decrease indicating great durability on the thermal performance end. For a span of 20 years this type of performance drop would be equivalent to a few hundred dollars for single detached family house in Canada while a 3600m^2 office would have to several hundred dollars extra, neither of which are significant enough for that time span. The actual U-value of the units ranged from 1.5-1.8 (W/m^2K) (for both pristine and aged conditions) which is slightly higher than Cabot's own Lumira granular aerogel which has 1.38 W/m^2K.

The visible transmittance of all the units is quite low (>10%) which is due to the lack of an integrating sphere which could catch all the scattering caused by the granular aerogel. Generally granular aerogel, depending on the thickness and opacity, is expected to be in the range of 30-70%. After the accelerated ageing, the units in the climatic chamber saw a maximum of 5% decrease to the average visible transmittance while the units aged in the humidity chambers saw up to 111% decrease in transmittance indicating that moisture causing silica network breakage.

None the less, granular aerogel glazing, when manufactured commercially has been used successfully in many buildings to provide roughly equivalent thermal performance to more traditional double and triple glazed glazing. While on the optical end, granular aerogel fills a more niche role as a great material for large glazed facades where a combination of privacy, daylighting and glare control is needed, where it excels.

It is important to note that in both sets of ageing, shrinking of the aerogel inside of the IGUs was noticed which can be combated by proper compaction during the manufacturing process. Also, a slightly abnormal phenomena was noticed with the granules that were aged in the oven where they shrunk quite significantly, but after equalize in room temperature and shaking of the IGU, the aerogel returned to its original volume. Also, some discoloration of particles was noticed among several of the aged units for both types of aerogel (Cabot P300 and Airglass). Although the discoloration did not have much of an impact on thermal performance, but for optical performance it might be a more of factor especially when considering the entire panel and not just the center which where the spectrophotometer measures. It is common practice to use frosted or translucent glass in combination with granular aerogel which maintains the aesthetic quality of the assembly even if some discoloration maybe occur over the lifespan of the building.

Overall granular aerogel demonstrated to have great durability and a relatively long time would be needed to observe the changes described in natural outdoor conditions. A few things can be done to guarantee the long term performance of a granular aerogel glazing. Controlling moisture penetration into the IGU would be critical and can be done through a combination of factors such as tightness of assembly and use of desiccant. When the assembly is designed with the precautions to moisture, the reduction in performance would be even smaller and the energy performance of the building can be maintained for a long service life. The granular aerogel can even be combined with various low-E coatings, and gas fills to further increase performance making it an attractive material for future research and investigations.

7 RECOMMENDATIONS AND FUTURE WORK

Granular aerogel has a lot of potential for both opaque and transparent applications for the building industry. A lot of the research that been already completed is focused mostly on the pristine performance of granular aerogel IGUs. Studying the performance of the aged AGUs would prove very valuable to help understand which ageing mechanism or combination of mechanisms and in which configuration is the most harmful for the long term performance. This would help guide the synthesis, assembly and product selection to be optimized for both pristine and long term performance of the granular aerogel glazing.

The number of identical samples should be increased to at least three to provide more comprehensive results where the probability of abnormalities is reduced. Asphaug et al. (2015) used 3 identical units for each variation of the experiment which helped increase the statistical significance of the results. The importance of a bigger sample pool size i.e. statistical significance, is to prove that he selected sample is indeed representative of the whole population and that the resulting measurements are not due to abnormalities or sampling error.

For thermal conductance measurements the increased samples to 3 per single variation would be sufficient to reach the significance level. Since an apparatus such as the flow meter does multiple measurements across multiple temperatures which could take up to 12 hours for 8 set points, repeating the measurement after flipping the IGU would provide little value since the cross section of the glass and granules through which the heat moves would still be the same. For visible transmittance measurements, changing the orientation could have an effect on the measurements since the tested cross section is small. Each test in the spectrophotometer is quite short (5-10min long for 200-2000nm) so it can be repeated multiple times for each sample by changing the orientation of the sample. The optical measurements could be the average of 5 measurements per units as was done by Asphaug et al. (2015).

The effects of accelerated ageing on various compaction level, aerogel granules type and size would be useful research area. Since there is an optimal compaction level as mentioned by Neugebaur et al. (2014) for pristine thermal performance, there should be an optimal compaction level for AGUs with taking into account aged performance. This can be repeated for various granules sizes since each size category could have a different requirement. The type of aerogel granules, excluding size differences, can be also studied to see how much of a difference there is between something like Cabot's P300 particles that are officially not marketed for glazing vs. Lumira particles are that meant for glazing applications. The emphasis of a study like that would be the comparison in pristine, aged, thermal and optical performance but with emphasis in terms of cost and ease of manufacturing to see if there indeed any real differences or is it just marketing propaganda.

The shrinking of the aerogel volume in the cavity that was observed for most of the units was consistent with the results by Gao et al. (2014), but unit 9 which showed very significant shrinking was able to regain some its volume after cooling down and shaking of the IGU. The temporary shrinking of the aerogel volume due to constant high temperature is a research topic for material sciences either from civil engineering or chemistry fields since it would involve deep understanding and studying of the properties on a molecular level and would be outside of the knowledge base for building science.

The second aspect of aerogel granular shrinking is also an opportunity for research but it split into two portions. The first type of research is on which mechanisms create what size of gap in the aerogel. This would include a combination between granular type, thickness and compaction and how each one of those is affected by various ageing mechanisms, i.e. how quickly and how big of they create. This research would also quantify the reduction in thermal performance for the IGUs due to the created gap size. The second type of research would deal with material sciences for the optimization of synthesis of the granular aerogel but also the assembly itself. This would help establish guidelines as to how eliminate the air gap either through better assembly or creating a better aerogel granular. Having an air gap in the aerogel fill reduces the thermal performance significantly since the air would be 3.5 more conductive than the aerogel fill.

This research was focused on the aged performance of the aerogel with a very basic assembly. Another research topic that could be of value is how the granular aerogel ages when combined with different types of glass and coatings. This would allow to see the changes to optical and thermal performance of the AGUs but also will allow to see if there are issues or potential benefits to combining aerogel with coatings/films and various glass types. Maybe there would be less discoloration of the particles or damage to the coating due to contact with aerogel particles.

At their current state, at double glazed glazing thicknesses, AGUs have roughly equivalent thermal performance to double glazed IGUs with argon and coatings. The annual energy savings for buildings would be quite small and not significant enough to study more than already existing research. On the other hand, daylighting simulation for glare control, could be quite useful to see if and by how much a given space can be improved by incorporating various configuration of AGUs in the façade. This would provide information as to the feasibility for existing buildings to upgrade their windows and potentially include a mix of IGUs and AGUs.

APPENDICES

APPENDIX A – General

Cabot P300 Aerogel

CABOT

DATA SHEET

Particles

P100, 200, 300

The superior properties of high performance Cabot aerogel particles make it the obvious choice for a variety of applications. Benefits in end-use applications include:

- Hydrophobic/water repellant
- UV stability
- Sound absorption
- Thermal insulation
- High light transmission
- Lightweight
- Non-combustible
- Inert

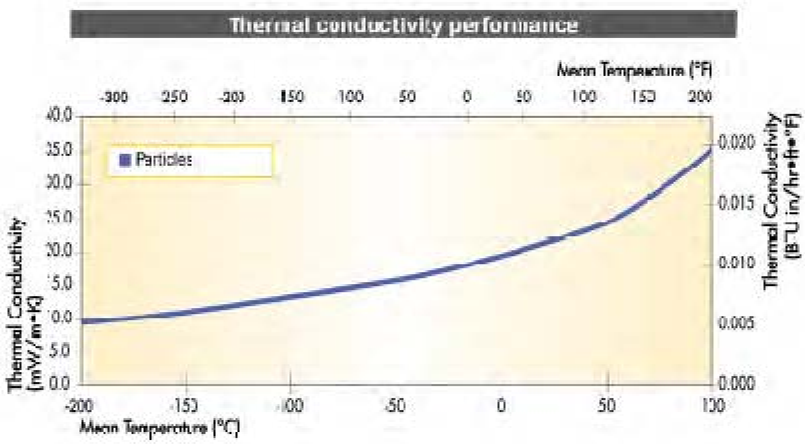
Cabot aerogel is safe for human and ecological systems, and is manufactured with little to no impact on the environment. It holds Silver Cradle to Cradle certification from McDonough Braungart Design Chemistry. This stringent independent certification process examines a product's manufacturing characteristics and ecological impact, aiming to eliminate waste entirely and create a healthy and sustainable society. Cabot certifies it has completed the EU REACH pre-registrations required for all Cabot aerogel products.

Product features

	P100	P200	P300
Particle size range	0.01 - 4.0mm	0.01 - 1.2mm	1.2 - 4.0mm
Pore diameter	~20nm	~20nm	~20nm
Porosity	>90%	>90%	>90%
Particle density	120 - 150kg/m³	120 - 180kg/ m³	20 - 180kg/m³
Bulk density	80 - 100kg/m³	75 - 95kg/m³	65 - 85kg/m³
Surface chemistry	hydrophobic	hydrophobic	hydrophobic
Surface area	600 - 800m²/g	600 - 800m²/g	600 - 800m²/g
CAS RN	102262-30-6	102262-30-6	102262-30-6
Oil absorption	540 - 650g DBP/100g particle		

Particles

P100 200, 300



For mean temperatures outside ranges shown, please contact Cabot Aerogel for more information, as performance varies based on material grade and specific application.

CABOT

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Cabot China Ltd.
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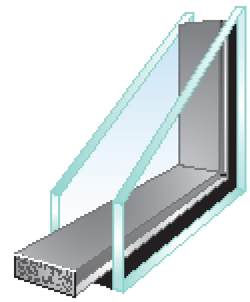
Spacer

Edgetech Super Spacer® Premium Plus Traditional

Technical Specification

Super Spacer® Premium Plus is a flexible, silicone foam spacer that provides the maximum in perimeter insulation for sealed glazing units. Desiccant-filled with pre-applied side adhesive, the structural foam product significantly simplifies insulating glass (IG) production.

Featuring a vapor barrier backing, the spacer must be used in combination with conventional IG sealants. For a list of verified sealants, please reference IG sealants Technical Bulletin RD0018, which is available on our website at www.superspacer.com in the technical section.



Characteristics	Norm	Specification / Typical Value
Composition:	—	Silicone foam base with desiccant pre-fill
Performance Characteristics: Thermal conductivity Colors Gas / Moisture vapor barrier Primary structural seal	 ASTM C 518 — ASTM F 1249 ASTM D 3985	 0.159 W/m°K Grey, Black, Aluminum, Almond, White, Blue White WVTR < 0.020 gm/m^2/day Oxygen < 0.009 cc/m^2/day Acrylic adhesive
Desiccant fill, 3A molecular-sieve	—	47% minimum by weight
Intermittent temperature range	—	-40°C to 121°C / -40°F to 250°F
Verified secondary sealants	—	Reference IG sealants Technical Bulletin RD0018
Fogging	ASTM E 2190 EN 1279 - 6 CAN/CGSB 12.8	No fog in visual area - Pass No fog in visual area - Pass No fog in visual area - Pass
Gas Retention	EN 1279 - 3	Pass*
I.G. Durability	ASTM E 2190 EN 1279 - 2	Pass Pass*

*with hot-melt butyl or curative butyl

Edgetech Super Spacer® Premium Plus Traditional

Technical Specification

Product Features

Warm Edge Benefits
Superior silicone foam insulation; low thermal conductivity; substantially reduced perimeter condensation; typical overall 0.2 W/m^2K (0.04 $BTU/h\text{-}ft^2\text{-}°F$) U-value window improvement (vs. aluminum spacer).

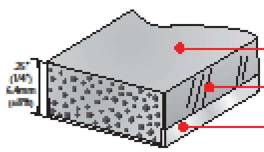
Silicone Foam Features
Excellent UV resistance; extreme temperature performance; fast dew-point drop; superior compression-set resistance; excellent color stability; enhanced sound dampening.

Edge-Seal Durability
Continuous vapor barrier at corners; no chemical fogging; very high desiccant content; proven edge-seal technology.

Unique Dual-Seal Design
Outer hot-melt butyl sealant for enhanced gas retention; inner structural acrylic adhesive seal; immediate unit handling; no cold flow or spacer/seal migration problems.

Improved Productivity
Fast application; elimination of desiccant filling; no corner key assembly; simplified production of shaped units; limited equipment investment; high-volume production with small labor force.

Pleasing Aesthetic Appearance
Warm grey color; additional color options; smooth matte surface finish; no surface blistering or bubbling; straight-line application with sharp 90° corners.



Protective Packaging
To provide desiccant protection, the rolls are sealed in moisture-proof foil bags. The rolls are then shipped in recyclable cardboard boxes.

SPEC DATA SHEET

SEALANTS

877 SUPER SPACER SEALANT

PRODUCT NAME
CRL 877 Super Spacer Sealant
One-Component Polyurethane Adhesive/Sealant

PRODUCT DESCRIPTION
CRL 877 Super Spacer Sealant is a one-component, fast cure, low solvent, permanently flexible polyurethane adhesive/sealant. CRL 877 Super Spacer Sealant cures in the presence of atmospheric moisture to provide a permanently elastic bond to fasten materials which have dissimilar coefficients of expansion. It is ideal for the fabrication of quality single-seal insulating glass units as well as for general purpose sealing application.

BASIC USES
CRL 877 Super Spacer Sealant is especially designed for the fabrication of quality single-seal insulating glass units. The special low-solvent formulation is made to be compatible with Super Spacer's adsorbent, and does not require a polyisobutylene primary seal. CRL 877 Super Spacer Sealant may also be used to fabricate I.G. units made with adsorbent fill aluminum spacers.
CRL 877 Super Spacer Sealant is also used in the fabrication and repair of trailers, trucks, buses, trains, RV utility bodies, van conversions and specialty vehicles. Applications include: vehicle bodies and cab construction including panels, underbody components, roofing, front and rear spoilers, auto trim, moldings, body seams and welding joints; waterproof lap seams and molding in truck trailers, RV's and auto body repair. Construction applications for new or repair of joints on such materials as pre-painted metals plywood, glass, aluminum, steel, and many plastics and composites.

LIMITATIONS
CRL 877 Super Spacer Sealant should not be used in the following applicaitons:

- Assembly of I.G. units when the temperature is under 40°F (5°C) and the humidity is less than 40%.
- Frozen surfaces or through standing water..
- Over silicones or in the presence of curing silicones.
- In contact with alcohol and solvents during cure.

7 SEALANTS 877 Super Spacer

JANUARY 2003

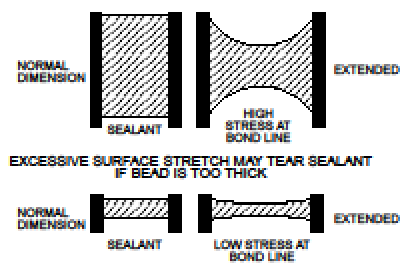
TECHNICAL DATA
The physical properties of CRL 877 Super Spacer are shown in Table 1.

TABLE 1 - PHYSICAL PROPERTIES

Property/Test Methods	Value
Tack Free Time 77°F (25°C), 50% RH	45 to 60 minutes
Curing Time 77°F (25°C), 50% RH.	3/16 inch per 24 hours
Durometer Hardness, Shore A (ASTM D-2240)	45-50
Ultimate Tensile Strength (ASTM D-412)	350 psi
Elongation at Ultimate Break, (ASTM D-412)	700%
Sag or Slump (ASTM C-639)	Nil
Application Temperature	40°F (4°C) to 110°F (43°C)
Service Temperature	-40°F (-40°C) to 200°F (93°C)

PRINCIPLES OF JOINT DESIGN
Figure 1 illustrates why a thin bead of polyurethane sealant will accommodate more movement than a thick bead. Obviously, the thin bead is the most desirable.

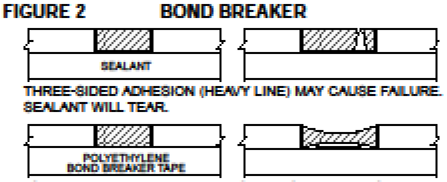
FIGURE 1 SURFACE OF BEAD



SURFACE STRETCH IS NOT EXCESSIVE IF A THIN BEAD IS USED
NOTE: WITH SILICONE SEALANTS MORE IS NOT USUALLY BETTER!

Figure 2 illustrates why polyurethane sealants need bond breaker tape to prevent undesirable three-sided adhesion.

FIGURE 2 BOND BREAKER



USE OF A BOND BREAKER GIVES TWO-SIDED ADHESION AND ALLOWS SEALANT TO STRETCH FREELY WITH JOINT.

JANUARY 2003

7 SEALANTS 877 Super Spacer

AVD3785-1/03

C.R. LAURENCE CO., INC. • CORPORATE HEADQUARTERS: POST OFFICE BOX 58923, LOS ANGELES, CA 90058-0923
TOLL FREE TELEPHONE (800) 421-6144 • TOLL FREE FAX (800) 262-3299
E-MAIL: CRL@CRLAURENCE.COM WEBSITE: www.crlaurence.com

LIMITED WARRANTY NOTICE

CRL and its manufacturer warrant our products to be of good quality and will replace or, at our election, refund the purchase price of any products proved defective. Satisfactory results depend not only upon quality products but also upon many factors beyond our control in the application process. Therefore, except for such replacement or refund CRL and its manufacturers make no warranty or guarantee, expressed or implied, including warranties of fitness or merchantability, respecting its products. CRL and its manufacturers shall have no other liability with respect thereto. User shall determine the suitability of the product for his intended use and assume all risks and liability in connection therewith. Any authorized change in the printed recommendations concerning the use of our products must bear the signature of the CRL Product Manager.

COOPERATIVE TESTING

Materials submitted for testing should be sent to:

C.R. Laurence Co., Inc.
Technical Sales Department
PO Box 58923
Los Angeles, CA 90058-0923

This program is intended to eliminate potential field problems by pretesting CRL construction sealants with samples of the building materials on which the sealant will be applied. The test will aid in determining the proper surface preparation method, effective solvents for cleaning and whether priming is necessary to achieve optimum adhesion. Following this procedure will remove many of the unknown variables which affect field success.

Test samples of substrates should be identified as to manufacturer, origin, designed use, building project, person and firm originating the request. Appropriate sketches or drawings showing the intended use can be helpful.

C.R. LAURENCE CO., INC. LOCATIONS

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APPENDIX B – Thermal result tables and graphs

Test 1

Sample 3 Test 1 - No aging 30x30 cm Clear IGU								
Number	Temperature (Mean) °C	Temperature (Delta) °C	Thermal Conductivity (W/m*K)	Thermal Conductance	Thermal Resistance (m^2*K/W)	Temperature Gradient (°K/m)	Test Time	
							(Hours)	(Minutes)
1	-10.84	20.36	0.102652	4.234633	0.236148	839.74	2	10
2	0.91	19.96	0.116421	4.787117	0.208894	820.59	1	49
3	11.32	19.92	0.126528	5.175314	0.193225	814.61	1	19
4	21.34	19.94	0.137375	5.575224	0.179365	809.18	1	15
5	24.93	19.88	0.141868	5.740232	0.174209	804.33	1	0
6	30.59	19.17	0.148904	5.993371	0.166851	793.51	1	2
7	40.15	19.45	0.160232	6.383291	0.156659	775.01	1	13
8	49.73	19.22	0.172451	6.771948	0.147668	754.91	1	12
					total test time:	**11**	9	2

Sample 4 (control) Test 1 - No aging 30x30 cm Cabot Aerogel P300 (not fully filled)								
Number	Temperature (Mean) °C	Temperature (Delta) °C	Thermal Conductivity (W/m*K)	Thermal Conductance	Thermal Resistance (m^2*K/W)	Temperature Gradient (°K/m)	Test Time	
							(Hours)	(Minutes)
1	-11.73	20.43	0.035619	1.459545	0.685145	836.97	2	10
2	0.30	19.81	0.038577	1.574868	0.634974	808.68	1	33
3	9.19	19.61	0.040877	1.659404	0.602626	796.02	1	6
4	20.52	19.92	0.043469	1.746954	0.572425	800.45	1	7
5	24.49	19.85	0.044001	1.760802	0.567923	794.27	0	49
6	30.22	19.71	0.045849	1.822051	0.548832	783.44	1	0
7	39.82	19.53	0.049440	1.940086	0.515441	766.22	1	17
8	49.41	19.33	0.052583	2.084371	0.479761	766.25	1	18
					total test time:	**10.33333333**	8	2.3333333

Sample 9 Test 1 - No aging 30x30 cm Cabot Aerogel P300 (too much aerogel)								
Number	Temperature (Mean) °C	Temperature (Delta) °C	Thermal Conductivity (W/m*K)	Thermal Conductance	Thermal Resistance (m^2*K/W)	Temperature Gradient (°K/m)	Test Time	
							(Hours)	(Minutes)
1	-10.90	20.36	0.033957	1.399206	0.714691	838.95	2	7
2	0.84	19.82	0.036464	1.498392	0.667382	814.36	1	42
3	9.77	19.66	0.038458	1.572233	0.636038	803.53	1	13
4	19.18	19.51	0.040775	1.654484	0.604418	791.61	1	26
5	22.91	19.45	0.041672	1.684503	0.593647	786.05	1	2
6	30.63	19.90	0.043989	1.760591	0.567991	796.35	1	29
7	40.18	19.69	0.047107	1.855143	0.539042	775.47	1	19
8	49.79	19.51	0.050657	1.950827	0.512603	751.15	1	22
					total test time:	**11.66666667**	9	2.6666667

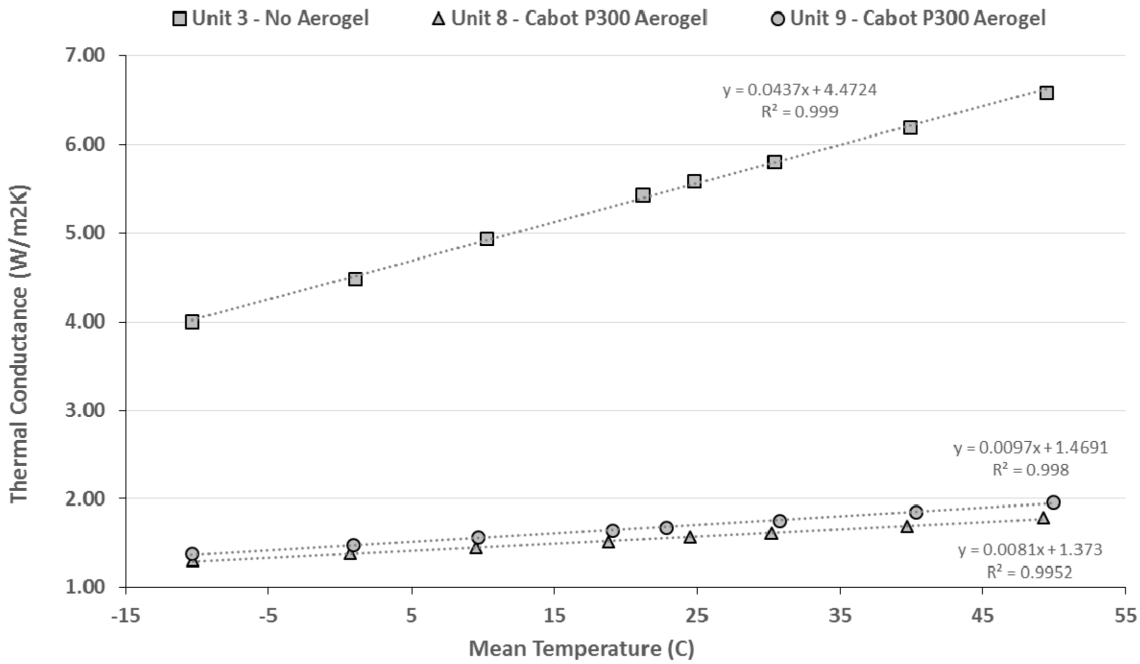
Sample 8 Test 1 - No aging 30x30 cm Cabot Aerogel P300 (Perfect Fill)								
Number	Temperature (Mean) °C	Temperature (Delta) °C	Thermal Conductivity (W/m*K)	Thermal Conductance	Thermal Resistance (m^2*K/W)	Temperature Gradient (°K/m)	Test Time	
							(Hours)	(Minutes)
1	-10.43	20.28	0.031951	1.289637	0.775412	818.65	1	58
2	0.76	19.84	0.034223	1.379963	0.724657	800.17	1	29
3	9.76	19.66	0.036226	1.454431	0.687554	789.28	1	17
4	19.17	19.54	0.038220	1.522693	0.656731	778.61	1	32
5	22.92	19.46	0.039161	1.554313	0.643371	772.51	1	6
6	30.62	19.90	0.040985	1.612128	0.620298	782.76	1	17
7	40.22	19.69	0.044000	1.707554	0.585633	764.15	1	14
8	49.78	19.52	0.047377	1.802367	0.554826	742.61	1	14
					total test time:	**11.11666667**	8	3.1166667

Test 2

Sample 3 Test 2 - 1 month 30x30 cm Clear IGU								
Number	Temperature (Mean) °C	Temperature (Delta) °C	Thermal Conductivity (W/m*K)	Thermal Conductance	Thermal Resistance (m^2*K/W)	Temperature Gradient (°K/m)	Test Time	
							(Hours)	(Minutes)
1	-10.36	20.33	0.097685	3.999008	0.250062	832.46	2	8
2	1.03	19.96	0.110001	4.489761	0.222729	814.67	1	38
3	10.27	20.03	0.121423	4.937296	0.202540	814.48	1	43
4	21.20	19.94	0.134671	5.437590	0.183905	805.26	1	23
5	24.79	19.88	0.138709	5.583847	0.179088	800.27	1	57
6	30.40	19.76	0.145244	5.813278	0.172020	791.07	1	2
7	39.86	19.55	0.156599	6.198283	0.161335	773.75	1	11
8	49.42	19.34	0.168882	6.594784	0.151635	755.10	1	15
					total test time:	**12.28333333**	9	3.2833333

Sample 9 Test 2 - 1 month 30x30 cm Cabot Aerogel P300 (too much aerogel)								
Number	Temperature (Mean) °C	Temperature (Delta) °C	Thermal Conductivity (W/m*K)	Thermal Conductance	Thermal Resistance (m^2*K/W)	Temperature Gradient (°K/m)	Test Time	
							(Hours)	(Minutes)
1	-10.40	20.25	0.034137	1.378063	0.725656	817.32	2	16
2	0.87	19.81	0.036711	1.476989	0.677053	797.17	1	39
3	9.65	19.61	0.039106	1.565450	0.638794	784.99	1	12
4	19.06	19.50	0.041495	1.645300	0.607792	773.24	1	16
5	22.82	19.42	0.042596	1.681413	0.594738	766.60	1	0
6	30.70	19.89	0.045012	1.758378	0.568706	777.15	1	22
7	40.31	19.70	0.048284	1.859165	0.537876	758.53	1	25
8	49.91	19.52	0.051899	1.967501	0.508259	740.10	1	21
					total test time:	**11.51666667**	9	2.5166667

Sample 8 Test 2 - 1 month 30x30 cm Cabot Aerogel P300 (Perfect Fill)								
Number	Temperature (Mean) °C	Temperature (Delta) °C	Thermal Conductivity (W/m*K)	Thermal Conductance	Thermal Resistance (m^2*K/W)	Temperature Gradient (°K/m)	Test Time	
							(Hours)	(Minutes)
1	-10.31	20.3	0.032062	1.302731	0.767618	824.79	2	15
2	0.7	19.85	0.034051	1.378082	0.725646	803.37	1	40
3	9.49	19.67	0.036016	1.448950	0.690155	791.26	1	19
4	18.8	19.56	0.037994	1.515857	0.659693	780.30	1	7
5	24.52	19.91	0.039513	1.565663	0.638707	788.93	1	18
6	30.17	19.79	0.040875	1.607611	0.622041	778.42	1	5
7	39.66	19.6	0.043647	1.692179	0.590954	759.88	1	7
8	49.24	19.42	0.047143	1.794102	0.557382	738.92	1	11
					total test time:	**11.03333333**	9	2.0333333

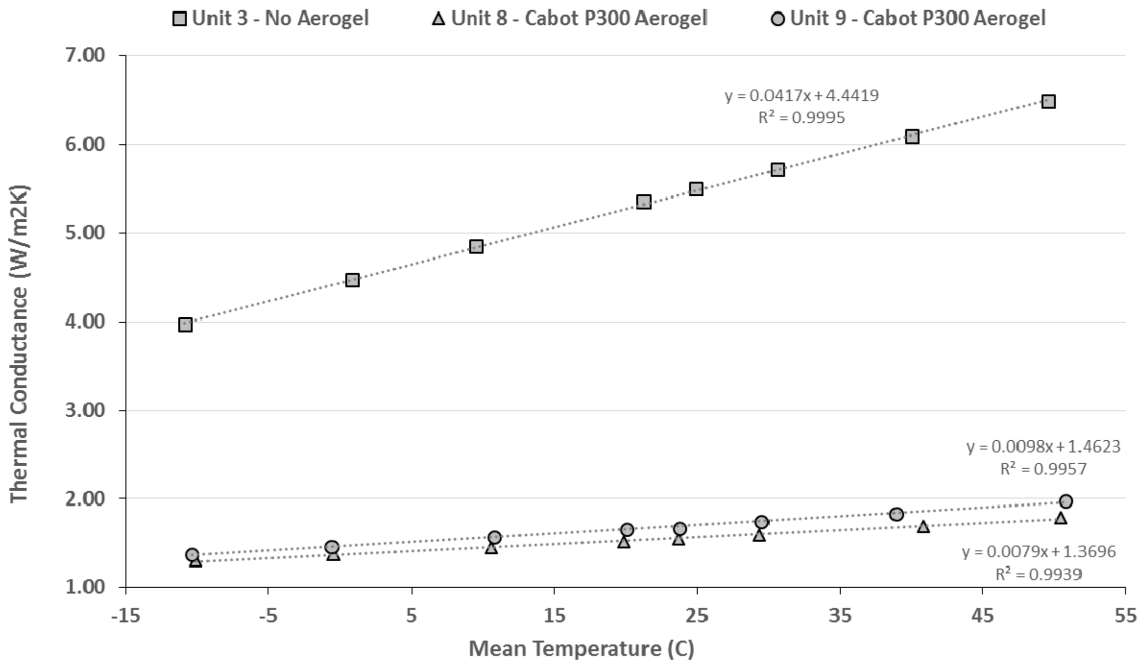


Test 3

Sample 3 Test 3 - 2 month 30x30 cm Clear IGU							
Number	**Temperature (Mean) °C**	**Temperature (Delta) °C**	**Thermal Conductivity (W/m*K)**	**Thermal Conductance**	**Thermal Resistance (m^2*K/W)**	**Temperature Gradient (°K/m)**	**Test Time**	
							(Hours)	**(Minutes)**
1	-10.86	20.49	0.097664	3.967372	0.252056	832.39	2	10
2	0.85	20.00	0.110438	4.471252	0.223651	809.61	1	46
3	9.47	20.09	0.120352	4.844562	0.206417	808.67	2	0
4	21.27	19.92	0.134435	5.357392	0.186658	793.96	1	25
5	24.90	19.86	0.138565	5.502245	0.181744	788.74	0	57
6	30.57	19.75	0.145100	5.723378	0.174722	778.99	1	3
7	40.03	19.53	0.156479	6.095703	0.164050	760.99	1	12
8	49.58	19.31	0.168852	6.490514	0.154071	742.41	1	13
					total test time:	**11.76666667**	9	2.7666667

Sample 9 Test 3 - 2 month 30x30 cm Cabot Aerogel P300 (too much aerogel)								
Number	Temperature (Mean) °C	Temperature (Delta) °C	Thermal Conductivity (W/m*K)	Thermal Conductance	Thermal Resistance (m^2*K/W)	Temperature Gradient (°K/m)	Test Time (Hours)	(Minutes)
1	-10.35	**10.13**	0.034009	1.373840	0.727887	409.02	2	27
2	-0.61	19.86	0.036154	1.456677	0.686494	800.28	1	19
3	10.82	19.90	0.039250	1.570411	0.636776	796.22	1	38
4	20.11	19.76	0.041774	1.655615	0.604005	782.95	1	16
5	23.80	19.68	0.042544	1.671598	0.598230	776.55	0	53
6	29.50	19.58	0.044555	1.744507	0.573228	766.58	1	2
7	38.96	19.39	0.047601	1.838678	0.543869	749.13	1	9
8	50.83	19.89	0.052244	1.979046	0.505294	753.60	1	31
					total test time:	**11.25**	8	3.25

Sample 8 Test 3 - 2 month 30x30 cm Cabot Aerogel P300 (Perfect Fill)								
Number	Temperature (Mean) °C	Temperature (Delta) °C	Thermal Conductivity (W/m*K)	Thermal Conductance	Thermal Resistance (m^2*K/W)	Temperature Gradient (°K/m)	Test Time (Hours)	(Minutes)
1	-10.08	**10.31**	0.032238	1.302618	0.767685	409.18	2	36
2	-0.45	19.93	0.034047	1.371161	0.729309	802.58	1	4
3	10.62	19.91	0.036332	1.451528	0.688929	795.40	1	27
4	19.9	19.8	0.038391	1.516912	0.659234	782.16	1	9
5	23.7	19.71	0.03932	1.545218	0.647158	774.75	0	57
6	29.35	19.61	0.040748	1.588020	0.629715	764.18	0	58
7	40.86	19.9	0.044303	1.694100	0.590284	760.97	1	27
8	50.47	19.72	0.047821	1.790825	0.558402	738.50	1	19
					total test time:	**10.95**	7	3.95

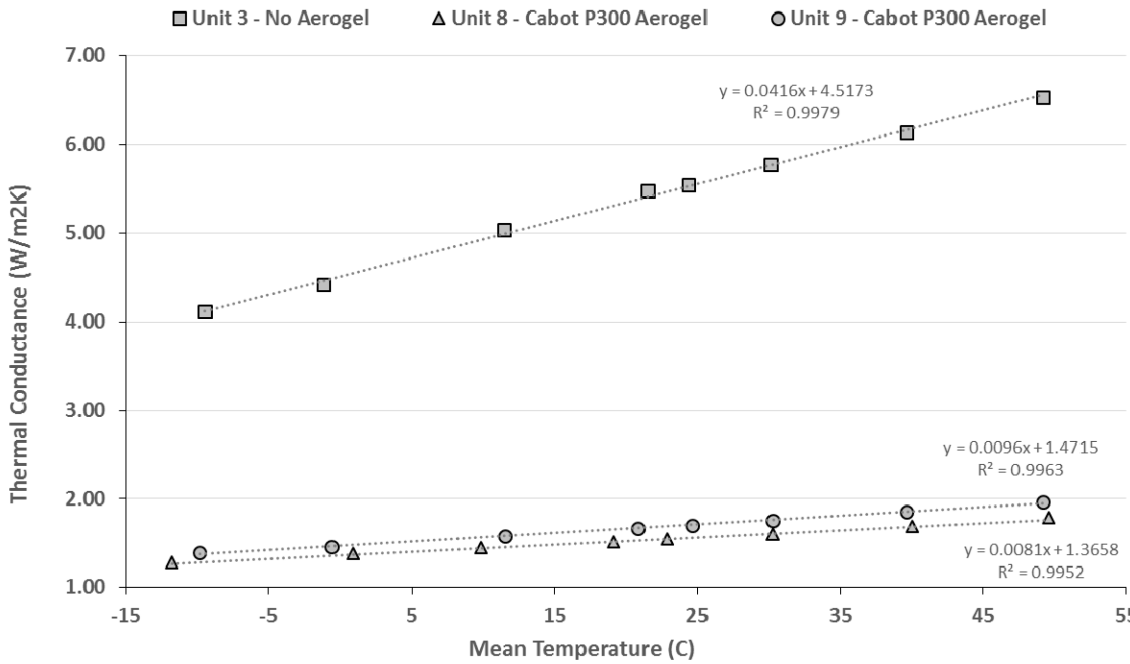


Test 4

Sample 3 Test 4 - 3 month 30x30 cm Clear IGU								
Number	Temperature (Mean) °C	Temperature (Delta) °C	Thermal Conductivity (W/m*K)	Thermal Conductance	Thermal Resistance (m^2*K/W)	Temperature Gradient (°K/m)	Test Time (Hours)	(Minutes)
1	-9.48	10.10	0.100860	4.108632	0.243390	411.30	1	35
2	-1.13	19.43	0.108556	4.417546	0.226370	790.81	0	38
3	11.47	19.93	0.124719	5.037428	0.198514	804.80	1	15
4	21.54	19.92	0.136803	5.472525	0.182731	796.88	1	7
5	24.41	19.91	0.139059	5.546619	0.180290	794.22	0	25
6	30.15	19.77	0.145931	5.780180	0.173005	783.13	0	36
7	39.58	19.56	0.156849	6.137643	0.162929	765.36	0	43
8	49.15	19.33	0.169197	6.532489	0.153081	746.14	0	44
					total test time:	**7.05**	3	4.05

Sample 9 Test 4 - 3 month 30x30 cm Cabot Aerogel P300 (too much aerogel)								
Number	**Temperature (Mean) °C**	**Temperature (Delta) °C**	**Thermal Conductivity (W/m*K)**	**Thermal Conductance**	**Thermal Resistance (m^2*K/W)**	**Temperature Gradient (°K/m)**	**Test Time**	
							(Hours)	**(Minutes)**
1	-9.83	**10.18**	0.034482	1.397653	0.715485	408.45	2	6
2	-0.63	19.89	0.035961	1.453829	0.687839	804.10	0	48
3	11.54	19.85	0.039257	1.576730	0.634224	797.23	1	5
4	20.80	19.70	0.041836	1.665246	0.600512	784.23	0	47
5	24.67	9.63	0.042983	1.703459	0.587041	777.88	0	38
6	30.26	19.52	0.044736	1.759715	0.568274	767.64	0	42
7	39.58	19.33	0.047628	1.849803	0.540598	750.77	0	45
8	49.19	19.15	0.051271	1.961319	0.509861	732.43	0	47
					total test time:	**7.633333333**	3	4.6333333

Sample 8 Test 4 - 3 month 30x30 cm Cabot Aerogel P300 (Perfect Fill)								
Number	**Temperature (Mean) °C**	**Temperature (Delta) °C**	**Thermal Conductivity (W/m*K)**	**Thermal Conductance**	**Thermal Resistance (m^2*K/W)**	**Temperature Gradient (°K/m)**	**Test Time**	
							(Hours)	**(Minutes)**
1	-11.78	**9.96**	0.031384	1.277397	0.782842	405.59	2	19
2	0.88	19.87	0.034165	1.382642	0.723253	804.02	1	35
3	9.81	19.68	0.035918	1.443424	0.692797	790.92	1	17
4	19.13	19.53	0.03794	1.509115	0.662640	777.04	1	27
5	22.88	19.47	0.038968	1.543060	0.648063	770.93	1	12
6	30.26	19.93	0.040754	1.596605	0.626329	780.65	1	6
7	40.01	19.72	0.043844	1.687240	0.592684	758.92	1	22
8	49.55	19.54	0.047303	1.785663	0.560016	737.65	1	14
					total test time:	**11.53333333**	9	2.5333333



Test 5

Sample 3 Test 5 - 4 months ageing 30x30 cm Clear IGU								
Number	**Temperature (Mean) °C**	**Temperature (Delta) °C**	**Thermal Conductivity (W/m*K)**	**Thermal Conductance**	**Thermal Resistance (m^2*K/W)**	**Temperature Gradient (°K/m)**	**Test Time**	
							(Hours)	**(Minutes)**
1	-10.29	10.08	0.097450	3.974563	0.251600	411.05	1	28
2	1.62	19.99	0.115755	4.700485	0.212744	811.69	0	54
3	9.02	20.03	0.122108	4.939320	0.202457	810.4	0	26
4	20.78	19.97	0.140032	5.590184	0.178885	797.22	0	43
5	23.46	20.03	0.136857	5.452652	0.183397	798.08	0	25
6	31.13	19.96	0.150274	5.924346	0.168795	786.93	0	44
7	39.99	19.97	0.151585	5.924346	0.168795	779.47	0	21
8	50.78	19.97	0.177169	6.794124	0.147186	765.78	0	46
					total test time:	**5.783333333**	1	4.7833333

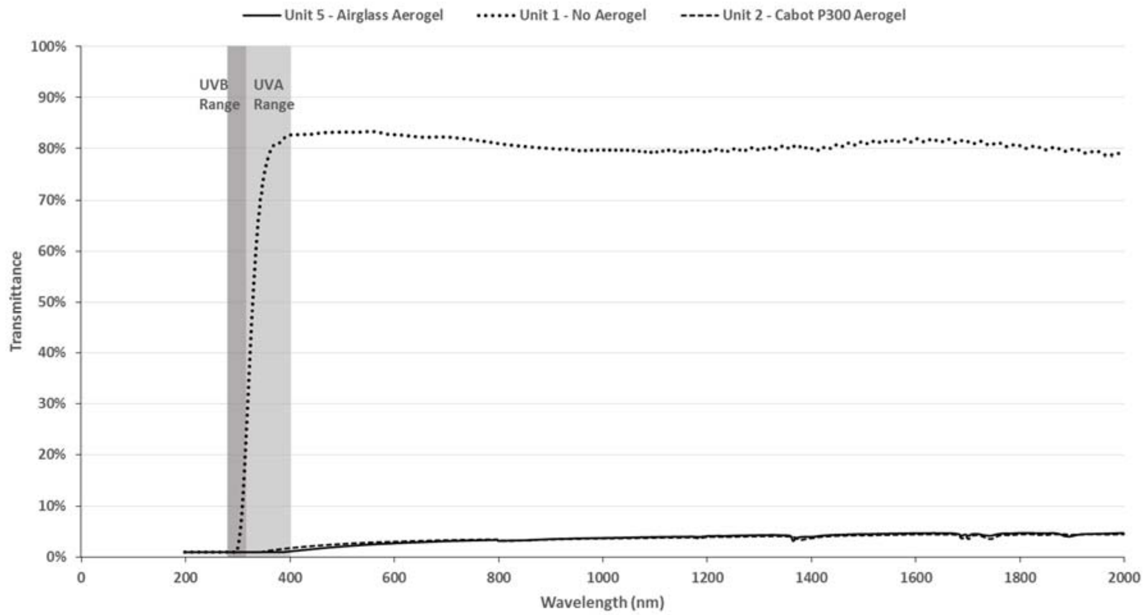
Sample 4 (control) Test 2 - No ageing 30x30 cm Cabot Aerogel P300 (not fully filled)								
Number	Temperature (Mean) °C	Temperature (Delta) °C	Thermal Conductivity (W/m*K)	Thermal Conductance	Thermal Resistance (m^2*K/W)	Temperature Gradient (°K/m)	Test Time	
							(Hours)	(Minutes)
1	-10.14	9.95	0.035205	1.461542	0.684209	413.26	2	2
2	-0.24	19.64	0.038157	1.580795	0.632593	813.75	0	44
3	11.23	19.98	0.042197	1.741232	0.574306	824.54	1	6
4	21.46	19.95	0.044969	1.844838	0.542053	818.42	1	8
5	24.20	19.90	0.044815	1.835418	0.544835	814.87	0	24
6	30.00	19.84	0.046981	1.914872	0.522228	808.78	0	34
7	40.85	19.99	0.052177	2.104103	0.475262	805.97	1	4
8	51.89	19.97	0.055228	2.198309	0.454895	794.70	1	5
					total test time:	**8.116666667**	6	2.1166667

Sample 9 Test 5 - 4 months ageing 30x30 cm Cabot Aerogel P300 (too much aerogel)								
Number	Temperature (Mean) °C	Temperature (Delta) °C	Thermal Conductivity (W/m*K)	Thermal Conductance	Thermal Resistance (m^2*K/W)	Temperature Gradient (°K/m)	Test Time	
							(Hours)	(Minutes)
1	-10.03	9.93	0.033434	1.357121	0.736854	402.97	2	10
2	-0.16	19.63	0.036656	1.482802	0.674399	794.08	0	42
3	11.88	19.96	0.040928	1.642314	0.608897	800.86	1	8
4	21.78	19.92	0.043230	1.715657	0.582867	790.52	1	3
5	24.64	19.91	0.043489	1.720910	0.581088	787.86	0	24
6	30.43	19.78	0.044919	1.763354	0.567101	776.67	0	35
7	41.96	19.80	0.047666	1.841166	0.543134	764.72	0	37
8	51.25	19.99	0.053272	2.024197	0.494023	759.46	1	2
					total test time:	**7.683333333**	5	2.6833333

Sample 8 Test 5 - 4 months ageing 30x30 cm Cabot Aerogel P300 (Perfect Fill)								
Number	Temperature (Mean) °C	Temperature (Delta) °C	Thermal Conductivity (W/m*K)	Thermal Conductance	Thermal Resistance (m^2*K/W)	Temperature Gradient (°K/m)	Test Time	
							(Hours)	(Minutes)
1	-10.29	10.06	0.032042	1.300583	0.768886	408.54	2.000000	8
2	-0.95	19.87	0.033886	1.372247	0.728732	804.72	0.000000	49
3	10.71	19.91	0.036096	1.450495	0.689420	800.27	1.000000	41
4	19.96	19.78	0.038369	1.526436	0.655121	786.82	1.000000	22
5	23.67	19.71	0.039259	1.554456	0.643312	780.42	1.000000	3
6	29.31	19.59	0.040755	1.599995	0.625002	769.14	1.000000	7
7	40.73	19.90	0.044098	1.697021	0.589268	765.69	1.000000	22
8	50.31	19.72	0.047549	1.793577	0.557545	743.67	1	14
					total test time:	**10.76666667**	8	2.7666667

APPENDIX C – Optical result graph and tables

Test 2



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