Light-diffusing insulation: existing solutions and new prototypes for glazing interlayers

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ABSTRACT: Daylighting is an important strategy for low energy buildings today, yet glass compromises the overall thermal resistance of building envelops: even expensive triple-glazed windows conduct heat at over twice the rate of opaque exterior walls, insulated to energy code minimums. Triple glazed windows are also heavy, expensive, and energy intensive in their manufacturing. Today, lighting consumes 1/3 of electricity in commercial buildings, and daylighting may potentially reduce building energy use by 28% or more (Williams 2012). As the energy code continues to constrain the prescriptive window-to-wall ratios of commercial buildings, it is important to develop envelope systems that admit energy-saving daylight while better managing heat gains and losses. A series of graduate courses at Kansas State University examined the performance of several existing glazing-integrated insulation solutions, using this research to propose a variety of innovative alternatives that can increase the thermal performance of transparent assemblies in building facades. With both computer analysis and instrumented testing of small prototypes, the research seeks to better understand the physics of fenestration interlayers, while also identifying new strategies for improving the performance of basic double glazed insulated glass units and double wall construction. Test results in the paper present the thermal performance, light transmission, and light diffusion of existing light-diffusing and translucent products and student-developed prototypes. Following a discussion of the research work, a generalized model attempts to better explain the physics at work in interlayers, and propose how such systems can be optimized to maximize light diffusion while improving the thermal performance of glazing units.

KEYWORDS: Daylight, Prototyping, Thermal Testing, Simulation,

INTRODUCTION

Fenestration remains a contentious issue in the architectural field today. On one hand, architects and many building owners value transparency in buildings for a variety of legitimate reasons – among them the broad benefits of daylight, visual connection to outdoor spaces, and introduction of beneficial solar radiation into passive buildings. On the other hand, energy codes and energy efficiency experts abhor the overuse of fenestration in buildings, and the architectural field has come to accept increasingly strict limits (typically in the form of window-to-wall ratios) on the amount of glazing that can be used in buildings. For today's high-performing buildings, fenestration has to deliver ever-higher levels of performance in order to balance thermal resistance with the benefits of transparency – specifically daylight. While incoming solar radiation is also an important performance factor in transparent assemblies, this research focuses on the transmission and diffusion of daylight.

Conventionally wisdom tells us that highest-performing thermal barriers are opaque. Transparent assemblies allow light to pass through them, at the expense of transmitting heat more quickly than opaque assemblies. While the thermal resistance of transparent assemblies can be improved with invisible measures like coatings, additional layers of glass, and special gasses in the fenestration cavity, even the best-performing transparent fenestration falls short of the thermal resistance of opaque assemblies, leaving the impression that thermal resistance, light transmission, and light diffusion are opposing criteria.

Interlayers – materials added between fenestration layers – can greatly improve the thermal performance of fenestration, while still preserving transparency. Among the variety of interlayers available are matrices that tend towards openness, versus fibrous with increasing density that reduces transparency. This paper proposes a new perspective on how insulating interlayers may perform in order to admit and diffuse light more effectively, while providing a high level of thermal resistance.

1.0 BACKGROUND

1.1. The need for better-performing fenestration

Daylighting alone may potentially reduce building energy use by 28% or more (Williams 2012), though adding glass area to buildings can create new efficiency problems unless the thermal resistance of glazing is improved. Triple glazing (and experimental quadruple glazing), deliver such improved fenestration thermal resistance, but pose new critical issues. For example, a third layer of glass adds 50% more glazing cost, weight, and embodied energy to an insulated glass unit (IGU), versus a conventional double glazed IGU. Like insulation in opaque assemblies, adding layers to windows has diminishing returns: each layer produces less performance improvement than the layer before. In addition, the long-term performance of the highest-performance IGUs depends on gas infill such as Argon, which can escape the IGU over time (or even during manufacturing and construction) to reduce performance.

In many building types, the potential energy savings from glass is further hampered by comfort issues caused by the failure to control direct sunlight or very bright daylight. Such conditions cause occupants to leave window shades and blinds in a closed position indefinitely, actually increasing the reliance on electricity for lighting. As such, a building with a large amount of glass may rely on triple glazing to manage heat transfer, only to fail in realizing efficiency due to lack of daylight control. The latter problem, in part, can be solved by 'daylight fenestration': a sector of materials, products, and systems that makes incoming daylight (or sunlight) useful by diffusing it, rather than simply transmitting it. Thus a better performing fenestration should address both heat transfer but also light transmission and diffusion.

1.2. Fuzz vs. physics: misconceptions from biomimicry and opaque assemblies

Insulating opaque cavity walls was one of modern building science's first innovations, combating convective heat transfer in open cavity spaces by filling them up with insulating material. Creating thermal resistance with fibrous, foamed, granular, and spongy materials is an insulating strategy that we see around us everywhere: incorporated in ubiquitous fiberglass batting but also in jackets, quilts, and mittens. We are assured of the reliability of this strategy because we see it frequently in nature.

'Fuzz' is only one way to combat heat transfer, however. The impetus of this paper began in an earlier research project where a group of students created a multilayered façade system where multiwall polycarbonate created a deep envelope cavity (Gibson 2015, Figure 1). As the students rushed to prototype their concept, the question was asked: what goes in the cavity, and can this insulation still allow some transmission of light through the façade? The team decided to solve the problem with fuzz: a dozen or so bags loose polyester fiber (aka 'teddy bear fill') from the nearest big-box craft store. The fuzz method worked, but the resultant assembly wasn't very translucent anymore.

The challenge in fenestration interlayers, stated earlier, is that you want the interlayer to resist heat transfer while also allowing light to pass through. While fibrous insulation is known to work well as an insulator, the physics of fibrous insulation is somewhat fuzzy (pun intentional). Textbooks lump fibrous insulation together with a range of other insulating methods (such as foams) that 'trap air' in order to take advantage of its great insulating properties when free convection is prevented. While the trapped air method certainly prevents convection, this doesn't fully explain what's happening inside of the fibers. Studies to improve fibrous insulation's thermal resistance have shown that increasing fiber diameter and density can actually decrease thermal resistance; the same study proposed adding thin layers of radiant barrier between fiber layers in order to boost thermal resistance (Wan & Fan 2012). In summary, the problem of reducing heat transfer through a fenestration cavity isn't just about shutting down convection; a significant amount of heat transfer is also occurring from radiation as well.

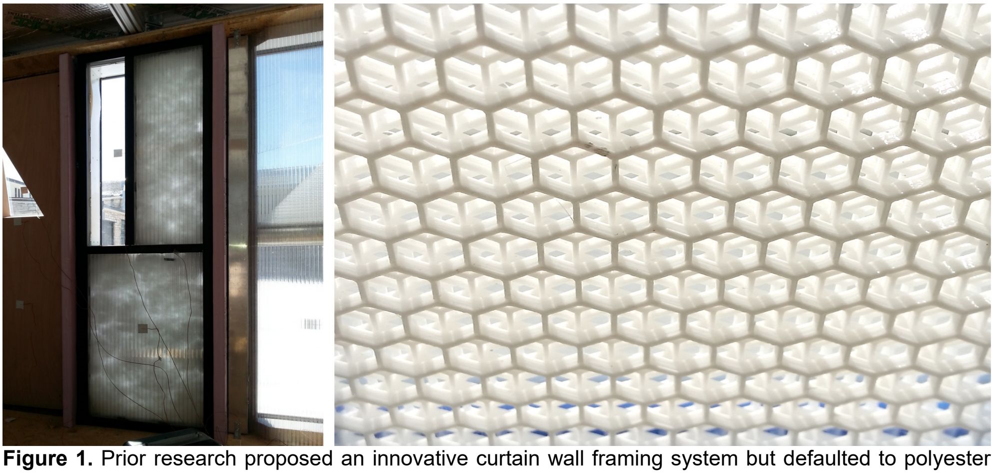


Figure 1. Prior research proposed an innovative curtain wall framing system but defaulted to polyester stuffing for 'translucent' insulation, assuming 'fuzz' was the best interlayer. At right is the honeycomb prototype tested in a later seminar. The honeycomb prototype's U-factor was about halfway between double glazing and triple glazing, and retained a significant amount of light transmittance (50% measured VLT). (Author 2015 and 2016)

Recent studies comparing the performance of double, triple, and quadruple glazing configurations show that radiation (rather than just convection) plays a primary role in heat transfer in glazing cavities, accounting for 45 to 75% of heat transfer (Arici, Karaby, & Kan 2015). As glass planes are added, radiation is reduced between planes and surface temperature differentials fall as well, controlling convection. In the same study, the gap width between glazing didn't make as much impact as adding additional layers, supporting the argument against simply thickening the IGU assembly itself.

These studies suggest that an interlayer should not just address convection, as is the case with fibrous insulation, but also should address radiation. Thus a better optimized interlayer could trade density for transparency as it balances its counteraction of both convection and radiation.

1.3. Heat transfer physics of translucent insulation materials – theoretical model

Few studies have attempted to characterize the physics taking place in fenestration interlayers. While architects have been 'sold' on the possible benefits of plastics and metals inside glazing systems, some recent research has jumped to propose exotic interlayers. For example, a recent study demonstrated a nearly 40% reduction in heat transfer using a phase change material (PCM) as an interlayer (Li, Zhong, Zhou & Zhang 2014), while multiple projects are evaluating the thermal benefits of electrochromic 'switchable' glazing.

In contrast to exotic technology, it actually takes very little to disrupt the heat flows affecting a glazing unit. Insect screens have been shown to increase thermal resistance considerably, yielding a 7% reduction in U-Value when placed on the exterior of windows and 14% when placed on the interior of windows (Brunger, Dubrous, & Harrison 1999). The presence of even a very porous material near the glazing extends the convective 'film' present at the window, decreasing the heat transfer coefficients of convection and radiation. Another study examining cellular shades indicates a 14.4% reduction in heating energy and 14.8% reduction in cooling energy with cellular shades operated according to a standardized protocol, and 10.5% and 16.6% (respectively) when shades were down all the time (Petersen, Merzouk, Sullivan, Metzger & Cort 2016), along with a 33% average reduction in U-factor during the experiment. If window screens or inexpensive cellular shades can almost match the performance of an exotic PCM interlayer, one might ask: why not just introduce these materials to the inside of IGUs as interlayers? Would they not serve the same thermal functions inside the IGU as they would on the interior side?

This paper does not attempt to propose mathematical models, but rather intends to reference an exercise in prototyping and testing to propose an improved theory for glazing interlayers. Reiterating earlier discussion, a great interlayer must reduce both radiation and convection – while taking advantage of the air gap in the fenestration assembly that also prevents conduction. That said, potential sources of conduction across the layers should be avoided; thus interlayers should have a low thermal conductivity, avoid density that would multiply conduction pathways, and minimize contact with either glass layer. Importantly, disrupting both convection or radiation does not require continuity, as the insect screen and cellular shade examples suggest. For natural convection. it is generally known that air will resist convection through gaps less than about 1/4” (6.4 mm); when air is moving slowly, visually porous materials can create nearly the same barrier to convection as a continuous surface. Similarly, most thermal radiation is transferred across vectors normal to the glazing surface, following the cosine law. Thus an interlayer that blocks normal radiation can be an effective barrier to thermal radiation, even if it allows angled or diffused visible light to pass through open voids. In summary, the interlayer can use geometry and layering, rather the microscopic redundancy of fiber batting, to reduce heat transfer – and by doing so, both admit and diffuse light.

2.0. TESTING METHODS

2.1. Overview of experiments

Over the course of two years, students in a research seminar developed interlayer solutions for fenestration, testing them against a variety of existing products, which they tested along with their prototypes. In the first seminar, teams examined solutions for glazed IGUs while in the second seminar, teams explored solutions for a double layer wall with multiwall polycarbonate on each side and a 3 ½” (88.9mm). Test results presented hereafter present the assemblies’ U-factor including the respective glass or polycarbonate layers; though it may be noted that these strategies are interchangeable between glass or polycarbonate assemblies.

Two primary testing methods were engaged by research teams and presented here: computer analysis and the live testing of instrumented prototypes. The value of instrumented prototypes to this research project should not be understated, particularly because convection is difficult to predict with the empirically-derived and interdependent equations for convective heat transfer that serve as the underpinnings for computer software.

2.2. Computer analysis

The software THERM was used by research teams to analyse combined two-dimensional heat transfer through their proposed interlayer systems in early development. THERM uses finite element analysis with detailed, 2-dimensional geometry inputs along with the ability to input custom material properties. While the accuracy of THERM versus live testing methods has been independently validated, THERM simplifies certain aspects of convective and radiative heat transfer. Interested readers can look at this in greater detail in THERM literature available on the web. For the research presented in this paper, the actual prototype tests are considered to be the most accurate results.

2.3. Prototype testing for thermal performance

As teams developed concepts with greater detail, they constructed small prototypes measuring approximately 14 inches by 14 inches (35.6 cm by 35.6 cm). Thermal testing was conducted to determine thermal resistance of the prototypes, following parts of the standard testing methods ASTM C-1046 and C-1155 (see References) for determining thermal resistance of assemblies in-situ. The prototypes were installed on the face of a compact freezer with its temperature maintained by a micro-controlled thermostat to simulate a cold exterior environment. The interior room in which tests were conducted served as the interior boundary condition. Data was collected from thermocouples and a heat flux sensor[1], together which were used to determine thermal resistance[2] using the summation method from ASTM C-1155. While the duration of tests was shorter than that dictated by ASTM testing, tests achieved 10% convergence as described in ASTM C-1155.

2.4. Prototype testing for light diffusion and transmission

Testing for visible light transmission (VLT) was carried out using handheld light meters and a single projection LED light source at a fixed distance. Values for VLT are shown in Table X. Readings were taken normal to the specimen surface and normal to incoming light.

Regarding light diffusion, the physical property of interest is diffuse hemispherical transmittance: the shape at which light is spread as it passes through a material. Perfect hemispherical diffusion is considered to be ideal for daylighting materials as it distributes light energy evenly to the building interior, specifically tempering direct sunlight. As diffusion becomes more specular, light energy passing through the material retains its directionality and intensity. Measuring diffuse hemispherical transmittance is normally accomplished with a goniophotometer: a large, expensive, specialized apparatus not available to the research project. Instead, the research team used an improvised method[3] to measure transmitted light at fixed intervals (15, 30°, 45°, 60°, 75°, and 90°) across two planes (vertical and horizontal) using 3-dimensional masks. The masks consisted of angled tubes and flanges, coated in light-absorbent paint, that mated to a light meter. An LED light source was focused on the specimen while the light meter measured incident light from a specific angle through each mask, maintaining a consistent distance to the surface of specimens. Readings were then used to construct a hemispherical diffusion curve for the specimen. Comparing these curves to a perfect hemisphere demonstrated the system's effectiveness in diffusing light (see Fig. 3).

3.0. SYSTEMS TESTED AND RESULTS

3.1. Existing systems

Select alternatives to conventional glazing were tested by research teams prior to the development of prototype systems. A summary description of each system along is shown in Table 1 with results from computer analysis and live testing are summarized in Tables 2. Note that all of the values presented in this paper are for 'center of glass' thermal resistance; in other words, contributing impact of fenestration frames is not included in the results, although this has been a subject of previous student research conducted with the author (Gibson 2015). U-Factors for double- and triple-glazing are included in the tables for comparison, though these systems weren't evaluated with live testing.

Panelite was one of the first systems examined in the research. This proprietary product consists of a polymer creating an array of tubes perpendicular to the glass. Panelite is marketed for its daylighting and solar control benefits only; though one may suspect that the honeycomb sandwiched between the glass serves some thermal purpose in preventing free convection in the IGU. Testing revealed that, in fact, Panelite is about 8% *less* thermally resistant than the tested double pane IGU, attributed to unobstructed radiation transmission and conduction across the air gap via the plastic matrix.

Kalwall, another proprietary system, was tested by the teams. The specimen tested was a standard 4" wall panel with crystal FRP on each side, non-thermally broken edges, and air in the cavity. While Kalwall markets translucent fiberglass batting and nanogel infill options for their products, neither were available for testing in this study. The Kalwall specimen performed slightly better (10%) than the tested double-glazed IGU, and somewhat better than product brochures report.

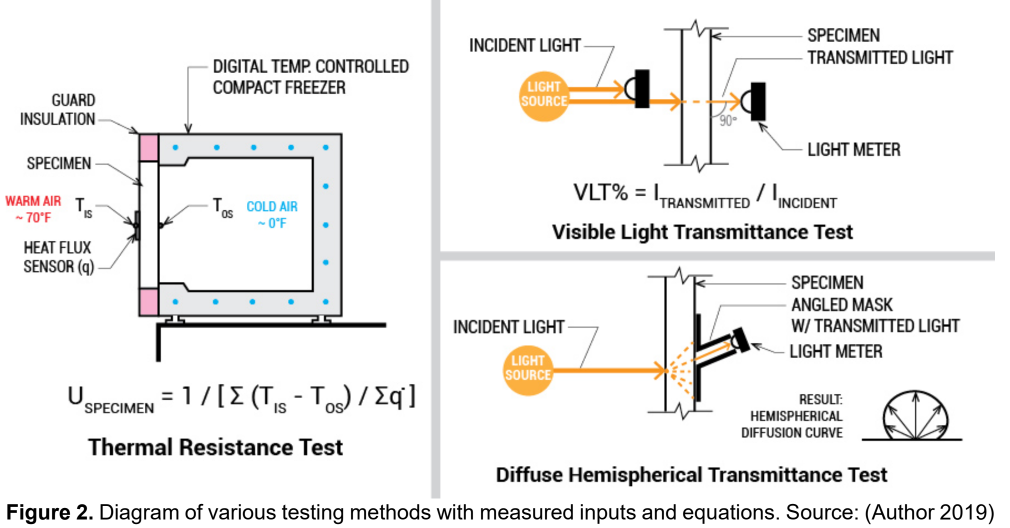


Figure 2. Diagram of various testing methods with measured inputs and equations. Source: (Author 2019)

Multiwall polycarbonate is a common, inexpensive substitute for curtain wall systems and Kalwall. A cavity-wall-type application of this system was tested, using triple-wall 16mm polycarbonate for an inner and outer skin, and leaving 3.5" of air gap in between. These two layers of polycarbonate, before adding any interlayers, yielded a 46% improvement over the double glazing. Student researchers also tested the results of adding a single layer of cellular shades within the polycarbonate assembly, which yielded an assembly with a 29% better U-Factor than the best triple glazing while retaining a remarkable VLT of 19.1% when closed.

Lastly, research teams were also interested in 'switchable' interlayers. An off-campus university affiliate had a 37-year-old installation of 'Beadwall' – a now-defunct system in which loose polystyrene beads were alternately blown and vacuumed from fenestration cavities to provide insulation in solar buildings. While there is no room to discuss the details of the collaboration within this paper, the Beadwall's purported R-22 (U-0.045) performance claims inspired the research team to mock up a small prototype of Beadwall for testing. When filled, the Beadwall assembly delivered about half the performance it promised – yet was still over 5 times more thermally resistant than double glazing and 3 times more thermally resistant that two layers of multiwall polycarbonate. In order to be switched, Beadwall required many valves, motors, and pipe connections to work properly; something that couldn't be sustained in the local installation over time. Eventually the Styrofoam beads ended up 'stuck' in the cavities, either partially filled or empty. Observing the Beadwall's fate underscores the importance of fixed – or at least greatly simplified – interlayers for fenestration.

3.2. Glazed IGU interlayer prototypes

While developing interlayer designs, research teams intended to create systems that would improve upon the performance of double glazing systems, while striving to approach the performance of triple glazing systems and diffuse incoming light.

Three systems were tested as part of a 1" IGU assembly. The first employed various sizes and configurations of polyethylene bubblewrap, before settling on a final solution where two layers of bubblewrap were affixed to the inner glazing surfaces of the IGU. Remarkably, the bubble wrap yielded a U-Factor that was 50% better than double glazing, and even exceeded triple glazing. The second system used 3 layers of 3-D printed honeycomb offset within the glazing gap. While the honeycomb produces a more modest performance outcome than the bubblewrap, it improved the U-factor by 13% despite an open structure. Another team experimented with layering 6mm multiwall polycarbonate within glass layers; their best performing prototype IGU had a 23% improved U-factor over high-performance triple glazing.

Table 1. Source: (Author 2019)

Summary of Systems Testing				
	Total System Width	Interlayer Config.	Int. and Ext. Faces	Fill
Existing Systems				
Double Glazed IGU	1” (25.4mm)	None	¼” Clear Glass	air
High-Performance (HP) Double Glazed IGU	1” (25.4mm)	None	¼” Glass, Low-E on #2 surface	argon, no interlayer
Triple Glazed IGU	1.25” (31.8mm)	None	¼” Glass	air
High-Performance (HP) Triple Glazed IGU	1.25” (31.8mm)	None	¼” Glass, Low-E on #2 and #5 surface	argon, no interlayer
Panelite IGU	1” (25.4mm)	Fixed	¼” glass	polymer honeycomb infill, air
Kalwall	4” (102mm)	None	FRP	air
Dbl 16mm Polycarb	4.1” (104mm)	None	16mm 3-wall polycarb.	3.5” air
Dbl 16mm Polycarb w/ Cellular Shades	4.1” (104.mm)	Movable	16mm 3-wall polycarb.	Single Layer Cellular Shade
Beadwall	3.6” (91.4mm)	Movable	FRP	3.5” loose polystyrene beads, air
Prototype Systems				
Bubblewrap IGU	1” (25.4mm)	Fixed	¼” glass	2 layers of bubblewrap laminated to inner glazing faces, air fill
Layered Honeycomb IGU	1” (25.4mm)	Fixed	¼” glass	3 layers 0.17” offset 3D-printed interlayers, air fill
Layered Polycarbonate IGU	2.5” (63.5mm)	Fixed	¼” glass	3 layers 6mm multiwall (2-wall) polycarbonate, ¼” spacing with air fill
Foam Strips	4.1” (104mm)	Movable	16mm 3-wall polycarb.	Single layer vert. 1/8” polyethylene foam strips wrapped in nylon, interior side reflective.
Foam Louvers, 45° Open	4.1” (104mm)	Movable	16mm 3-wall polycarb.	1” polyisocyanurate horz. louvers wrapped in aluminum
Quilted Tesselation	4.1” (104mm)	Movable	16mm 3-wall polycarb.	2 layers cotton with 1/16” polyester batting

3.3. Polycarbonate interlayer prototypes

Research teams later developed three movable interlayer systems that were incorporated inside 16mm multiwall polycarbonate skins. It should be considered that these systems could work within glass units as well. Though the systems were designed to be movable, this paper considers them as potential fixed systems.

The first system used polyethylene foam strips configured vertically, and wrapped with synthetic fabrics – the inside facing layer with a reflective covering. These thin foam strips did not form a complete ‘seal’ and presented a number of ways in which they could be opened, closed, or positioned to allow light transmission. Yet the foam strips yielded a U-factor that was 45% of the base polycarbonate configuration, with an estimated U-factor contribution on their own that was similar to basic triple-glazing. Another system used horizontal 1” polyisocyanurate foam louvers with a reflective coating, producing a U-factor that was 53% of its U-factor even when open at 45 degrees – creating openings that almost 2” wide in the cavity. A third system used a quilting of cotton of polyester batting in a folding configuration, producing similar improvements over the base polycarbonate assembly from a very thin but translucent interlayer.

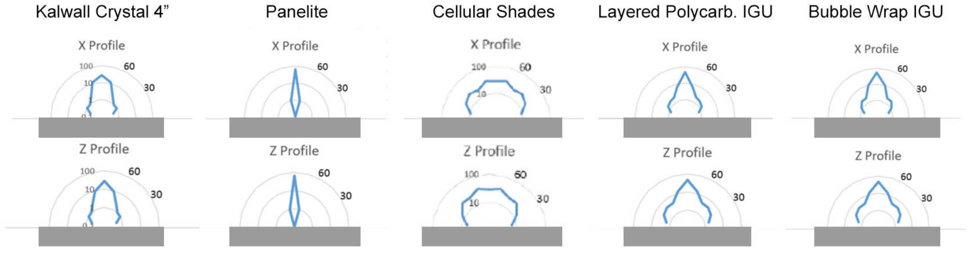


Figure 3. Various results from diffuse hemispherical transmission testing. While the Crystal FRP is not the most diffusing skin available from Kalwall, it is still considered to have excellent light distribution properties. Off-the-shelf cellular shades offer almost the same diffusion performance. Most of the prototypes diffused light more effectively than the Panelite specimen, which shows nearly complete specular transmission. Source: (Author 2019)

Table 2. Source: (Author 2019)

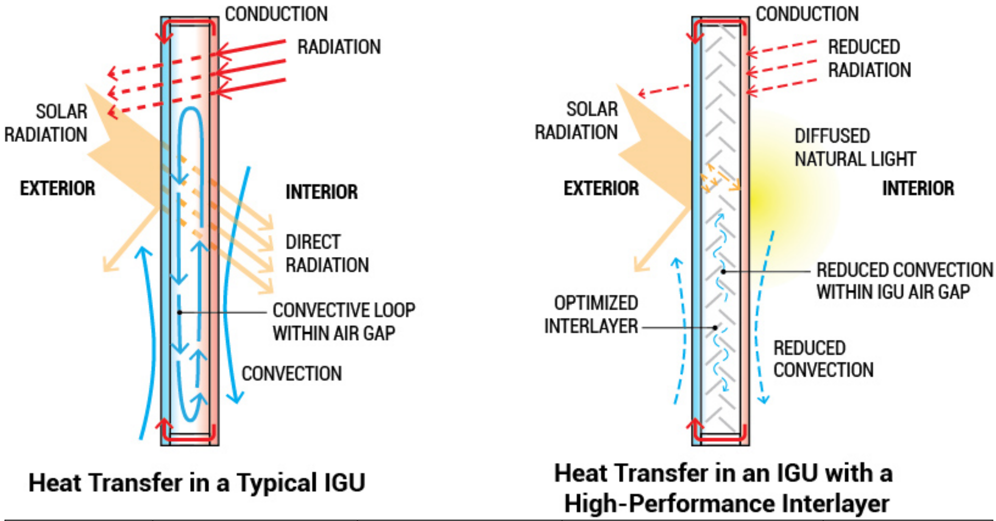
Summary of Test Results				
System	Simulated U-factor, THERM [1] (Btu/ft2*h*F)	Tested Prototype U-factor [2] (Btu/ft2*h*F)	Est. Contribution of Interlayer, U-factor (Btu/ft2*h*F)	Visible Light Transmission (VLT) %
Existing Systems				
Double Glazed IGU	0.476 [4]	0.408	-	-
HP Double Glazed IGU	0.247 [4]	[3]		-
Triple Glazed IGU	0.307 [4]	[3]	-	-
HP Triple Glazed IGU	0.123 [4]	[3]	-	-
Panelite	0.26	0.439	- 5.882	63.3%
Kalwall	0.49	0.366	-	47%
16mm Polycarb	0.425	[3]	-	-
Dbl 16mm Polycarb	0.200	0.220	-	-
Dbl 16mm Polycarb w/ Cellular Shades	[5]	0.114	0.235	19.1%
Beadwall (beads in place)	0.074	0.075	0.092	<0%
Prototype Systems				
Bubblewrap	0.26	0.204	0.410	43%
Layered Honeycomb	0.14	0.356	2.778	50%
Layered Multiwall Polycarb	0.17	0.124	0.178	36%
Foam Strips, Vertical	[5]	0.120	0.263	2.1%
Polyiso Foam Louvers at 45°	[5]	0.116	0.246	12.6%
Quilted Tesselation	0.124	0.111	0.226	2.1%

[1] U-Factor presented is total U-Factor with air films, as outputted by THERM software and following National Fenestration Ratings Council practice. Divergence between 2D THERM analysis and live tests seem to increase with both large air gaps and small geometry.
[2] ASHRAE Handbook air film thermal resistances of R-0.68 for interior and R-0.17 for exterior have been added to the surface-to-surface U-Factors observed from testing, in order to be appropriately compared to published values and THERM results.
[3] Units were not available for live testing.
[4] U-Factor shown is center-of-glass value from the analysis software WINDOW and standard for NFRC ratings.
[5] Simulation results not shown due to limitations in modeling continuous air volumes in THERM; this reinforces the importance of testing prototypes when complex heat transfer is at play.

4.0. A REVISED THEORETICAL MODEL FOR FENESTRATION INTERLAYERS

The array of solutions investigated illustrate several important points about glazing interlayers and how these assemblies can increase thermal resistance, while conducting and diffusing light. Of the prototypes tested, none employed dense, fibrous insulation to fill the air gap. In fact, some of the better performing prototypes consisted of rather thin interlayers and others were even discontinuous: gaps and openings resulting from their materiality and construction didn't seem that detrimental to their performance as insulating systems.

Certainly convection occurred in the gaps and openings in the prototypes' interlayers, yet the net flow of heat from combined convection and radiation was greatly reduced compared to double glazing. Estimations of the U-factor improvements contributed by the prototypes systems suggests that a properly designed, discontinuous interlayer can transmit significant quantities of natural light while interrupting significant amounts of detrimental radiation. As discussed earlier in this paper, radiation plays a major role in transferring heat within insulated fenestration units. An optimized interlayer shouldn't treat fenestration like opaque walls, stuffing the air cavity with fibers; an optimized interlayer should instead interrupt thermal radiation and convection just enough to slow heat transfer, while let natural light diffuse through it.



Chaudhury, Cooke, Cowie & Razaghi (2017); Canada	Literature Review. 103 full-text, 94 empirical studies, 9 reviews, published after 2000.	Home-like Character, Sensory Stimulation, Unit Size, Spatial Layout, and Orientation Cues, Small-scale dining area	The influence of unit size, spatial layout, home-like character, sensory stimulation, social spaces, dining, bathing and outdoor spaces on residents' behaviors	Environmental characteristics, Social spaces, Social interaction
Young Lee, Chaundhury & Hung (2016); Canada	Longitudinal study. traditional large-scale setting and small-scale, home-like setting	N/A	Small-scale facilities have positive effects on health and behavior of residents in long-term care facilities.	Small-scale home, Social interaction, QoL
Forsund & Ytrehus (2016); Norway	Qualitative study with interview and observation in Specialized care units (SCU)	Family pictures in individual rooms, decorating the room in a home-like style. The common area needs to be home-like.	The individual room is an important feature in maintaining spousal contact and interaction throughout all phases of dementia, including the final phase.	Privacy, Relationship with spouse
Calkins (2009); USA (Ohio)	Literature review	Household, Building configuration, Non-institutional design, Wayfinding, Safety, Outdoor areas, Dining rooms, Bedrooms	The positive benefits of private bedrooms on outcomes such as the satisfaction of residents, families, and staff, QoL, preference and reduced neuro-disability.	Private bedrooms, Satisfaction of residents
Smit, Willemse, Lange & Pot (2014); Netherlands	Explorative Study. 57 residents in 10 dementia care facilities	Home-like décor and furniture arrangement	LTCF with more home-like atmosphere supported social interaction through the environment and had no central activity program is preferable.	Furniture arrangement, Stimulated social interaction
Nordin, McKee, Wallinder, Koch, et.al. (2017); Sweden	Comparative Case Study with mixed-method, convergent analysis. 54 residents, 25 staff members, 4 relatives.	Open plans, automatic doors, smooth flooring, safety devices, and elevators in buildings	Private accessible apartments, safety, and dining areas showed high environmental quality, whereas the overall layout had lower quality.	Residents' activities, Interaction, Relationship
Werezak & Morgan (2003);	Literature Review	Social, physical and psychological environment	The psychosocial environment involving social interaction are critical to high-quality institutional dementia care.	Psychosocial environment, Social interaction
Rooij, Luijkx, Schaafsma, et.al. (2012); Netherlands	Quasi-experimental, longitudinal research design. 179 residents with dementia	Traditional versus small-scale long-term care settings	Residents in small-scale settings had higher mean scores on 'social relations', then residents in traditional settings.	Small-scale settings, Social relations, Positive affect, QoL
Beerens, Boer, Zwakhalen, Tan, et.al. (2016); Netherlands	An observational study with 115 participants. Mean age was 84 years' old	Social interaction to promote good QoL	PwD with higher QoL were more engaged in active, expressive, social activities and less passive/purposeless activities than PwD with lower QoL	Social interaction and QoL
Kontos (2011); Canada (Southern Ontario)	Ethnographic study. 79 residents (11 men and 68 women) in Orthodox Jewish LTCF	Inclusion criteria: cognitive impairment; and two times more women than men.	Empathy, social etiquette, the power of gesture are major aspects of selfhood.	Sociability, Selfhood and Person-centered dementia care
Abbott, Sefcik, Haitsma, (2017); USA	Observation Study using 29 residents with medical charts and visitor logs	Interaction: 1) Location, 2) context, 3) type 4) quantity and 5) quality of interaction	Interaction were brief, verbal and social in nature, and occurred in public areas.	Activities areas, Close proximity, Social environment
Boer, Hamers, Zwakhalen, et.al. (2017); Netherlands	Longitudinal observation study. 115 nursing home residents. Mean age of 82 years.	To investigates whether residents of green care farms are more engaged in (physical) activities and social interaction than are residents of other nursing homes.	Residents living at green care farms are more active, significantly more often participated in domestic activities, outdoor/nature-related activities and significantly less often engaged in passive/purposeless activities.	Green care farms, Engaged in domestic activities, Interaction
Edvardsson, Sandman, Rasmussen (2011); Sweden	Grounded theory design, Interview & Observation in a psycho-geriatric hospital unit with 24 residents.	'Sharing place and moment', 'sharing place but not moment' and 'sharing neither place nor moment	Staff presence and absence emerged as the core concept influencing the psychosocial climate and the well-being of people in dementia in a psycho-geriatric setting.	Staff presence, Psychosocial climate
Smit, Willemse, Lange, Pot (2014); Netherlands	The explorative study using 8th edition of Dementia Care Mapping (DCM) with 57 residents in 10 dementia care facilities	Home-like environment	Reminiscence, leisure, expression, and vocational occupation had the greatest potential to enhance well-being.	Small-scale home, Social interaction, QoL
Garcia, H´ebert, Kozak, et.al. (2012); Canada	Qualitative research, nominal focus groups with family and staff members. The mean 83 years with moderate to severe dementia.	To reduce disruptive behaviors and facilitate QoL or encourage disruptive behaviors and impede the QoL of residents.	Social/human environments were perceived to be more important than physical environments. A mnemonic – C.A.R.E.F.U.L. – was developed.	Social/human environments, Physical environments

Figure 4. Heat flows within fenestration are at left. Convection in the air gap transfers heat, but so does radiation. At right is a proposed high performance interlayer that works without fibrous batting. Using the right materials and geometry, an interlayer can greatly slow down convection while blocking significant radiation, increasing the thermal resistance of the fenestration while letting light through. Source: (Author 2019)

CONCLUSION

Rather than attempt to engineer fibrous batting into translucency (the ‘fuzzy’ solution), this research argues for an approach to fenestration interlayers where the right material properties, with respect to conduction and radiation, are combined in an optimized geometry that slows convection rather than attempts to completely eradicate. Such an assembly can still transmit critical daylight, and while doing so provide a functional, affordable, and sustainable option to process-energy-intensive, heavy, and expensive triple glazing. Presently, this research is investigating geometric and material solutions that can be inexpensively manufactured, while meeting objectives of the theoretical model described herein. The next steps for this research will be to conduct a new round of computer analysis and prototype testing for an updated interlayer system, emphasizing the lessons learned thus far.

Among many possible concluding observations, the author emphasizes that continuation with the testing of physical prototypes is essential in understanding the performance outcomes of fenestration concepts. Virtual testing, like that afforded by THERM and similar analysis software, does not fully capture the complexity of the invisible physics taking place within fenestration cavities.

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ENDNOTES

[1] Instrumentation used in the thermal resistance tests are explained as followed. Surface and air temperature was measured using standard K-type thermocouples and a model OMB-DAQ-2416 data acquisition unit. Tests sites were verified to be representative of typical specimen surface temperature using thermography, and thermocouple junctions were masked according to ASTM 1046 recommendations. Heat flux was measured via an HFS-4 calibrated heat flux sensor and DP-41E meter using an analog output board for logging.

[2] Uncertainty for thermal resistance calculations is 5.03% of R-value or U-factor for a representative measured U-factor of 0.20 ft2*h*F/Btu from observed ∆T of 50F and heat flux (q) of 10 Btu/h*ft2. Absolute measurement error for the DP-41E meter is ±0.005% of range or ±0.38 Btu/h*ft2. Absolute measurement error for the OMB-DAQ-2416 is ±0.825F for a total of ±1.65F for ∆T.

[3] The importance of measuring diffusive hemispherical transmittance is increasingly relevant as translucent materials are evaluated with the widely-used lighting simulation program Radiance. While not strictly a part of this research, it should be noted that all translucent materials in Radiance are simulated with perfect hemispherical diffusion. This is problematic for designers who rely on the results of simulations to understand the performance of a light-diffusing material; the result in real life may be quite different if the material isn’t a perfect hemispherical diffuser.