CHANGING WHAT'S POSSIBLE

Single-Pan Highly Insulating Efficient Lucid Designs (SHIELD) Program Overview

B. PROGRAM OVERVIEW

1. SUMMARY

Building heating, ventilation, and air conditioning (HVAC) accounted for 14.0% of primary energy consumption in the United States in 2013, or 13.6 quadrillion British thermal units ("quads") per year. In addition to the season and weather in various U.S. regions, this consumption is determined by the heating and cooling facilities in the buildings, by the thermostat settings and other choices of building managers and occupants, and finally by the building envelopes. Windows are essential and costly elements of building envelopes, and the heat that flows out through windows in cold weather across the U.S. consumes about 3.9 quads of primary energy. The ARPA-E Single-pane Highly Insulating Efficient Lucid Designs (SHIELD) program seeks to reduce this consumption by funding the development of energy-efficient and cost-effective retrofits for the substantial remaining stock of single-pane windows in the U.S. ARPA-E analysis indicates that a fully successful single-pane retrofit campaign will reduce total building energy consumption by 1.2 quads, or 1.3% of domestic energy use. As envisioned in this SHIELD program, it will also address the water condensation and occupant discomfort that are associated with single-pane windows in cool climates.

SHIELD will support research on three broad technology categories. The first category will enable products that are applied onto existing windowpanes. The second is for manufactured windowpanes with similar weight and thickness to current panes, and that could be installed as replacements for existing windowpanes without necessitating replacement of the sash in which the pane is mounted. For both of these research categories, the program's primary goals are to develop cost-effective technologies (i) to improve the thermal insulation (U-factor) and (ii) to reduce cold weather condensation of single-pane windows. A secondary goal of the SHIELD program is to develop synergistic improvements in window performance such as soundproofing that would make these window retrofits highly desirable to building occupants and owners. ARPA-E envisions that these technologies will be used in both the residential and commercial building sectors, and that the impact of the retrofits on the appearance of the window will be minimal. In addition to the two categories for comprehensive technology development, as a third category, SHIELD will support proof-of-principle development of innovative components that will enable superior performance in the first two technology categories.

2. MOTIVATIONS: IMPROVED SINGLE-PANE WINDOWS AND REDUCED NATIONAL ENERGY CONSUMPTION

Figure 1 illustrates estimates of the primary energy required to support heat flow out of heated buildings and through their windows in the four broad Census Bureau regions of the United States and for the residential and commercial building sectors.[1] The subdivision of each bar indicates the energies for single-pane and multipane buildings; the label at the bottom is the fraction of windows that are estimated to be single-pane. As expected, single-pane windows are relatively common in the warmer South and West regions; in the South, more than 40% of residential buildings still have single-pane windows instead of multiple pane (almost always double pane) windows. In the colder Northeast and Midwest regions, somewhat less than 30% of windows are typically single-pane.

These relatively small fractions become quite significant when heating energy is considered. For the primary energy usage calculated for each region and sector, the weighting of single-pane buildings has been doubled. This approximately accommodates the fact that single-pane windows conduct at least twice as much heat as average multi-pane windows.[2] Thus, of the 3.95 quads per year that can be attributed to heat conduction through windows, 2.0 quads per year are

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[1] These estimates were calculated by ARPA-E using the 2011 Buildings Energy Databook, the 2009 Residential Energy Consumption Survey (RECS), and the 2005 Commercial Buildings Energy Consumer Survey (CBECS) following the methodology of ref. 2.

[2] Apte, J. and Arasteh, D., "Window-Related Energy Consumption in the US Residential and Commercial Building Stock", Lawrence Berkeley National Laboratory Report 60146 (2006).

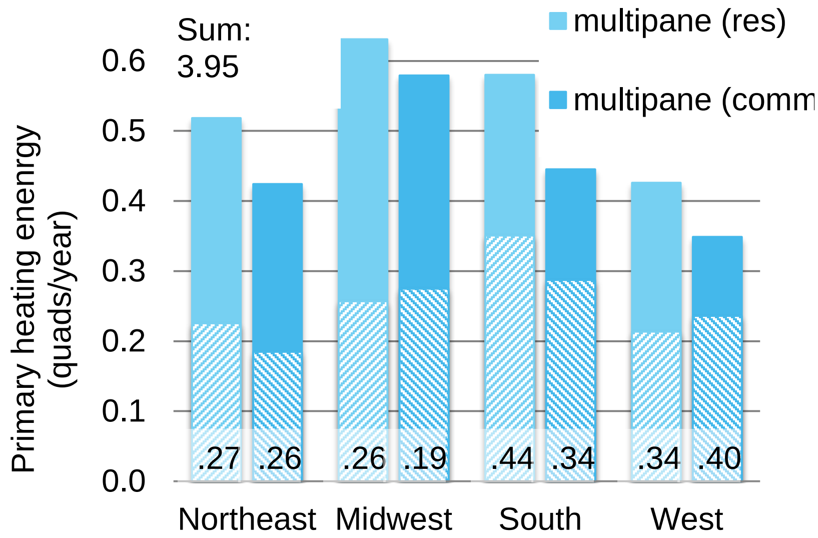

Fig. 1: Estimates of primary energy usage for heat flow through the windows of heated buildings in the four U.S. census regions. The results are given for residential and commercial buildings, and for single-pane and multipane windows. The label at the bottom of each bar indicates the area fraction of single-pane windows in each region and sector.

associated with single-pane windows. At nominal consumer rates of $10 per million BTUs,[3] this amounts to a cost of $20 billion/year. Retrofitting single-panes for improved efficiency could save about 1.2 quads/year, where we assume that the retrofit reduced the heat flow to 40% of the flow through unimproved single-panes. The associated retrofit investments would return about $12 billion/year to energy consumers.

The dominant technology for efficient windows at present is the double-pane insulated glass unit (IGU) that incorporates a low-emissivity (low-*e*) coating on one of its panes.[4] Most new window installations in the United States incorporate these IGUs.[5] However, the area of single-pane windows is declining fairly slowly; the stock of single-pane windows in residences is declining at 2% per year.[6] The single-pane window technologies that will be developed by this research program will have properties intermediate between high performing IGUs and unimproved single-panes, and are likely to find first markets in buildings with historically and architecturally significant windows. These windows are not typically candidates for retrofitting with IGUs. As installed prices fall, the advanced single-pane technologies will be adopted in a wider range of buildings with single-pane windows. Ultimately, ARPA-E envisions that the technologies for advanced single-panes will also offer new options for reducing the cost and improving the performance of IGUs. IGUs are relatively thick and heavy

[3] Consumer prices for natural gas are compiled by the Bureau of Labor Statistics. For the current summary for major cities, see http://www.bls.gov/regions/midwest/data/AverageEnergyPrices_SelectedAreas_Table.htm . The March 2015 average US price was $9.85 per million BTU.

[4] Emissivity refers to how efficiently a surface emits thermal radiation, which carries heat away from the surface. Ordinary window glass has an emissivity of 0.84; the highest emissivity is 1.0, and polished metal surfaces can have emissivities as low as 0.01. See Muneer, T., Abodahab, N., Weir, G., and Kubie, J., *Windows in Buildings: Thermal, Acoustic, Visual and Solar Performance* (Architectural Press, 2000), p. 46.

[5] 2011 Buildings Energy Databook, Tables 5.2.5 and 5.2.7 . U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy.

[6] This estimate is based on comparison of the 2005 and 2009 Residential Energy Consumption Surveys (Energy Information Agency). ARPA-E has not established this rate for commercial buildings. ARPA-E estimated the window areas using the floor space of US homes and commercial buildings (RECS Table HC10.1, CBECS Table B5) with single-pane and multipane windows.

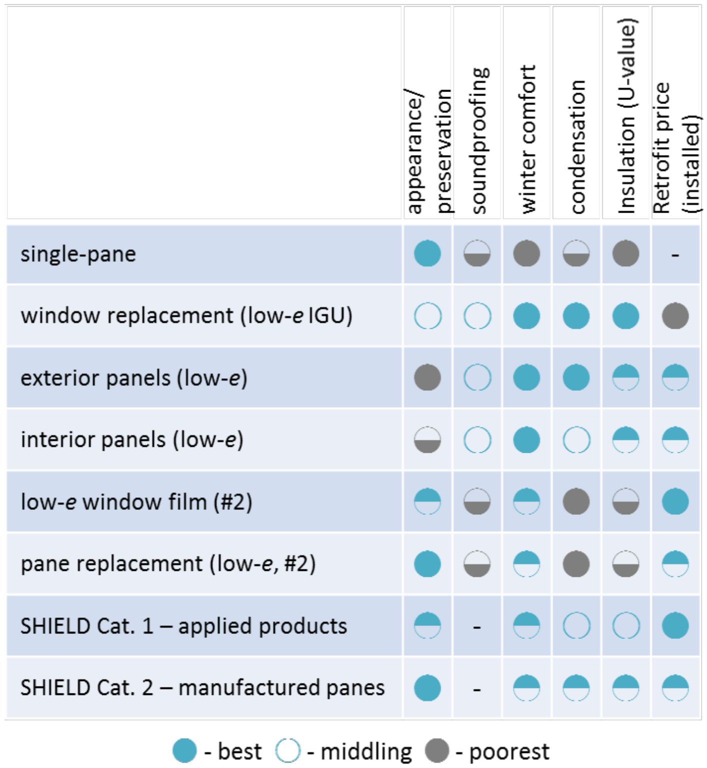

Fig. 2: Ball chart illustrating the relative performance of several window technologies for six qualities. Additional details are provided in the text.

compared to single-panes, and lower-quality IGUs have suffered from short service lifetimes due to the failure of the seal between the panes.[7]

The SHIELD program does not directly address summer cooling associated with windows, which uses another 2.3 quads of primary energy annually. Cooling is mostly needed in the summer season to compensate for solar heating through windows, and is not specific to the stock of single-pane windows.[8] Solar heating is an advantage in the winter heating season.

3. CURRENT APPROACHES TO EFFICIENCY RETROFITS OF SINGLE-PANE WINDOWS

Summary chart for single-pane window retrofits. Fig. 2 is a summary of several window retrofit options using a ball chart to illustrate qualitatively the characteristics of each retrofit for appearance, soundproofing, comfort, condensation, insulation, and price. The best performance is indicated by the solid blue balls, and the poorest by the solid black balls. Thus the appearance of a single-pane window is excellent, but most of the other aspects of the window are poor. In the following, we discuss the characteristics and the retrofit options individually. The last two rows of the chart are a guide to the goals of the SHIELD program for its two categories.

Window insulation: *U*-factor. The thermal insulation of a window is quantified by its *U*-factor, which is the ratio of the heat flux H per unit area through the pane to the difference ΔT between the interior and exterior temperatures. Lower U-factors corresponds to better insulating windows. In American units (BTU/hour/square-foot/degree-Fahrenheit),[9] an unimproved

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[7] O'Mara , Deborah L., "25 years of proof: Insulating glass unit analysis bolsters independent, third party certification", *Glass Magazine*, March 26, 2009.

[8] Sawyer, K. (editor), "Windows and Building Envelope Research and Development: Roadmap for Emerging Technologies". Building Technologies Office, EERE, U. S. Department of Energy, February 2014.

[9] Metric values for U ($W/m^2/K$) are 5.68 times larger than the American values (BTU/hr/sf/F).

glass pane has a *U*-factor of about 1.1.[10] The *U*-factor for an entire window, which includes the effects of the sash and the framing around the windowpane, needs to be less than 0.30 to achieve Energy Star certification in colder regions of the US.[11]

Window comfort and condensation resistance. On a cold, windy day, the temperature of the interior surface of a single-pane window is nearly as low as the outside temperature. A consequence is that a significant region around the window will be uncomfortably chilly compared to the rest of the heated interior. The cold temperature of the pane also means that moisture from the interior of a building will condense on its surface. Condensation is not merely unsightly. It also limits the humidity level of the interior of a building, which is a concern for the indoor air quality. A 30% relative humidity is a lower limit recommended by health experts.[12-14] In a single-pane building on windy days, this level of humidity can only be maintained when the exterior temperature is above -2.5 C.[15]

Window properties: soundproofing. Soundproofing by a window is often characterized by the "sound transmission class" (STC), which is one indicator of the attenuation of exterior acoustic noise by the window. A window with a 1/8 inch thick single-pane typically has an STC of 29 db, where 30 db indicates approximately a thousand-fold drop in noise intensity. Thicker panes have larger STC values; a ½ inch pane has an STC of about 37.[16] Good soundproofing generally requires windows that have an STC class of 40 db, about ten times better than the single-pane.

Replacement by an IGU. A straightforward approach to improving a window's performance is to replace the entire window (frame, sash, and glazing[17]) with a modern window incorporating an advanced IGU. These are not simply double panes: they incorporate a low emissivity ("low-e") coating on one pane. Emission of thermal radiation by an unimproved glass pane is a major source of heat loss. The low-*e* coating can reduce this loss by up to tenfold. Filling the space between the panes with inert gases such as argon further improves advanced IGU insulation.

Beyond the improved efficiencies of IGUs, the ball chart illustrates that IGUs mitigate the problems of single-panes with comfort and condensation, and improve soundproofing as well. Despite these advantages, single-pane windows are being replaced by more advanced multipane windows fairly slowly in the US; the area of residential single-pane windows is declining at about 2% per year.[6] The fairly high cost of window replacement is one difficulty; one rough estimate for consumers is about $50-$100 per square foot with installation.[18] Simple payback from the energy savings of a complete replacement takes decades even in cold climates.[19] The change in a building's appearance with contemporary windows may preclude replacement by IGUs for esthetic and historical reasons (including location in an historical district),[20,21] or due

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[10] Carmody, J., Selkowitz, S., Arasteh, D., and Heschong, L., *Residential Windows: Third Edition* (Norton, 2007), p. 39. *U*-factors are somewhat affected by measurement conditions; this document uses the winter U-factor conditions specified by the National Fenestration Rating Council (NFRC), which are an interior temperature of 21 C, an exterior temperature of -18 C, and an exterior wind speed of 5.5 m/s.

[11] "Energy Star performance criteria for windows, doors, and skylights", Environmental Protection Agency. Accessed May 26, 2015.

[12] Sterling, E.M., Arundel, A., and Sterling, T. D., "Criteria for Human Exposure to Humidity in Occupied Buildings", *ASHRAE Transactions*, Vol. 91, Part 1, pp. 611-622 (1985). This paper is the origin of the "Sterling Chart" summarizing the effect of indoor humidity on diseases such as respiratory infections and allergies. The authors recommend an indoor relative humidity in the range 40 – 60%.

[13] Makinen, T. M., Juvonen, R., Jokelainen, J., Harju, T., Peitso, A., Bloigu, A., Silvennoinen-Kassinen, S., Leinonen, M., and Hassi, J., "Cold temperature and low humidity are associated with increased occurrence of respiratory tract infections", *Respiratory Medicine* 103, 456-462 (2009). doi:10.1016/j.rmed.2008.09.011

[14] Berlin, G. L., "Restoring the low limit for indoor relative humidity", *Engineered Systems,* February 2014 issue, pp. 48 – 52. Berlin takes issue with the absence of a low limit for relative humidity in ASHRAE standard 55, and recommends 30 – 35% as a reasonable low limit. The ASHRAE standard recommends a maximum relative humidity of 65% at an interior temperature of 72 F.

[15] In this document, condensation resistance will be defined in terms of the exterior temperature T_C at which condensation appears at the center of the windowpane. The interior relative humidity is assumed to be 30%. The additional, fixed conditions are those at which the winter *U*-factor is reported by the NFRC:[50] interior temperature = 70 F (21 C), exterior windspeed = 5.5 m/s, and no solar illumination (dark).

[16] Schimmelpenningh, J., "Acoustic Interlayers for Laminated Glass– What makes them different and how to estimate performance", *Glass Performance Days South America – 2012*.

[17] The term "glazing" refers to the entire transparent structure, which in this case is the IGU.

[18] "How Much Does It Cost to Replace Windows?", *Angie's List*, June 2, 2015.

[19] "Home window buying guide", *Consumer Reports*, January 2015.

[20] Sedovic, W. and Gotthelf, J. H., "What replacement windows can't replace: the real cost of removing historic windows", *Journal of Preservation Technology* **36** (4), 25 (2005).

[21] "Saving Windows, Saving Money: Evaluating the Energy Performance of Window Retrofit and Replacement", (National Trust for Historic Preservation, 2012).

to homeowner association covenants.[22] Finally, the curtain walls of some large buildings built in the 1950s and 1960s cannot support the additional weight of IGUs. The weight of an IGU is typically more than double that of the single-pane window it replaces.[23]

Storm windows and interior panels. Exterior storm windows are a long-established technology for improving the efficiency of a single-pane window. With the addition of a low-*e* coating they can be nearly as efficient as an IGU, and have most of the other good qualities as well.[24] They are fairly inexpensive (ca. $15 per square foot installed).[25] The primary disadvantages are their change to the exterior appearance of a building (as detailed above) and interference with opening and closing of some existing windows.

Interior panels that are sealed against the existing window frame are also much less expensive than full replacement, and again largely duplicate the good qualities of IGUs for soundproofing, comfort, and efficiency. They may interfere with the operation of the original window and with existing shades. Cold-weather condensation of water between the panel and the original pane is also a concern with interior panels.[26]

Low-*e* window films. Adhesive window films are widely used to modify the optical properties of existing windowpanes both in buildings and vehicles; they are typically applied to the interior (#2) surface of the pane. One low-*e* product reduces the winter *U*-factor of a 1/8" pane from 1.04 to 0.61.[27] Low-e window films are priced at roughly $10/sf (installed); pane replacement is about $20/sf (installed).[28] An interior surface low-*e* layer also increases comfort levels.
Interior condensation resistance is diminished by the low-*e* layer.[29] Condensation also affects emissivity, and interior surface low-e layers are only effective on windows without condensation. Water and ice are high emissivity substances, and even a very thin layer of condensed water or ice is sufficient to turn a low-*e* surface back into a high-*e* one.

Low-*e* replacement panes. Windowpanes with low-*e* surfaces can replace a conventional single-pane at a price similar to that of replacing broken panes. The "hard coat" layer is a permanent and durable change of one surface of the glass pane; this type of pane is also used for low-*e* storm windows and interior panels. The layer is effective in lowering the *U*-value. As a representative example, one company's uncoated 1/8 inch glass pane has a winter *U*-factor of 1.04; a similar pane with a low-e "hard coat" has a *U*-factor of 0.66.[30] As for low-e window films, when the low-*e* layer is on the #2 (interior) surface, occupant comfort is improved compared to an unimproved single-pane, but the condensation properties are degraded.[29]

4. PROGRAM APPROACHES

The SHIELD program will support research on modifying existing glass windowpanes and on advanced manufactured windowpanes. These are to be designed as retrofits for existing single-pane windows that significantly improve their insulation. Changes in the window's appearance should be minimal. The occupant should notice improved comfort, condensation resistance, and possibly soundproofing.

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[22] The Covenants, Conditions, and Restrictions (CC&R) agreements of homeowner associations can be a barrier to total window replacement. See the webpage "Installing New Windows in HOAs: Regulations and Best Practices" published by Educational Community for Homeowners.

[23] Browning, W., Hartley, A., Knop, T. and Wayne, Curtis B., *Mid-Century (Un)Modern: An environmental Analysis of the 1958-73 Manhattan Office Building* (Terrapin Bright Green LLC, 2013).

[24] Modern IGUs often incorporate argon or xenon between the two panes, which improves their performance over a simple air gap between panes. See ref. 10.

[25] Cort, K. A., "Low-E Storm Windows: Market Assessment and Pathways to Market Transformation", report PNNL- 22565 published by Pacific Northwest National Laboratory (2013).

[26] Curcija, C., Goudey, H., Mitchell, R., and Dickerhoff, E., "Highly Insulating Windowpanel Attachment Retrofit", report published by Lawrence Berkeley National Laboratory (2013).

[27] "Enerlogic 70 film technical information", webpage published by Solutia, Inc. (retrieved May 16, 2015). The visible transmittance of a clear pane with film applied is 0.70; an unimproved, clear pane's transmittance is about 0.91 .

[28] Consol, Inc. (February 24, 2014). "Energy Analysis for Internal and External Window Film Applications for Existing Homes in Florida". Report commissioned by the International Window Film Association.

[29] Wright, J. L. (2014). "The use of surface indoor low-e coatings: The implications regarding condensation resistance", presented at the ARPA-E Workshop on Single-pane Window Efficiency (November, 2014).

[30] Pilkington, Inc. products "Optifloat clear" and "Energy Advantage" panes; see *Pilkington North America Architectural Glass Product Guide*, pp. 41-42 (October 2014). The low-e layer reduces the visible transmittance of the 1/8 inch pane from 0.91 to 0.84 .

U-factor and condensation in single and double pane windows: Among the existing retrofit technologies, improving the single-pane window with a low emissivity coating on the pane is the closest to achieving the combination of properties that SHIELD is targeting. The coating significantly improves the insulating properties of the pane, in some cases with only a modest change in its appearance.[27,30] However, the goals of SHIELD are not achievable by emissivity control alone.

This is explained further by Fig. 3, which illustrates design exercises for three types of window: (i) (label: single) single-pane with coatings of varying emissivity, (ii) (label: double) double pane with coatings of varying emissivity, and (iii) (label: single + barrier) single-pane with a low-e coating and a thermal barrier of varying *R*-value. The exercises compares the U-factor and condensation temperature of the glazing over a range of design parameters for each type of window.

For the single-pane exercise, each point on the curve corresponds to a different emissivity e_2 for the interior, #2 surface of a single 1/8 inch thick pane of glass. The emissivity of a surface is the ratio of its thermal radiation emission compared to the theoretical maximum for its temperature. By definition, emissivities range from 0 to 1; glass has an emissivity of 0.84, and a good low-e layer has an emissivity of 0.1 or lower.

In the figure, the "condensation temperature" T_C is plotted against the *U*-factor for the center of the pane. In this document, T_C is defined as the exterior temperature at which condensation will appear at the center of the interior surface of the pane with standard interior & exterior conditions.[31] Physically, condensation occurs when the temperature at the center equals the dewpoint of the interior of the building. The results for the U-factor and the condensation temperature were obtained using window modeling software published by Lawrence Berkeley National Laboratory.[32]

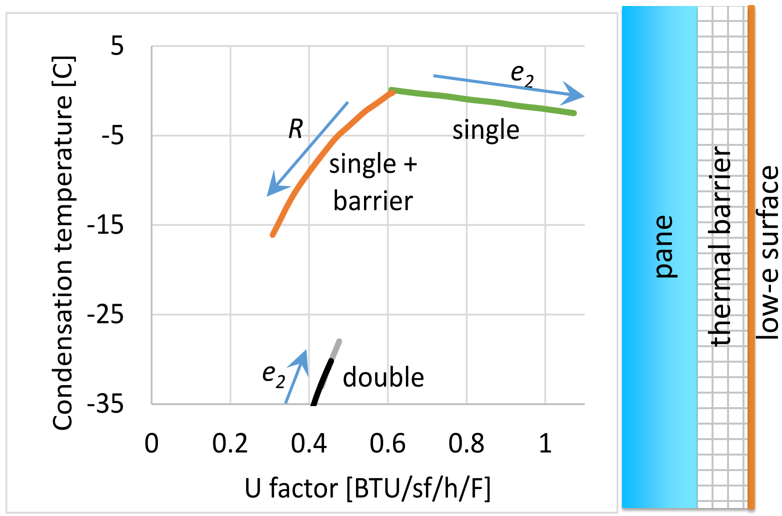

Figure 3: Condensation temperature T_C as a function of *U*-factor for three types of window: (i) (green line) Single-pane with varying surface 2 emissivity e_2. The direction of the blue arrow corresponds to e_2's change from 0.1 (left terminus) to 0.84 (right). (ii) (black) Air-filled double glazing. e_2 now indicates the varying emissivity of the interior surface of the outer pane; only the region from 0.65 to 0.84 (right terminus) is shown. (iii) (orange) Single-pane with fixed e_2 = 0.10 and a thermal barrier layer, as illustrated at right. The direction of the arrow corresponds to variation of the barrier layer's *R*-value from 0.0 (upper terminus) to 2.0 sf·hr·F/BTU.

An interesting feature for a single glass pane is that, while the lowest emissivity (e_2 = 0.10) gives a substantially lower *U* than the higher values of e_2, it also corresponds to an increased (poorer) T_C. High emissivity surfaces emit nearly the maximum possible flux of thermal radiation, and they also absorb incident thermal radiation nearly completely. Thus an unimproved, e_2 = 0.84 glass pane is warmed both by the heated air inside the room and by absorbing nearly all of the thermal radiation incident on it from the room. An improved, e_2 = 0.10 pane reflects most incident thermal radiation back into the room. This reduces the transfer of heat to the windowpane, but it also leaves the pane colder than it was for an unimproved pane. The lower *U*-factor for the improved pane is a direct consequence of this, but it also corresponds to a T_C that is 3.5 C higher than it was for the unimproved pane.[29]

The properties of a double pane window with a 0.5 inch air gap between the panes are shown near the bottom of the figure. A double pane window without a low-e coating has a center-of-glass *U*-factor of about 0.48, which is somewhat better than the single-pane with a low-*e* surface. However, the condensation temperature is far lower. This can be understood from the *R*-value $R = \Delta T/H$ between the panes, which is the ratio of the temperature difference ΔT between the panes and the heat flux *H* between them (F·sf·hr/BTU). This R-value is similar to the R-value between the interior pane and the room, and the two resistances dominate the ultimate *U*-factor calculation for the window. The interior pane's temperature is thus about halfway between the exterior temperature and the interior temperature, which is far better than the situation with a single-

[31] The standard interior conditions are temperature of 21 C and relative humidity of 30%. The exterior wind speed standard is 5.5 m/s.

[32] The data were calculated using the "Therm" window modeling software published by Lawrence Berkeley National Laboratory; winter *U*-factors correspond to an exterior temperature of 0 F (-18 C). Therm, version 6.3 (July 2013); see the webpage "Therm – Windows and Daylight Group".

pane. A low-*e* layer on surface #2 (outer pane, interior surface) further insulates the space between the panes, and both the U-factor and the condensation temperature continue to improve to values typical of contemporary IGUs.[33]

The remainder of this section consists of examples of possible technical approaches to improve on the performance of a single-pane window. These examples are provided for illustration only. ARPA-E welcomes all innovative solutions that meet the technical performance targets in Section I.E of the FOA.

Transparent thermal barriers. Transparent thermal barrier layers are one approach that could improve a single-pane window's properties beyond what can be obtained by emissivity control alone. These might be applied as a paint or an adhesive film to an existing pane. For newly manufactured panes, they might also be created by modifying a pane's surface at the factory, as is presently done to manufacture "hard coat" low-emissivity panes.

The third curve in Fig. 3 illustrates the T_C-U behavior of a single-pane with a thermal barrier between the pane and a low-*e* layer ($e_2 = 0.1$). The structure is illustrated at the right of the figure. As the *R*-value of the barrier increases, the condensation temperature falls and the *U*-factor of the window improves. The terminal point at $U = 0.30$ corresponds to an *R*-value $R = 2.0$ sf·hr·F/BTU (0.35 m^2·K/W). Achieving this with a 3 mm barrier layer would require a material with a thermal conductivity of 0.01 W/m/K. As a guide, $U = 0.40$ needs 0.02 W/m/K, and $U = 0.50$ needs 0.05 W/m/K with a 3 mm layer. For reference, 0.02 W/m/K is achieved in highly porous silica aerogels.[34]

Materials for transparent thermal barriers. Thermal barrier materials used in building envelopes are usually porous. This fact can be roughly understood from the "minimum thermal conductivities" of solids. These are estimated from the fundamental properties of phonons (the vibrational quanta that carry heat and sound). Thermal conductivity is related to the distance a phonon can travel without being scattered. The crucial assumption leading to a minimum thermal conductivity is that the worst that disorder can do is to limit this phonon scattering length to the distance between neighboring atoms. The thermal conductivity of silica glass, which is about 1 W/m/K near room temperature, is consistent with this picture.[35] A solid glass pane conducts heat well enough that it hardly affects the final U-factor for a window.[33]
Introducing porosity reduces the thermal conductivity by removing the material in which phonons propagate. The thermal conductivities of porous, silica-based materials in vacuum are also fairly consistent with minimum thermal conductivity rules that allow for porosity.[35]

In practice, highly porous thermal insulators are usually used in air, and heat transfer is then via the entrained gas and not the solid matrix. The porous, air-filled materials continue to work as good thermal insulators because gases have intrinsically low thermal conductivities compared to solids. The conductivities are lowered even further when the pores are micron size or smaller, which is known as the "Knudsen effect".[36]

While low thermal conductivity materials are generally porous, in some non-porous materials thermal conductivities below "minimum" values have been found. One example is a tungsten selenide material that was found to have a thermal conductivity about six times lower than the predicted minimum thermal conductivity.[37] The fact suggests that a breakthrough in lowering the conductivity without resorting to porosity is at least conceivable. As explained further below, this approach might more readily lead to a transparent thermal barrier than do porous materials.

For transparent barrier layers, the solid material used as the matrix of a porous material is intrinsically transparent. However, the pores cause Rayleigh scattering of light, which may cause an unacceptable "haze" in the window.[38] Porous, silica-based

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[33] Harvey, L. D. Danny, *A Handbook of Low-Energy Buildings and District-Energy Systems* (Earthscan, 2006), p. 72. Fig. 3.21 shows the temperature profiles for several designs of double pane windows.

[34] Baetens, R., Jelle, B. P., and Gustavsend, A., "Aerogel insulation for building applications: A state-of-the-art review", *Energy and Buildings* 43, 761–769 (2011).

[35] Hopkins, P. E., Kaehr, B., Piekos, E. S., Dunphy, D., Brinker, C. J., "Minimum thermal conductivity considerations in aerogel thin films", *J. Appl. Phys.* 111, 113532 (2012). http://dx.doi.org/10.1063/1.4729325.

[36] "Experimental validation of the Knudsen effect in nanocellular polymeric foams", Notario, B., Pinto, J., Solorzano, E., de Saja, J.A., Dumon, M., Rodríguez-Perez, M.A., *Polymer* 56, 57-67 (2015).

[37] Catalin Chiritescu, C., Cahill, D. G., Nguyen, N., Johnson, D., Bodapati, A., Keblinski, P., and Zschack, P. "Ultralow Thermal Conductivity in Disordered, Layered WSe_2 Crystals", *Science* 315, 351-353 (2007).

[38] Haze is defined as the percentage of an incident light beam that is scattered when it passes through a window. For reference, low-*e* "hard coat" glass panes have a haze as large as 0.5 %, which is usually considered acceptable. See "Haze in Glass Products", Cardinal Glass, Inc., Bulletin #CG07 (September 2013).

aerogels provide a good example. Depending on their preparation, silica aerogel films may scatter light fairly strongly. This reflects a broad pore size distribution that extends to sizes comparable to the typical wavelength of sunlight (500 nm). Aerogel powders are used for translucent thermal barriers in skylights and other products,[34] but transparent forms have not yet been used for commercial windows.

There are several less-developed approaches that could also yield a transparent, porous thermal barrier layer suitable for use in windows. One approach embeds silica nanocapsules into polymer films. Here the pore size distribution has little dispersion, since it is set by the diameter of the nanocapsules. A second approach is templating of silica and other materials using self-assembled block copolymers as templates. This approach can yield porous structures that are fully periodic, again giving more control over the dispersion of pore sizes.[40] Polymer nanofoams could also potentially yield transparent porous materials if formation of larger pores can be sufficiently suppressed.[41]

Materials for low-emissivity. Low-e materials are likely be needed as part of SHIELD program technologies. Such materials have a low emissivity because their interfaces reflect thermal radiation with a wavelength around 10 microns. On the other hand they must transmit visible light nearly completely. Existing products mainly achieve this using two approaches. One is to sputter several layers including a very thin metal layer onto glass or onto a polymer carrier film; the resulting layers are termed "soft coat" in the trade. The second is pyrolysis at the factory to create a transparent conducting oxide on the surface of glass. This is more durable than the soft coat and has been termed a "hard coat". One commercial hard coat glass has an emissivity of about 0.15 with a visible light transmittance of more than 80%.[30] Soft coated glass or window films can have still lower emissivities, typically with lower transmittances as well.[27]

These approaches were developed for windows in the 1970s and 1980s, and have been extensively optimized. There are newer materials with potentially suitable properties that are being explored for use as transparent conducting electrodes in solar cells and transparent electronics. These include amorphous conducting oxides, graphene, and layers of nanowires or nanotubes.[42] The SHIELD program may be an opportunity to examine new structures with low emissivity interfaces that have higher visible transmittance, are less costly, or are synergistic with the requirement of improved insulation or the possibility of improved soundproofing.

Soundproofing. A single-pane of glass that is 1/8 inch thick has a sound transmission coefficient (STC) rating of about 29 db; most sound from the outside is reflected by the pane, with the reflection generally increasing with acoustic frequency. 29 db is inadequate if the exterior noise is significant. The STC rating can be increased by using more glass (the "mass law"),[43] but weighty panes and structures aren't suitable for retrofitting of existing panes and sashes.
Incorporation of a sound-deadening layer is also effective. Laminated glass consists of two panes with an adhesive polymer interlayer. It was developed as a "safety glass" for vehicles, but it turns out that laminated glass also has a soundproofing property. It outperforms a monolithic glass pane with a similar weight by up to 4 db.[16] The sound-deadening performance of the interlayer is related to a remarkable "coincidence effect" for sound transmission in windowpanes and more generally in thin panels.[43] At specific combinations of frequency and angle of incidence for sound, the weight-dictated reflection of sound is nearly canceled by the launching of bending waves in the glass itself, leading to significantly enhanced sound transmission near the coincidence frequencies. The viscoelastic layer directly absorbs this sound sufficiently well that it reduces the coincidence effect sound transmission.

Polyvinyl butyral (PVB) that has been optimized for its sound deadening effect is available commercially.[44] The development was a byproduct of the widespread use of PVB as the interlayer for laminated glass, and there are likely other transparent

[39] Liao, Y., Wua, X., Wang, Z., Yue, R., Liu, G., and Chen, Y., "Composite thin film of silica hollow spheres and waterborne polyurethane: Excellent thermal insulation and light transmission performances", *Materials Chemistry and Physics* 133 (2012) 642–648.

[40] Coquil, T., Richman, E. K., Hutchinson, N. J., Tolbert, S. H., and Pilon, L., "Thermal conductivity of cubic and hexagonal mesoporous silica thin films", J. Appl. Phys. 106, 034910 (2009).

[41] Forest, C., Chaumont, P., Cassagnau, P., Swoboda, B., and Sonntag, P., "Polymer nanofoams for insulating applications prepared from CO_2 foaming", *Progress in Polymer Science* 41 (2015) 122–145.

[42] Ellmer, K., "Past achievements and future challenges in the development of optically transparent electrodes", *Nature Photonics* 6, 809-817 (2012). http://dx.doi.org/10.1038/NPHOTON.2012.282.

[43] Long, Marshall, "Thin Panels: Bending Waves and the Coincidence Effect", *Architectural Acoustics – Second Edition* (Academic Press, 2014), pp. 354-358.

[44] "Saflex® QS acoustic PVB interlayer" (Eastman Chemical Co., October 2014).

materials with suitable properties for sound deadening that would not be suitable for lamination. Researchers have also done calculations showing additional soundproofing by marrying a viscoelastic polymer layer (such as PVB) with a porous layer.[45] That research reflects the fact that open-cell porous materials, including silica aerogels, are also well-known to have significant sound-absorbing properties.[46,47] Since porous materials are often good thermal insulators, it appears probable that layer structures on single windowpanes can be designed that will improve both the thermal insulation as well as its soundproofing.

A much more recent approach to sound absorption is acoustic metamaterials. These involve small, acoustically active structures that are engineered to manipulate acoustic waves in ways that can be quite surprising. Among other possibilities, they present the possibility of directly absorbing low-frequency acoustic waves.[48] The current approach to low frequency soundproofing relies on increasing the total weight of glass in the window to increase its mass law reflection, which is undesirable because of its usage of materials and is unsuitable for single-pane retrofitting. It is also plausible that acoustic metamaterials could be designed to mitigate the coincidence effect as an alternative to viscoelastic and porous layer soundproofing.[49] On the other hand, acoustic metamaterial structures are intricate and may be too costly to incorporate into windows; they have also not been designed with an eye to optical transparency.

The examples of possible technical approaches provided in Section I.B of the FOA are for illustration only. ARPA-E welcomes all innovative solutions that meet the technical performance targets in Section I.E of the FOA.

C. PROGRAM OBJECTIVES

The technical categories for this program are: (i) products that can be applied to existing windowpanes, (ii) manufactured windowpanes that can replace existing windowpanes in their current sashes, and (iii) innovative components that will enable superior performance in the first two categories. While the objectives for the first two categories are similar, the performance goals are more stringent for the second category. The overarching goal is to create single-pane window retrofit technologies that will be widely and rapidly adopted by building owners and managers.

1. HEATING ENERGY EFFICIENCY, CONDENSATION RESISTANCE, AND COMFORT

SHIELD seeks technologies that will improve cold weather *U* factors of the glass pane of a single-pane window and reduce winter energy usage. Standard temperatures and exterior wind speed for winter and summer *U*-factors have been established by the National Fenestration Research Council (NFRC).[50] While the NFRC typically rates an entire window's performance, including the window's frame and averaging over the entire area, the present document will refer exclusively to "center-of-glass" (cog) *U* values. Broadly speaking, center-of-glass *U*-factors are higher than window-average values, but this depends on the details of the sash and frame.[10] The center-of-glass *U* values should be lower than 0.5 and 0.4 for the applied product and manufactured windowpane categories, respectively, which may be compared to the unimproved value $U = 1.1$.

At the same time the condensation resistance should be improved compared to that of an unimproved single-pane of glass. The targets for the maximum condensation temperatures are T_c = -5 C and -10 C for first and second technology categories, respectively. They are 2.5 and 7.5 C better than that of an unimproved single-pane window. The targets reflect the value of a healthful minimum relative humidity indoors of 30% or larger (at 21 C).[13] Additionally, water or ice that is condensed on low-e window surfaces erases the *U*-factor and comfort improvements associated with a low-*e* coating. This erasure will occur in the coldest weather, which is when the low-e surface's insulating properties are most needed.

The more stringent *U*-factor and T_C targets are approximately those calculated for the "low-e + barrier" structure of Fig. 2 assuming a 3 mm barrier layer with thermal conductivity 0.02 W/m/K.

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[45] Suresh, S., Lim, T.C. and Kastner, J., "Predicting acoustic transmission loss through laminated glass with air and porous layers", *Int. J. Vehicle Noise and Vibration*, Vol. 8, no. 3, pp.237–260.

[46] Allard, J. F.. and Atalla, N., *Propagation of Sound in Porous Media: Second Edition* (Wiley, 2009).

[47] Ricciardi, P., Gibiat, V., & Hooley, A., "Multilayer absorbers of silica aerogel", *Proceedings of Forum Aucusticum, Sevilla* (September 2002).

[48] "Dark acoustic metamaterials as super absorbers for low-frequency sound", Mei, J., Ma, G., Yang, M., Yang, Z., Wen, W., and Sheng, P., *Nature Communications* 3, article number 756 (2012). doi:10.1038/ncomms1758

[49] Xue Jiang, X., Liang, B., Li, R. Q., Zou, X.-Y., Yin, L.-L., Cheng, J.-C., "Ultra-broadband absorption by acoustic metamaterials*", Appl. Phys. Lett.* 105, 243505 (2014). doi: 10.1063/1.4904887.

[50] "Document 100-2014: Procedure for Determining Fenestration Product U-factors" (National Fenestration Research Council , 2013), p. 24.

Occupant comfort is related to the temperature and emissivity of the innermost surface of the window as well as the properties of the rest of the room. The ASHRAE standard is that the temperature of a cool wall should be no more than 10 C below the overall temperature of the air and remaining walls of the room.[51] The temperature difference leads to a "radiant asymmetry" in a room, since the cool wall provides less radiant heating to a person than the warmer walls, ceiling, and floor. The 10 C criterion is intended to satisfy 95% of a random sample of occupants.

Huizenga, *et al.*,[52] have done a comprehensive analysis of the research behind this standard and of its applications to windows. Most work on comfort with windows has assumed an interior surface emissivity of 0.84, which is the value for ordinary glass. A comfort index that applies to low-e interior surfaces has apparently not been published. A plausible extension of the radiant asymmetry concept is to define a radiant temperature T_{rad} of the window that includes both the direct thermal radiation from the window and also the reflected thermal radiation originating from the other interior surfaces in the room. T_{rad} is measured by an infrared thermometer that assumes a surface emissivity of 1.0 at the point being measured.

For a room temperature of 21 C and an exterior wind speed of 5.5 m/s, which are the NFRC assumptions for winter *U*-factors, ARPA-E will use a criterion that T_{rad} should exceed 11 C for exterior temperatures greater than 0 C. This is similar to the results expected for an unimproved double pane window without a low-e coating.[52] A single-pane window with a low-e surface $e_2 = 0.1$ meets this standard.

2. CLARITY, COLOR, AND TRANSPARENCY

SHIELD seeks technologies that only minimally change the appearance of a clear single windowpane as viewed either from outside or inside the building. The clarity of the view through the windowpane can be approximately quantified using the measured "haze" of the windowpane, which is defined as the percentage of incident light that is scattered away from a normally incident beam by the window. Clean float glass has a haze that is well below 1%. Hard-coat low-*e* glass has a haze up to 0.5%, and some laminated glass products reach 1%.[38] ARPA-E anticipates that haze may be a limitation for some technologies, and has set maximum haze targets of 2% and 1% for the applied product and manufactured pane technology categories, respectively. Haze that is significantly below 1% is plainly an advantage in the marketplace, as evidenced by the informal online discussions of blue scattered light from low-*e* windowpanes under certain conditions.[53] On the other hand, only freshly cleaned windows have haze values below about 2%.[54]

The visible transmittance V_T of a window is a standard characterization, and clear single-panes transmit about 91% of visible light and reflect about 9%.[30] Windowpanes developed for this program should have V_T values greater than 70%. They also must not significantly color the transmitted light; the color rendering index R_a according to ISO standard 9050 should be 0.90 or larger.[55] ARPA-E is not setting a specific value for the reflectivity of the glazings, although lower reflectivity products may be more acceptable in the marketplace.

3. WEIGHT AND SIMPLICITY OF RETROFIT, LOW INSTALLED COST, AND SERVICE LIFETIME

ARPA-E's goal in this program is to develop technologies that can be used with existing window frames and sashes, and that will not add substantially to the weight of the pane. Assuming the thickness of the existing windowpane is 1/8 inch, the total thickness of the improved windowpane should be ¼ inch or less, which will be usable with many existing sashes. While ARPA-E is not setting a specific value for the weight of the technologies developed for SHIELD, note that windowpane weight is an issue for some buildings.[23]

[51] "Standard 55-2013: Thermal environmental conditions for human occupancy", ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers, 2013).

[52] Huizenga, C., Zhang, H., Mattelaer, P., Yu, T., Arens, E., Lyons, P. "Window performance for human thermal comfort", University of California, Berkeley (February 2006). Report commissioned by the National Fenestration Research Council.

[53] "Why not more complaints on haze with low-e windows?", Green Building Advisor website (posted October 24, 2013).

[54] "Appearance of installed Pilkington Energy Advantage™ Low-E Glass", Pilkington bulletin ATS 137-3 (July 13, 2005).

[55] "ISO Standard 9050:2003 Glass in building — Determination of light transmittance, solar direct transmittance, total solar energy transmittance, ultraviolet transmittance and related glazing factors", International Standards Organization (2003). The standard uses a standard "D65" light source, and characterizes the light transmitted through the window with regard to the light's ability to render different colors.

ARPA-E has set maximum manufacturing costs at $5 and $10 per square foot for Category 1 and Category 2 technologies, respectively. This cost is to apply at a manufacturing scale of 1 million square feet per annum. Installation of a product to an existing windowpane is likely to add $5 per foot to the price. Installation that requires removal of an existing windowpane and replacement by a new pane is likely to add $15 per square foot to the installed price. These prices are similar to the range of prices for installed window films[28] and for replacement of broken single windowpanes, respectively. These price targets can be set in the context of savings on heating costs. ARPA-E estimates that improvement in a single-pane from U = 1.1 to 0.4 would have saved about $1.50/square foot over the 2014 heating season in Chicago, Illinois; savings will be less in warmer climates.

ARPA-E has set service lifetime targets of 10 and 20 years (median time to failure) for the Category 1 and Category 2 technologies, respectively. For comparison, warranty periods are typically 5 years for window films and 20 years for IGUs. Warranty periods are generally substantially shorter than the actual median service lifetimes.

4. SOUNDPROOFING AND OTHER SYNERGISTIC OPPORTUNITIES

ARPA-E encourages applicants to propose the measurement and development of additional properties beyond the program objectives described above. The objective is to significantly improve the performance and marketability of products based on these technologies.
Soundproofing provides one illustration. The sound transmission class (STC) of a single windowpane (1/8 inch thick) is about 29 decibels (db). An IGU with two 1/8 inch panes has an STC of about 33 db.

An additional example of a synergistic improvement is blockage of ultraviolet light. This is a considered a desirable feature because ultraviolet light accelerates deterioration of room furnishings and contributes to health problems such as skin cancer and eye damage. Ultraviolet blockage is a feature of current window films.[56]

D. TECHNICAL CATEGORIES OF INTEREST

1. CATEGORY 1: APPLIED PRODUCTS

The first category of technologies is for adhesive products that can be applied to an existing windowpane. The thickness of the applied product should be less than 1/8 of an inch. Final tests should be conducted on a single-pane window unit to which the adhesive product has been applied. Applications should specify the size of the windowpane for their technology development.

2. CATEGORY 2: MANUFACTURED PANES

The second category is for manufactured windowpanes that can be installed in existing sashes to replace 1/8 inch thick panes. The windowpane should be less than ¼ inch. The pane should be similar or better in its resistance to breakage than a 1/8 inch pane made from soda lime glass. Final tests should be conducted on a single-pane window unit into which the test pane has been installed. Applications should specify the size of the windowpane for their technology development.

3. CATEGORY 3: INNOVATIVE PARTIAL SOLUTIONS

The third category is for development of components that are beyond the current state-of-the-art and that would enable technologies to substantially exceed the performance, cost, or lifetime metrics in Section I.E of the FOA. Of specific interest are advances in (i) highly transparent thermal barrier layers and (ii) low-emissivity layers. Applicants should describe how the component would be integrated into either a Category 1 or a Category 2 technology. Full Applications must specifically address how the innovative component technology would enable an integrated system to meet or exceed the Category 1 or Category 2 Technical Performance Targets listed in Section I.E of the FOA. This category is particularly appropriate for proof-of-concept awards (see Section II.A of the FOA).

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[56] Boye, C., Presser, F., and Schaeffer, T., "UV-blocking window films for use in museums – revisited", WAAC Newsletter Vol. 32, No. 1 (Western Association for Art Conservation, January 2010), pp. 13-18.

E. TECHNICAL PERFORMANCE TARGETS

For both categories, the technology should be designed for consistency with current ASTM standards for abrasion resistance (ASTM D1044) and fire safety (ASTM D635 – test for flammability, ASTM E84 – test for surface burning, ASTM D1929 – test for ignition properties, and ASTM D2843 – test for smoke density).

CATEGORY 1: APPLIED PRODUCT TARGETS

Measurement conditions and procedures are summarized below.

ID	*Property*	*Metric*
1.1	winter *U*-factor (center-of-glass)	less than 0.50 BTU/sf/hr/°F
1.2	exterior temperature for interior condensation (center-of-glass)	less than -5 C
1.3	exterior temperature at which the interior pane surface has radiative temperature 11 C (center-of-glass)	less than 0 C
1.4	haze	less than 2%
1.5	visible transmittance	more than 70%, with a color rendering index R_a > 0.9 .
1.6	estimated manufacturing cost	less than $5 per square foot
1.7	estimated median service lifetime	more than 10 years

CATEGORY 2: MANUFACTURED PANE TARGETS

ID	*Property*	*Metric*
2.1	winter *U*-factor (center-of-glass)	less than 0.40 BTU/sf/hr/°F
2.2	exterior temperature for interior condensation (center-of-glass)	less than -10 C
2.3	exterior temperature at which the interior pane surface has radiative temperature 11 C (center-of-glass)	less than -5 C
2.4	haze	less than 1%
2.5	visible transmittance	more than 80%, with a color rendering index R_a > 0.9 .
2.6	estimated manufacturing cost	less than $10 per square foot
2.7	estimated median service lifetime	more than 20 years

EXPLANATION OF METRICS:

SHIELD awardees will be required to demonstrate achievement of the technical metrics listed above through measurements following these guidelines.

Winter *U*-factor: Measurements of the center-of-glass *U*-factor should be consistent with NFRC document 100-2014 “Procedure for Determining Fenestration Product U-factors”. NFRC defers to ASTM standard C1363 for insulation measurement procedures, but specifies its own environmental conditions for windspeed (5.5 m/s), interior temperature (21 C), and exterior temperature (-18 C).

Haze and Visible Transmittance: Measurements should be consistent with the procedures of ASTM D 1003 (illuminant C).

Condensation temperature: Measurements of the actual temperature at the center-of-glass are acceptable instead of direct condensation measurements. This procedure assumes that condensation will occur when this temperature falls below the dewpoint in the room. For a room at 21 C and 30% relative humidity, the dewpoint is 3 C.

Radiative temperature: An infrared thermometer calibrated for a surface emissivity of 1.0 can be used to measure the radiative temperature. The measurement should be done at the center-of-glass of the window.

Estimated manufacturing cost and product lifetime: Applicants should provide assessments of manufactured cost and product lifetime to assure that large deviations from the project metrics are unlikely. Awardees will conduct technoeconomic analyses as part of their projects; the indicated manufacturing costs should be achieved for a factory producing 1 million square feet of product annually. Awardees will propose and execute accelerated lifetime measurements as part of their projects.