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Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Windows and Envelope R&D Opportunities Workshop

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Preface

The Department of Energy's (DOE) Building Technologies Office (BTO), a part of the Office of Energy Efficiency and Renewable Energy (EERE) developed this report on a two-day workshop on "Windows and Envelope R&D Opportunities." The workshop was held on May 31 and June 1, 2017, at the Illinois Institute of Technology in Chicago, Illinois. A broad range of expert stakeholders from industry, academia, national laboratories, and government participated, and their feedback was offered to help inform and augment BTO's research and development activities.

In this report, the activities identified by workshop participants are suggestions for BTO to pursue in an effort to achieve DOE's energy efficiency goals. Inclusion in this report does not guarantee funding; activities must be evaluated in the context of all potential activities that BTO could undertake to achieve its goals.

Prepared for: U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Building Technologies Office

List of Acronyms

AAMA	American Architectural Manufacturers Association
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BEC	Building Enclosure Council
BTO	Building Technologies Office
DOE	Department of Energy
ET	Emerging Technologies Program
ICC	International Code Council
IECC	International Energy Conservation Code
IGU	Insulated Glass Units
IR	Infrared
NAHB	National Association of Home Builders
R&D	Research and Development
EERE	Office of Energy Efficiency and Renewable Energy
PCM	Phase Change Material
VIG	Vacuum Insulated Glazing
WDMA	Window and Door Manufacturers Association

Executive Summary

The U.S. Department of Energy (DOE) Building Technologies Office (BTO) Emerging Technologies Program (ET) held a two-day workshop on "Windows and Envelope R&D Opportunities" on May 31 and June 1, 2017 at the Illinois Institute of Technology in Chicago, Illinois. A broad range of about 100 experts from industry, academia, national laboratories, and government participated, contributing their ideas, insights, and perspectives. Their feedback is intended to help inform and augment BTO's research and development activities.

The building envelope is the thermal and mass barrier between the interior and outdoor environment and is one of the primary determinants of how much energy the building consumes and how comfort and indoor air quality are maintained. In fact, approximately 35% of the energy consumed in commercial and residential buildings is used to maintain a comfortable and safe interior environment.

One of BTO's long-term objectives is to reduce the energy use intensity of homes and commercial buildings by 50%. However, currently available building envelope technologies provide only incremental improvements in energy efficiency and will not provide sufficient thermal and mass barrier performance to meet BTO's long-term objective. Because innovative next-generation building technologies are needed, DOE engaged leading building scientists and application experts to help identify new research that can lead to building envelope and windows technologies that can significantly contribute to meeting BTO's long-term objective.

Workshop participants analyzed a variety of technical challenges and explored innovative research areas and activities to identify building envelope technical breakthroughs. The workshop was structured along two major tracks: one for windows and one for opaque building envelopes. Both of these tracks were examined in three breakout sessions, where participants broke off into smaller groups. The three breakout sessions were as follows: 1. Gaps, Barriers and Opportunities, 2. Technical Solutions, and 3. Innovative Technology Pathways and Implementation.

Workshop participants analyzed activities and technologies that could significantly reduce the amount of energy used to heat, ventilate, and cool buildings, and improve occupant comfort and health. They identified 18 opportunities that BTO could choose to prioritize in its early-stage R&D activities, which are listed in Table 1 and Table 2.

Table 1. Technology Concepts & Potential Implementations – Windows

	Topic	Opportunity		Suggested Action	Metrics
1	Higher Thermal Performance	Reduce thermal loads by developing flexible window glazing options that improve performance and occupant comfort. Improve thermal performance for vision and non-vision areas of windows, which would reduce heating and cooling loads and reduce up-front HVAC costs.		Analyze the advantages and trade-offs of thin triples, thermal barriers, better gas filling, and recharge for existing insulated glass units (IGUs). Develop thermally insulating foams usable for structural fill, develop paste-on framing materials, and minimize thermal shorts at IGU perimeters.	Same overall thickness as existing IGUs, self-sealing, fast fill, and longer performance lifetime. Proposed emissivity target of less than 0.03, improved cost target, and proposed thermal conductivity less than 0.10.
2	Switchable glazing, meta-materials, solid state window coatings	Durable materials with independent switching between visible and near infrared (NIR); clear to light scattering or light redirecting properties; neutral color with rapid switching over a broad temperature range.		Develop multi-functional switchable materials; understand the physics of failure of these materials, low-cost manufacturing; understand human factors as related to material properties (e.g. color, glazing switching speed)	Comparable to low-emissivity coating costs ($7/square foot or better). Link material properties to the overall value proposition.

	Topic	Opportunity		Suggested Action	Metrics
3	Daylighting for energy efficiency and comfort with minimal glare	Micro-scale technologies (inorganic microstructures, shape memory alloys) for between-pane applications that have durable modes of actuation and limit off-gassing so they are compatible with low-e sputtered coatings.		Define the optimization goal, create test methods, couple with architectural space to reduce angle of incidence, and examine human factors (health, IEQ impacts).	Spatial daylight autonomy $sDA_{300,50\%} > 50\%$ of the 15-40 ft deep zone from the window; Class A annual daylight glare probability for the view facing the window.
4	Dynamic façades	Self-configuring, self-commissioning, adaptable smart controls that minimize energy, demand, and discomfort while accounting for zone, building, campus, and grid priorities. The façades would be self-powered with turnkey installation.		Adaptive models for distributed control, low-cost sensors, self-reporting, diagnostics; improved comfort models; move beyond static to dynamic parameters.	Components and/or systems that improved energy efficiency over state of the art; methodology and specifications for controls.
		Technology Support Research			
1	Characterization of benefits of advanced windows	DOE achieves energy savings goals by getting consumers to buy in to the benefits of energy efficient windows and proper installation.		Prove the problem through data and studies, create the message to prove benefits, form an advisory council, and disseminate information products.	Leverage existing networks and partners like ICC, Building Enclosure Councils, NAHB, AAMA, WDMA. and the DOE Solution Center.

	Topic	Opportunity		Suggested Action	Metrics
2	Education campaign to promote the benefits of high-efficiency window products for new and existing buildings	DOE achieves energy savings goals by getting consumers to buy in to the benefits of energy efficient windows and proper installation.		Prove the problem through data and studies, create the message to prove benefits, form an advisory council, and disseminate information products.	Leverage existing networks and partners like ICC, Building Enclosure Councils (BECs), NAHB, AAMA, WDMA. and the DOE Solution Center.
3	Financing mechanisms	Mechanisms to reduce the upfront cost to consumers and the cost of manufacturing line upgrades.		Metrics for real estate valuation of non-energy benefits, improved comfort and amenity; methods for re-tooling at lower cost.	Preferential financing terms for window replacement; possible packaging with comprehensive façade upgrades that increase building value.
4	Improved modeling	Design more energy efficient products faster and more cheaply. Rate and compare products.		Integrate public tools with commercial tools; expand construction libraries; modeling tool as an expert system; improve validation.	Tied to open source /not for profit; input to BTO models from finite element analysis; open source model; point thermal bridges; one-step setup from feedback.

Table 2. Technology Concepts & Potential Implementations - Envelope

	Topic	Opportunity	Suggested Action	Metrics
1	Tunable thermal storage in building envelopes	Inexpensive, easily installable materials/assemblies that passively and rapidly capture and release heat to shave peak energy demand, which lowers heating and cooling costs. Tuned for environmental conditions in specific climate zones and buildings. Storage that has a high cycle life.	Leverage nano-based composites and develop evaporative phase change materials and tunable phase change materials.	Phase change materials (PCMs) that melt or solidify within 0.5 degrees of target; number of cycles to failure; range of temperature variation; rate of energy movement.
2	Thermal energy redirection to the ground, sky, or thermal sink using heat pipes or anisotropic materials	Inexpensive, easily installed methods that depending on interior and exterior conditions passively transport heat to/from building spaces rapidly, reduce total heating and cooling energy use, shave peak energy demand and provide resilience in power outages (“passive survivability”).	Map ground/sky heat capacity by climate, season, and depth. Improve existing heat pipes. Develop solid connectors.	Rate of heat removal. Costs of new methods favorable when compared to conventional methods. Positive power generation efficiency.
3	Heat diodes that allow movement of heat in only one direction	Materials and construction methods that passively block heat flow in one direction, thereby allowing retention; or removing heat when needed in response to ambient conditions, thus minimizing energy use for space conditioning.	Determine physical processes, characterize phonon scattering, and assess potential BTO impact.	Thermal rectification factor of about 10.

	Topic	Opportunity	Suggested Action	Metrics
4	Vapor/moisture diodes that allow movement of water vapor and liquid in only one direction	Materials and strategies that passively block vapor/moisture transport in one direction to optimize envelope system drying and occupant comfort, which would reduce energy use and maximize building materials durability.	Literature survey, Scout impact tool market potential estimate, develop materials, and examine scale-up potential.	Quantify performance of product. Produce 10 square feet of material—enough for large scale testing.
5	Ultra-low conductivity insulation materials	Inexpensive, durable insulation materials that achieve ultra-high R values in vanishingly small thicknesses, thus minimizing heat transfer and enabling retrofits of existing buildings.	Scattering studies in 60 nm pore size materials, self-healing polymers for vacuum insulation, and analysis of degradation mechanisms.	Less than 10% R-value loss after 20 years. Increase materials lifetime to 40+ years and R-80 per inch.
6	Materials with greater resilience to installer error and behavior	Inexpensive and adaptable envelope materials that offer fault-tolerant installation and that self-correct improper installation or indicate to builders/installers when improperly installed or not achieving their design performance, thus improving energy efficiency, construction quality, and reducing installation time. Compatible with existing products and installation processes	Materials show visual indication of air leaks or a response to acoustics. Materials exceed performance of existing products.	Reduce time required for test methods by 90%. Develop standards for test methods.

	Topic	Opportunity	Suggested Action	Metrics
7	Diagnostic method to detect insulation values and air tightness during installation	A method that is rapid, requires low levels of effort, and provides a clear indication of the levels of insulation or air sealing achieved. During installation provides installer with feedback that enables immediate remediation, thereby improving as-built energy efficiency and reducing installer cost overruns and overall installation time.	Image processing and big data machine learning with existing tools. Improved detection around natural temperature variations.	Output wall classification per RESNET/IECC with 90% accuracy; identify true R-values; full 3D imaging of walls and cavities.
8	Whole house/building aeroseal for improved air tightness	Inexpensive, durable, rapid whole-building aeroseal to improve or remediate building air sealing, thus increasing energy efficiency and comfort while reducing air sealing time and cost. Compatible with existing and occupied buildings	Research durability, delivery options of interior vs. exterior, safety, cost efficacy, and a delivery system for interior spaces.	Existing standards, safety, and code requirements; lasts unspecified number of years; lack of residue after delivery.
9	Guarantee that new high-performance buildings energy efficiency measures are durable	Databases and models of materials and use cases detailing degradation mechanisms and failure modes to provide architects, engineers, and builders with knowledge of limit states for improved building design and durability, yielding improved energy efficiency over the life of a building.	Identify industry partners and develop understanding of degradation processes; develop and validate models.	Define material classes, mainstream analysis, and implementation method in all high-performance buildings.

	Topic	Opportunity	Suggested Action	Metrics
10	Develop information materials and to better educate customers about advanced window and building technology benefits	Create models and databases based on empirical data gathered from buildings of varying efficiency/performance. These would inform contractors and building owners of the value proposition for various building modifications that improve energy efficiency and occupant comfort/health.	Develop de-rating factor and quantify negative impacts for construction deficiencies; pre-calculated model database of construction deficiencies; map defects to other non-energy benefits.	Derating factors and database for varying efficiencies; air leakages and comfort metrics (ASHRAE standards, for example).

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1 Background

The U.S. Department of Energy's Building Technologies Office hosted a workshop at the Illinois Institute of Technology on May 31 and June 1, 2017, to gather input from industry, academia, national laboratories, government, non-government organizations, and research stakeholders. Participants at the workshop identified emerging technologies and opportunities that could be pursued to develop the next generation of building envelope and window technologies that, if developed and deployed, could reduce heating and cooling loads in U.S. homes and buildings and save energy, reduce operating costs, and result in superior comfort and improved indoor air quality.

Prior to the workshop, participants provided feedback on their areas of interest. This feedback was considered as the overall structure of the workshop was developed (Figure 1). Participants were provided materials related to prior DOE meetings, roadmaps, strategic documents, and several reference documents regarding building envelope and window technologies. (For more information, see the links to references in the Addendum). A limited amount of new material was provided when sessions were conducted. Thus, the workshop participants had a shared understanding of the overall areas considered for research and development (R&D) and technology. About 100 people attended the workshop.

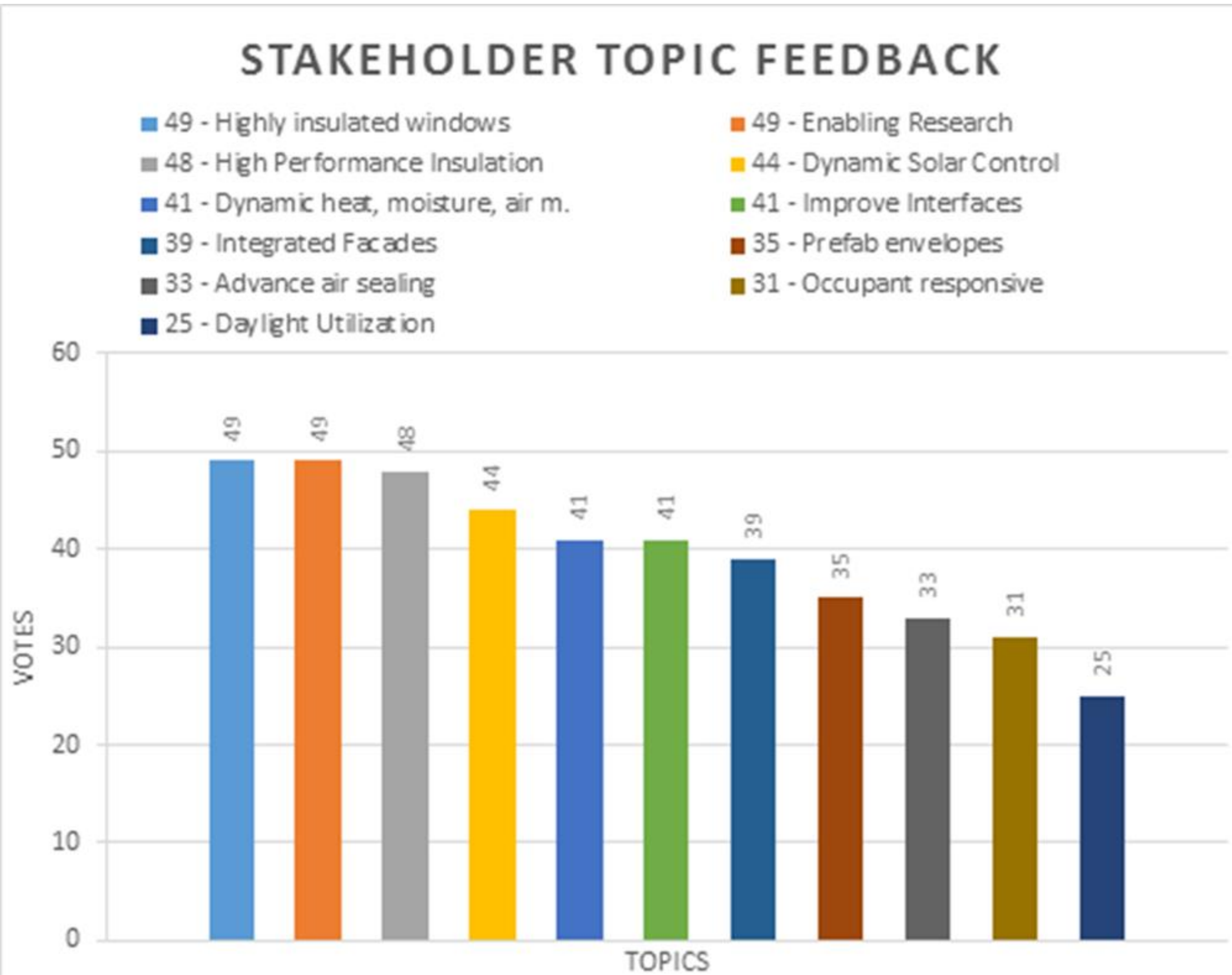

Figure 1 Participants Areas of Interest Prior to Workshop Attendance

1.1 Presentations

The following presentations were made to introduce participants to the objectives and structure of the Windows and Envelope R&D Opportunities Workshop. Plenary presentations from the workshop participants are also provided.

- Welcome and introduction to workshop goals and background, Windows projects and objectives
  Marc LaFrance, Building Technologies Office, DOE
- Overview of envelope program and objectives
  Sven Mumme, Building Technologies Office, DOE
- Envelope technologies
  Roderick Jackson, Oak Ridge National Laboratory
- Commercial windows and envelope technologies, demand-side
  Leonard Sciarra, Gensler
- Residential demand windows and envelope technologies
  Katrin Klingenberg, Passive House Institute US
- Plenary presentations
  Marc LaFrance, Building Technologies Office, DOE
  Sven Mumme, Building Technologies Office, DOE
  Roderick Jackson, Ph.D., Group Leader, Building Envelope Systems Research, Oak Ridge National Laboratory
  Leonard Sciarra, AIA, LEED ap+, ASHRAE, Gensler

1.2 Breakout Sessions

The workshop had two major tracks: one for windows and one for opaque building envelopes. Both tracks were discussed in three breakout sessions where participants broke into smaller groups. The three breakout sessions asked participants, in their professional opinion, to consider the following questions:

1. *Gaps, Barriers and Opportunities*—What are the most significant problems, what can be improved, and what barriers are holding back greater energy and cost savings in building envelopes and windows?

2. *Technical Solutions*—What can new technologies and approaches offer to provide greater value to building owners/operators? Which approaches are better for short-term solutions or long-term solutions? What areas beyond DOE's purview help produce successful innovative products?

3. *Innovative Technology Pathways and Implementation*—How could all stakeholders and DOE use the answers generated during the first two sessions to bring solutions to the market? What are priorities, metrics, and goals that can help make that happen?

1.3 Breakout Session 1 (Day 1, Morning) — Gaps, Barriers, and Opportunities

In the first breakout session, participants in the building envelopes track chose to join a new construction or an existing building group, and the participants in the windows track chose to join a residential or a commercial building group. The number of stakeholders in each breakout group was about the same. Each workshop started with the facilitator stating the goal for the group along with a few examples to get the group started. A leader and a notetaker each volunteered to help coordinate the workshop, record results, and report them to the overall group in plenary sessions. Each group identified and prioritized opportunities, in their professional opinions, by discussing the existing problems, gaps, and areas under investigation. Each group held a Pareto vote to collectively prioritize the opportunities. (Each priority opportunity received 20-25% of the votes relative to the number of items.) Table 3 provides a summary of the top priorities participants identified that they explored in more depth in Session 2.

Table 3. Gaps, Barriers, and Opportunities Identified by Participants

	Windows		Envelope	
	1A Residential	**1B Commercial**	**1C Existing Buildings**	**1D New Construction**
1	Higher thermal performance and solar control of windows	Need for dynamic façades	High thermal conductivity materials that can also manage directed heat flow	Fragility, cost; moisture-resistance and fire-resistance of advanced insulations
2	Modeling and the need for greater model fidelity	Need for efficient and affordable daylighting	New ways to use thermal mass, thermal storage, and multi-functional materials	Lack of knowledge around durability and useable life of envelope components
3	Better assessment and characterization of the energy benefits of efficient windows	Smart glass	Improved materials for air-sealing, vacuum sealing, flexible sealing	Need for improved education of stakeholders, and alignment of incentives
4	Better assessment and the characterization of the non-energy benefits of efficient windows	Grid integration of façades systems	Lack of code enforcement and need for education for code officials	Integration of envelope component definitions into modeling and design software
5	Other Lower Priority Items • Integration of other technologies to achieve lower cost • Education to decision makers • Large stock of existing windows	Other Lower Priority Items • Vacuum glazing performance • Non-energy benefits • Lack of standardization		Other Lower Priority Items • Misaligned incentives across stakeholders • Testing capabilities for assemblies for multiple materials • Optimizing design around “wrong” parameters, design criteria

				• Whole building leak testing • Lack of building performance info database

1.4 Breakout Session 2 (Day 1, Afternoon) — Technical Solutions

In the second breakout session, participants were again separated into four groups. The envelope groups were identical to those of the first breakout session. In general, each participant returned to his or her original breakout group. As for the windows groups, the top technology development items for both residential and commercial buildings were assigned to one group, and technology support (also called enabling research) items were assigned to another group. This change altered the participant mix in each group, which was beneficial because each group's participants now provided a more diverse range of expertise.

Each group focused on identifying technology solutions that showed early promise to potentially address one or more of the gaps, barriers, and opportunities identified and ranked high in importance during the first breakout session. Technology solutions identified by participants would ideally be 5-15 years from commercialization. That range increases the chance that proposed solutions would be within the technology readiness level range appropriate for the ET program. Each of the four breakout groups also identified gaps, barriers, or opportunities that were not identified during the first breakout session, and these were incorporated into the discussion.

Each group briefly reviewed the gaps, barriers, and opportunities to be discussed. Most of the session was devoted to brainstorming solutions. The length of the discussions and the number of solutions identified for each gap, barrier, or opportunity varied widely. Depending on the nature of the gap, barrier, or opportunity, participants sometimes readily proposed several potential solutions. For some items, extended discussion produced only one potential solution. Some of the gaps, barriers, and opportunities identified in the first breakout session were related to non-technical issues such as training, code enforcement, or financing. Participants were encouraged to think about these barriers expansively—not only direct solutions (e.g., an education campaign to address a lack of training), but also potential technology solutions that might circumvent the barrier (e.g., reducing component complexity to reduce the need for training).

Similar or overlapping solutions were consolidated, and the group ranked each potential solution. Participants were instructed to divide their choices evenly between those they felt had the greatest potential for energy savings and were feasible in the near term (0-5 years from commercialization), medium term (5-7 years from commercialization) and long term (10-15 years from commercialization). Participants were not permitted to vote more than once for any potential solution, thus ensuring an adequate distribution of votes across solutions.

Each breakout group identified a volunteer who reported a summary of the discussion to all the workshop participants. The report was limited to only those ideas the participants identified as having the most potential and were the most feasible. The major potential technical solutions or solution areas that were reported are identified by breakout group in Table 4.

Table 4. Technical Solutions Identified by Participants

Windows 2A Technology Support	Windows 2B Technology Development	Envelope 2C Retrofit Applications	Envelope 2D New Construction
Characterization of Benefits	Higher thermal performance	Thinner cladding with high R-value/inch (lower weight, fewer fasteners)	Better customer education; de-rate factors for improper installations; defect database
Modeling methods & climate energy performance	Smart glazing	Façade coating with air and water sealing, R-20, transparent	Materials R&D to enable confidence in durability
Education campaign, cost models, and value proposition	Daylight penetration	Grid-responsive thermal storage	Diagnostic method to detect insulation value during installation
Development of financing mechanisms	Dynamic façades	Thermal energy redirection to ground, sky, or useful work	Aerosol for whole house air sealing
Supply chain & distribution agreements	Grid integration	Materials with greater resilience to installation conditions, installer behavior	Rapid, quantitative method for testing air tightness of incomplete façades
	Shading and movable insulation		High-performance structural insulation materials

1.5 Breakout Session 3 — Innovative Technology pathways and Implementation

The most highly-ranked solutions advanced to the third breakout session, where the workshop participants discussed them in detail. Some revision and regrouping of the solutions was done immediately prior to the third breakout. The regrouping resulted in two categories for windows research: technology development and enabling research. The regrouping resulted in six technology pathways and solutions for envelopes: thermal materials for heat transfer; thermal storage and distribution; air sealing; diagnostic tools; durability and moisture; and education. Results of the third breakout session discussions are summarized in the remainder of this report.

2 Windows Sessions

2.1 Technology Development

2.1.1 Daylighting

Participants discussed how daylighting has significant potential to reduce indoor lighting energy use in commercial buildings. However, technological solutions to date have not been cost effective. These solutions have not achieved significant reductions in artificial lighting energy requirements over the full range of sun and sky conditions, nor within a significant fraction of the building space (e.g., 30–40 feet from the window). Some solutions can increase visual and thermal discomfort, as well offset lighting energy savings due to increased solar heat gain, which increases cooling energy and cooling peak demand. Participants noted that successful solutions increase occupants' connection to the outdoors by preserving some unobstructed, unmitigated view to the outdoors, improve the uniformity of brightness throughout the room cavity, preserve the natural spectrum of daylight, and provide temporal variation in daylight distribution and intensity as the cloud cover changes during the day. Daylighting is thought to improve health, productivity, and well-being in schools, hospitals, and general work places, but participants cautioned that these claims have not yet been verified.

In the near term, participants felt that daylighting design optimization goals could be more clearly defined. These could include such issues as what level of luminance non-uniformity is acceptable to occupants and whether some degree of chromatic dispersion is acceptable to occupants, among others. Participants felt that improved metrics and tools for modeling glare are needed so systems that make use of specular redirection can be designed. Participants noted they and other researchers could benefit from more reliable data regarding daylighting's links to health and productivity. Standardized test methods that verify daylighting provisions performance targets in energy efficiency codes and standards are being met need to be developed.

In the medium and long term, participants believed that R&D should focus on micro-scale technologies (e.g., inorganic microstructures, shape memory alloys) that can provide an optimal response over a wide range of solar intensities and incident angles. Those technologies could foreseeably achieve broad market adoption in both retrofit and new construction industries, participants said. In their professional opinion, these technologies would need to rely on modes of actuation that could withstand high solar intensities yet be durable over a 10–20 year life. Participants cautioned that if the technology includes a between-pane system, pragmatic considerations such as minimizing damage to low-e coatings when shipping, mitigating off-gassing within the between-pane gap, and similar concerns would need to be addressed. To achieve cost-effectiveness, participants said the technology should be capable of being manufactured at a large scale, and be capable of being installed and maintained at minimal cost (e.g., a self-powered, plug-and-play system). They also added that dual-purpose technologies would improve cost effectiveness, as well (e.g., power generation and daylighting). To gain market acceptance, participants also thought aesthetic considerations would need to be met.

2.1.2 Dynamic Façades

Dynamic façades actively modulate solar radiation and daylight intensity and direction, conductive and radiative heat transfer, and convective fresh air transfer across the boundary between the indoor and outdoor environments. Through automation, dynamic façades balance occupant requirements for daylight and views to the outdoors against glare, thermal comfort, and heating, ventilation, and air conditioning (HVAC) load minimization constraints, responding in real time to changes in outdoor and indoor conditions. As industry progresses toward net zero energy buildings, participants noted that integrated solutions could minimize window and lighting loads during critical peak periods by using synergistic low-energy cooling strategies. (One example participants gave described how dynamic façades could enable more efficient HVAC operation or installation of more efficient HVAC systems.) Participants stressed that dynamic façades could provide energy, peak demand, operating, and capital cost savings while providing a more optimally managed indoor environment and contribute to the health and well-being of building occupants. Dynamic façades are also adaptable, they said, and could be modified when space is reconfigured and as building uses and load profiles change. Dynamic façades, controlled in concert with other building energy systems components (such as lighting, HVAC, and the building perimeter and core), could be another way, participants noted, for utilities to manage grid loads.

Automated indoor and outdoor motorized shading have been commercially available since the mid-1970s, double façades in the 1990s, and switchable glazings in the mid-2000s. However, market adoption of dynamic façades has been limited, participants explained, because of various technical and market-related issues such as the perceived complexity of the technology. For example, participants spoke about building owners and operators who may believe that dynamic façades are technologically complex. In reality, participants said, properly designed and installed dynamic façades are simple both in concept and in operation. The participants also suggested that building owners and operators could also have concerns regarding technology lifespan and cost. In the participants' collective professional opinion, DOE's near-term activities could focus on stakeholder education and quantifying returns on investment that include "soft" benefits (i.e., comfort and productivity), as well as understanding and addressing how system costs inhibit market adoption. Participants hoped that, in the future, designs for new buildings, or buildings that are to undergo extensive retrofit, would include features that enable dynamic façades to be installed. To increase consumer confidence, participants proposed that standards for evaluating lifetime durability of components (e.g., motors, actuators) should be developed and implemented. Participants suggested that medium-term activities should define the appropriate markets and applications where dynamic façades are most cost effective (e.g., offices hospitals, and similar buildings) or most appropriate for meeting zero energy goals. In the long-term, participants thought activities should develop advanced technology and science that would enable dynamic façades to be implemented as turnkey, plug-and-play systems. They envisioned systems that could be self-powered, self-configuring, self-commissioning, integrated with other building systems, and able to adapt to the changes that occur at the zonal, building, campus, and utility grid levels during the 60–80 year lifespan of typical commercial building façades. Actuation mechanisms that are simpler, cost less, and are more durable should be developed, participants said. Models that can accurately predict the effect of dynamic façades on visual and thermal comfort will be needed, they said, and monitoring and verification tools – as well as fault detection and diagnostic tools – will be needed so that building operations are more transparent.

2.1.3 Highly Insulated Windows

Windows usually have the least effective thermal performance of all building envelope components. The multiple functions windows must serve—provide views, daylighting, egress, and other functions—limits their ability to block heat transfer when compared to walls and other opaque elements, which can simply add thick, opaque insulation layers. Participants noted that window glazing systems can significantly improve windows thermal performance because they can cover most of a window (typically 80% of the window can be covered with glazing). Past efforts to dramatically improve glazing thermal resistance have not resulted in products that moved into the market in significant numbers, participants noted. Introduction of conventional triple and quadruple glazed IGU designs increased window weight and thickness substantially, which in turn increased the complexity of the framing beyond what was cost effective. According to the participants, part of the cost increase was also due to the addition of a second spacer system and the additional effort required to assembly the IGU. Other efforts, such as low-e coated suspended films that effectively resulted in triple and quadruple glazing did not increase weight, but durability and reliability issues, as well as high materials and fabrication costs, they noted, prevented that technology from being more widely implemented.

Nevertheless, participants were optimistic about the technology's potential. In certain climate zones, they noted, windows with an IGU thermal resistance doubled to R7-R8 and managed with dynamic solar controls could result in close to net zero additional energy use due to windows when compared with opaque walls.

Participants identified three new technical approaches other than the convention ones outlined above:

1. Recent improvements in thin glass technology, driven by demand items such as large TV screens, have reduced the cost of sub-millimeter glass such that it is comparable in cost to standard double-strength glass. A single-spacer system with thin glass triple glazing and filled with krypton gas can achieve R7-R8, and could be a cost-effective drop-in replacement for double glazed windows. Recent reductions in the cost of krypton gas, which allows for much narrower gap space, also contributed to the lower overall cost. This thin glass triple glazing design more than doubles the thermal insulating value of a window from a nominal U-factor of 0.3 (R-3) to 0.14-0.15 (R-7).

2. Participants advised DOE that vacuum insulated glazing (VIG) could increase IGU R-value significantly. However, the complexity of window fabrication, edge-sealing, and high level of investment in complex fabrication equipment have limited development and adoption of cost-effective solutions for this technology. In the past few years, glass companies have increased their VIG products offerings, which participants hoped would lower costs of VIG products.

3. Ultra-low thermal conductivity, high transmittance, haze-free glazings based on nanoporous materials structures or new low-k materials that control phonon-scattering between atoms and are now incorporated into thin layers in a glazing package.

Although window framing represents about 20% of the window area on average, participants felt it was important to bring window framing thermal resistance in line with highly insulating glazing. This is particularly true for window systems in commercial buildings, they noted, where structural and cost-effectiveness requirements often require use of aluminum alloys. Participants discussed promising new thermal break designs that are being developed by both window companies and national labs. Higher thermal performance framing also improves the condensation resistance of windows and façades, they said, which is a major concern when designing commercial buildings. The thin glass triple glazing IGU design will enable commercial windows with insulating framing to achieve an overall thermal resistance of R7, which in the participants' eyes, could remove the need for special exemptions for metal commercial windows in energy codes.

2.1.4 Switchable Glazing

Switchable glazings include technologies that are capable of modulating solar-optical properties (spectral variation in ultraviolet, visible, near infrared, and infrared), scattering properties (e.g., clear to translucent; direction of refraction or reflection; within-pane patterns), and thermal properties (e.g., thermal mass, thermal insulation). According to the workshop's participants, switchable glazings reduce peak electricity demand, reduce peak cooling loads (thereby reducing the HVAC capacity needed), improve daylighting, improve comfort, lower maintenance compared to conventional motorized systems, and reduce use of or eliminate shades. Transparent switchable glazings also provide better views and connection to the outdoors, they felt.

Industry stakeholders and other workshop participants believed that the technologies of greatest interest to industry currently are:

- Active and controllable and have a tunable switching range that uses minimum power to switch quickly over a broad range of outdoor environmental conditions

- Technologies that exhibit minimum degradation in switching performance over the expected 30–60 year product installed lifetime
- Are optically clear with minimal haze and are aesthetically acceptable to owners, architects, and occupants (e.g., uniform neutral color during and upon completion of switching).

Tungsten-oxide electrochromic glazings have been introduced to the market during the past decade, participants said, which have achieved a modest level of adoption in high-end niche markets. Research to develop dynamic, light-redirecting metamaterials has not yet yielded viable prototypes, they said. Macroscopic systems have been developed that provide dynamic control of thermal properties (e.g., transparent phase change materials), but according to the best of the participants' knowledge, no low-cost, micro-scale switchable materials have been developed to date.

In the near term, participants felt that R&D activities should focus on educating stakeholders about the value proposition of switchable glazings, including non-energy benefits related to comfort, view, improved indoor environmental quality, productivity, health, and well-being. Studies that help stakeholders understand which building applications have worked so far and why they have worked could help build confidence, participants suggested. For example, more research is needed to understand and address the physics of coating failure, they said. Durability is one of their significant concerns, given that coating product warranties are for 5–10 years, significantly less than most window lifetimes.

Participants also thought more research into ways to reduce the cost of manufacturing switchable glazings is needed. This includes using new nano-based material science approaches for electrochromics and for passively switching thermochromics. These are potentially cheaper, they said, because their multilayer structure is simpler and they do not need power and controls. Participants suggested that researchers should test thermochromic switching technologies under realistic climate and use conditions to ensure they provide occupants energy efficiency as well as comfort. These new materials systems, participants noted, should be developed around high-yield, low-cost deposition methods and ideally provide independent control of switching in the visible and near-infrared (IR) range. In the medium- and long-term, participants wished for a better understanding of how the technologies' characteristics related to color, switching speed, modes of automatic control, as well as other attributes affect occupant comfort, satisfaction, the building environment, and acceptance of the technology.

2.2 Enabling Research

2.2.1 Characterization of Benefits Identified by Workshop Participants

Participants noted the importance of characterizing the benefits of windows and other fenestration systems for both manufacturers and users. Characterization helps manufacturers understand how to improve products' energy and non-energy benefits, and provides the ability to rate and label products for more effective marketing and code compliance, they explained. For users, characterization provides information—displayed on labels, websites, or other media—that helps them select the right product. In the past, research has focused on characterization of energy benefits, but going forward, participants stressed that researchers also need to consider non-energy benefits such as increased thermal and visual comfort, reduced sound, and reduced condensation.

How making different design or technology choices can affect energy and non-energy benefits is not well understood. Often, emphasizing one compromises the other, the experts cautioned. For example, the design of blast-resistant windows enhances the non-energy benefit of safety but degrades thermal performance. Occasionally, however, mitigating risk related to one type of benefit enhances the other type as well, they said. For example, laminated glazing enhances the structural characteristics of windows in that it prevents glass projectiles should the window shatter. Technology characteristics related to safety also improve acoustical performance by reducing sound penetration. (Of course, these are both non-energy benefits.) Instead of accruing these benefits in a non-directed way, participants thought researchers should be able to systematically understand and address how technologies' characteristics, energy benefits, and non-energy benefits interact. Participants expected that researchers will need to develop new algorithms and methods for some benefits such as acoustical performance and extend existing algorithms and methods to others, such as thermal and visual comfort. Once implemented in software tools and websites, these algorithms should become accessible to more professionals and consumers, participants noted. They also said that, in their collective professional opinion, developing rating systems or extending existing rating systems to include existing indices of performance would be the right approach for some benefits. Participants expect that easy access to software tools, websites, and cloud-based databases would enable designers to consider both energy and non-energy benefits when designing products.

2.2.2 Modeling

Advanced simulation software tools are intended to move the window industry toward a 21st-century paradigm of virtual, rapid product design and development. Participants stressed that manufacturers need rapid access to accurate, user-friendly and independently verified computer tools and associated measurement facilities to accelerate design-to-market delivery of new energy efficient window technologies and products. Lawrence Berkeley National Lab develops, maintains, supports, enhances, and validates the suite of databases and modeling tools that includes THERM, WINDOW, OPTICS, Radiance, and IGDB/CGDB databases. These tools are widely used by manufacturers to design window products, the Environmental Protection Agency, National Fenestration Rating Council, the newly chartered Attachments Energy Rating Council (to rate window attachment products), and architects and engineers to design high-performance building envelopes. This suite of tools is used not only to develop, optimize, rate, and label the performance of commercially available products, but also those moving through the R&D process toward the market.

Modeling tools are only useful if they yield credible results, participants said. Thus, some of these participants described DOE's lab and field validation as an "essential" and ongoing program activity. The DOE-supported window test facilities at national labs provide a wide range of support for BTO and private sector R&D. Validation studies are carried out for thermal properties in infrared thermography apparatus, guarded heater plate apparatus, outdoor calorimetric facilities, and other test bed type of facilities. In the participants' opinion, these facilities provide highly accurate measurements of U-factor, solar heat gain coefficients, and air flow, as well as net energy impacts of window and shading products. Optical properties for standard and complex glazing, chromogenic glazing, shading devices, and photovoltaic glazing are measured in the spectrophotometer, a large integrating sphere and a unique goniophotometer for measuring the bidirectional scattering distribution function of complex optical materials and assemblies. The testbed facilities also measure daylighting effects, including advanced controls for lighting. Another set of facilities is used to measure durability and long-term energy performance.

2.2.3 Education

One of the highest priorities the workshop participants identified for high-efficiency windows was the need for better education and promotion. Participants included manufacturers, trade groups, a building contractor, and national lab staff. An early portion of the conversation centered on the successes and weaknesses of the High-R Window Volume Purchase Program. This program identified volume purchasers and linked them to qualifying products. Industry stakeholders articulated the need to better educate residential and commercial consumers on the benefits of high-efficiency window products for new and existing buildings. Participants noted that performance metrics are often poorly understood by consumers, and labeling programs do not identify the best available products. In short, there is little information that could help consumers differentiate high-performance products from other products. Participants identified a need for DOE and the national labs to assist in educating the builder community about how to conduct validations of the field performance of high-efficiency windows. These validations would include measuring the energy and cost performance of these windows when integrated with other building components, such as HVAC systems. The stakeholder group noted that education should extend along the entire supply chain, but was especially needed for sales professionals, installers, and consumers. Stakeholders said that DOE could achieve energy savings by encouraging the adoption of high-performance windows into utility education and incentive programs, increasing education around labels to help consumers identify the most energy-efficient products, and encouraging the ongoing development of labeling programs such as ENERGY STAR®. Stakeholders encouraged DOE to form a collaboration group; coordinate with industry partners such as the ICC, BECs, NAHB, AAMA, WDMA; and provide more guidance on the Building America Solution Center.

2.2.4 Finance

The finance breakout session had two different themes: alternative financing mechanisms for windows, and financing needed for manufacturing line changes that would be required to produce more energy efficiency products. Participants included window manufacturers, a building contractor, window industry organization representatives, and national lab staff. Topics discussed during this session were reducing upfront costs to consumers (both retrofit and new buildings) and reducing the cost of manufacturing line upgrades for the next "step change" in energy efficiency. The participants were supportive of efforts to reduce upfront cost to consumers and financing mechanisms and programs that enabled other industries in the energy sector (such as solar and electric vehicles) to increase demand. The group recommended reviewing financing mechanisms that include, but are not limited to, utility rebate programs, time-of-use rates and demand response, on-bill financing, and property assessed clean energy programs. The R&D opportunities they saw for reducing the cost of re-tooling manufacturing lines involve analyses of the capital expenditures required to purchase more energy efficient products. This step can quantify the cost of upgrading manufacturing lines and the subsequent effect on product cost, and compare that to the benefits of more energy efficient products. Financing options that could reduce the upfront costs to manufacturers could also be analyzed, participants thought.

3 Envelope Sessions

3.1 Thermal Materials for Heat Transfer

3.1.1 Ultra-low conductivity insulation materials (beyond aerogels and vacuum insulated panels)

The development of ultra-low conductivity insulation materials would be a pre-eminent advance in energy efficiency for building envelopes; participants envisioned that ultra-low thermal conductivity insulation will be lightweight and thin in the future, allowing it to be used with recladding products and in interior retrofits without loss of floor space. In the participants' professional opinions, commercialization of these next-generation insulation materials will be of significant benefit for curtain wall systems and for modular construction and prefabrication. However, participants cautioned that careful consideration should be given to integrating these materials into the building envelope to avoid thermal bridging.

Participants expected that moving current concepts for ultra-low thermal conductivity materials to the early stages of commercial readiness will require near-, medium- and long-term R&D investments. For materials with controlled porosity (voids having dimensions of less than 60 nanometers), participants noted that measurements of radiation scattering by the voids need to be obtained, and strategies for suppressing radiation heat transfer need to be analyzed. For vacuum insulation panels, participants felt there is a "crucial" need to develop self-healing polymer films that can maintain the vacuum when a panel is punctured. DOE's near-term R&D goals are to develop standardized test procedures for predicting insulating materials performance over their service life, and to demonstrate insulation R values that are reduced over a 20-year period by no more than 10% of the initial R value. Participants expect long-term R&D goals for developing ultra-low conductivity materials to be constrained by health and safety requirements (e.g., flame retardation and control and human health risks), and the technology's requirement to conform to construction standards (e.g., size standardization for insulating panels). Some theoretical work should be undertaken to establish the ultimate limit for R-value, participants suggested, which is expected to be greater than R-100/inch. This work would also set a target for ultra-low thermal conductivity materials that would enable them to approach the theoretical limit of R-100/inch or greater.

3.1.2 Heat diodes/heat rectification

Thermal energy flows from a hot or warm domain to a cooler domain during the process of thermal equilibration. Participants noted that an ability to switch this flow off and on—or to prevent the flow from reversing direction if the temperatures of the domains are reversed—is a potentially useful innovation for managing and redirecting thermal energy and solar radiation in the building envelope.

This asymmetric heat conduction refers to the modulation of the thermal conductance of a material or device such that the conduction is much greater in one direction than it is in the opposite direction. This property can also be referred to as “thermal rectification” due to its similarity to electrical rectification. Currently, the technology readiness level of this concept is very low and current research is fundamental in nature. Substantial efforts have been made to conceptualize asymmetric heat conduction. However, in the opinion of workshop participants, few experiments have demonstrated that systems could provide thermal rectification for high-performance thermoelectric devices or large-scale energy efficiency. In early-stage research to date, the ratio R of conductance in the opposite directions has proved to be of limited magnitude ($R \sim 1.1$). The physical limitations for asymmetric heat transfer reported in the literature pertain to 1) the nature of the interface/thermal boundary between heat reservoirs (i.e., thermal boundary resistances), and 2) the atomic-scale building blocks for controlling or directing the flow of energy via phonons (e.g., via non-uniform defects in the lattice structure). The theoretical limit for rectification, if any, is currently unknown, participants said. Demonstration of $R \geq 10$ would provide proof of principle and bolster the case for continued R&D on this topic.

3.2 Thermal Storage and Distribution

3.2.1 Tunable thermal storage in building envelopes

Participants identified new thermal storage strategies as among the top three gaps, barriers, or opportunities for building envelope retrofits. Various phase-change materials (PCMs) could provide a means to tailor thermal storage in the building envelope to specific climates and seasons, they said. Participants thought that this passive thermal management strategy could potentially reduce the need for space conditioning, shave peak power demand, and boost resilience in extreme heat events (i.e., increase building comfort and reduce health risks when mechanical cooling is unavailable). It could, they suggested, also lower equipment costs because the size of HVAC units could be reduced. Participants envisioned a few near-term R&D goals include:

1. Identifying for incorporation in the building envelope PCMs with high volumetric heat storage capacity that melt or solidify near (e.g., within 0.5 K) building- and season-specific HVAC setpoint temperatures.

2. Developing ventilation strategies that complement phase-change thermal management, such as storing heat during the day and discharging it at night.

Medium-term R&D goals they suggested include creating durable PCMs that would experience many cycles before failure. These could be dynamically tuned, they thought, by mechanically applying pressure to PCMs stored in a pipe to melt or solidify over a temperature range wide enough to adapt to seasonal variations in building setpoint temperature.

Long-term R&D goals participants suggested include developing methods with high energy flow rates that transport heat from zones to meet local space conditioning needs. Potential strategies for this goal could include piping liquid PCMs to deliver heating, and using robots to move solid PCMs to deliver cooling. The technical breakthroughs and new knowledge required to meet these R&D goals could include:

1. Surveying the thermal characteristics of existing PCMs

2. Developing PCMs with higher heat of fusion

3. Creating PCMs that can be tuned to different temperatures

4. Identifying and developing evaporative phase change materials that can be safely incorporated in the building envelope. Risk mitigation strategies include ensuring that PCMs neither damage the building envelope nor degrade indoor environmental quality.

3.2.2 Thermal energy redirection to environmental heat sinks

Developing high-thermal conductivity materials to sink building heat to ground or sky was identified by participants as among their top three gaps, barriers, or opportunities for building envelope retrofits. Envelope materials with high and potentially anisotropic thermal conductivities, such as heat pipes, would be needed in the future, they said, to remove excess heat from thermally tight (well-insulated) buildings – especially those with high internal heat loads. Passive cooling of these spaces could possibly reduce the need for space conditioning, shave peak power demand, and boost resilience in extreme heat events (i.e., increase building comfort and reduce health risks when mechanical cooling is unavailable). It could also lower equipment costs because the size of HVAC units could be reduced, they said.

The near-term R&D goals participants thought of include:

1. Mapping ground and sky cooling resources by climate region, season, and ground depth.

2. Developing interior room surface radiators (e.g., metal or graphite embedded in drywall, wallpaper, paint) with high thermal conductivity to extract heat from occupied space.

3. Characterizing and developing vertical heat transport technologies with high effective thermal conductivity, such as capillary or gravitational heat pipes, or novel solid-state conductors, to transfer this heat to the ground or sky.

Ideal systems, in the participants' eyes, would provide heat removal at rates and costs competitive with mechanical cooling. Vertical heat transport technologies are "particularly critical" for near-term success, they said.

Medium-term R&D goals could include performance improvement or cost reduction, participants suggested. The long-term R&D goals they envisioned include electrical generation from building-to-sink temperature differences; however, significant improvement in the efficiency of thermoelectrics would be needed, they noted. In their expert opinions, technical breakthroughs and new knowledge required include:

1. Anti-gravity vertical heat pipes that perform on building height scale (current technologies are limited to short runs)

2. Solid conductors with thermal conductivities comparable to those of heat pipes

3. High-performance, low-cost wall/floor/ceiling radiators that thermally couple to the vertical heat conduit

Risk mitigation strategies, they said, should include ensuring that the interior room surface radiations and the vertical heat conduit offer thermal resistances low enough to provide useful rates of heat removal even when the temperature difference between the interior space and the environmental heat sink is modest.

3.3 Air Sealing

3.3.1 Improved field testing of installed material during construction

In the participants' opinions, building envelope and quality diagnostic systems could be improved in several ways: enabling testing of buildings during construction; increasing testing accuracy, reducing testing costs, and reducing the time required to test. Ideally, the time required for field testing would be reduced to 10% of current testing times, they hoped, and testing costs would also be reduced. Developing a method to provide rapid visual indication of major air leaks in buildings could be useful, participants said, for evaluating the cost-effectiveness of building air sealing and justifying air sealing investments. Ideally, any method developed to locate and quantify the severity of air infiltration should require only a single test, participants said, using one piece of equipment.

Participants said that several methods might satisfy most or all of these requirements. A mechanically-induced pressure differential between the interior and exterior of a building, combined with infrared imaging, can be used to visualize leaks. Alternative methods for locating and quantifying the severity of leaks that do not require pressurization should be investigated, they said, because these methods could significantly reduce the cost and time required for testing. Wave-based diagnostic methods—such as infrared, sound, and ultrasound techniques—are affected by intrinsic building material properties (e.g., heat conduction through metal window frames affects IR image accuracy; resonance of materials affects emitted acoustic waves). So the influence of material properties on test results, participants stressed, should be fully quantified to improve test accuracy. Low-frequency waves yield more accurate quantification of leakage than high-frequency sound, experts in attendance said. Thus, participants recommended that infrasound transmission through cracks be investigated as part of broader research on acoustic diagnostic methods. Likewise, if acoustic methods can be employed, the sound transmission loss should be calibrated to facilitate performance-based building standards that use sound leakage levels to characterize air sealing for new construction. Participants expect health and safety impacts of using infrasound to require further study before infrasound methods could be broadly implemented. Also, participants added that crack location methods that do not depend on wave reconstruction techniques should be researched and tested, since wave reconstruction is highly dependent on room geometry and configuration.

3.3.2 Improved processes to address common enclosure installation issues

Modular construction improves the efficiency of both residential and commercial construction processes and reduces total construction time when performed correctly. Modular construction methods can also yield more consistently assembled building envelopes, participants noted. Therefore, they feel it is important to identify and minimize issues relevant to modular construction techniques. Research is needed, they said, to understand common installation issues present in installing construction modules, such as wall panels, that were built offsite. Some preliminary data could be collected from insurance agencies and major professional associations, participants said; these data could help establish a baseline understanding of common problems, if any. Building mock-up walls with installers and testing and recording failure probabilities is a good way to formalize the data in the eyes of the workshop participants. They also said that building air tightness should be tested in a building built using modular construction and the air tightness should be compared with that of a building built using conventional methods. Participants believed that a larger sample set, e.g., 50 modular homes and 50 homes built using conventional methods, would provide a rich dataset that would quantify any envelope performance or durability gains achieved with modular construction. For quality assurance and verification, testing the modules (panels) is likely easier than testing the whole building, they said. Thus, the modules should be tested at the production site using building diagnostic methods before sending them to construction sites. Envelope interfaces, such as those between windows and the opaque envelope, can be a major contributor to infiltration. Innovative approaches to sealing these interfaces from air infiltration and water ingress are needed in the participants' minds. For windows, improved interfaces might also simplify replacement compared to current windows, they said.

3.3.3 Whole building aerosol treatment for improved air-tightness

Aerosols could be used in new and existing construction, participants suggested, to rapidly and easily seal small air infiltration and exfiltration points in unseen or inaccessible locations across an entire building façade. Reducing the cost of application (compared to current applications of aerosols for duct-sealing), establishing the long-term durability of candidate sealing materials, and conducting a health and safety analysis of candidate materials were identified by participants as "critical" near-term R&D steps. To make this technique suitable for existing buildings, research would be needed, they said, to develop an aerosol material and/or delivery system that does not leave residues on interior surfaces, such as carpet or furniture. This modification is important for occupied buildings because the residual aerosol material deposited on surfaces in the building could cause health issues for the occupants, and could damage furniture, fixtures, and equipment. More generally, the health and safety aspects of aerosol materials should be studied further, according to the participants, and changes to the composition of these materials might be needed to make them safer. An alternative approach they offered, particularly for occupied existing buildings, might be to apply the aerosol from the exterior and use induce negative pressure inside the building to deliver it. Studies should be performed, they said, to determine the feasibility, potential efficiency, and cost of either method when applied to new and existing buildings. Finally, the long-term durability of aerosol-based air sealing should be assessed.

3.4 Diagnostic Tools

3.4.1 Diagnostic tool to detect insulation values during installation

This R&D priority area addresses the deficiencies of the technologies and methods used to measure insulation properties and diagnose insulation problems during the installation process. In particular, participants identified a lack of appropriate diagnostic tools as a major barrier to ensuring that the installed R value in the envelope matches what was specified, and that insulation materials were installed correctly. Moreover, there are no standards related to in-situ testing methods currently.

The participants' near-term research suggestions include:

1. Developing image processing and machine learning methods that can utilize existing tools (e.g., thermographic and/or photographic imaging) during and after construction.

2. Improving existing thermal imaging techniques that do not require large (10–15 ºF) interior-exterior temperature differences.

3. Utilizing other existing imaging techniques (non-thermal or visual imaging) such as electromagnetic or acoustic methods.

Long-term research activities could include developing materials that produce a visual indication of installed thickness or "self-assemble" into a desired thickness. Another long-term activity they identified would be to develop novel measurement and imaging techniques that can quantify reduced temperature differences, can reject exterior heat sources, or utilize electromagnetics, sound, and vibration in completely new ways.

The technologies developed in the near term should be able to output wall classifications according to RESNET/IECC standards, participants said, automatically identify thermal bridges, and output information directly in a format usable by energy modeling programs. Technologies developed in the long term, participants envisioned, could be able to provide fairly untrained workers with the ability to rapidly and inexpensively address insulation problems that occur during installation. These solutions, they said, should also be able to provide full 3-D imaging of a complete or incomplete wall assembly (e.g., computed tomography scanning or magnetic resonance imaging) that also identifies wall properties.

3.4.2 Diagnostic tool to test building/envelope section air tightness before and after construction is complete

This R&D priority area addresses the deficiencies of technologies used to measure air leakage in building envelopes. Large areas of building space need to be measured quickly, but current methods for testing leakage are both slow and difficult to deploy until a significant portion of the envelope has been constructed. Near-term research needs, participants recommended, include developing digital image processing and machine learning methods designed specifically for existing tools, such as thermal imaging, blower doors, and acoustic tools currently being developed. Long-term research needs, participants offered, include developing new 3-D imaging techniques that identify air paths, and developing air barrier materials that can change properties when a tracer goes through or when imaged. Currently available and future diagnostic technologies need to be able to locate and quantify leaks during construction and seal them so that the envelope assembly will pass required tests, including ASTM requirements, participants noted. In their expert opinion, diagnostic tools that can evaluate curtain wall assemblies for air and water sealing as-built could significantly reduce testing costs for new construction. New diagnostic technologies need to be able to accurately size leaks so that they can be prioritized for sealing, and identify the entire air leak path to help construction crews determine the best location for sealing.

3.5 Durability and Moisture

3.5.1 Manufactured envelope systems to reduce installation errors

The performance of the best components and systems for energy efficiency in the building envelope can be compromised by inconsistent manufacture of materials, and by installer errors. Installers commit errors when they deviate from manufacturers' specifications and use improper installation and assembly techniques that can also inflict damage on components, which in turn may be inadequately repaired or even not repaired at all. As a result, participants said, the customer often does not receive the energy efficiency benefits of a properly installed product, and instead experiences the problems caused by the substandard performance of an improperly installed product.

Participants identified prefabrication and modular construction methods as potential remedies for installer error in building envelope energy efficiency installations. Some additional benefits of prefabrication and modular construction that participants discussed are reduced material waste, improved quality control, and better working conditions for workers in the construction industries. Computer-aided design and manufacturing systems, coupled with robotics-based automated assembly, have the potential in the participants' minds to provide "unprecedented" quality and performance for energy efficient building envelope components and systems. Market penetration is hindered by resistance among the building and construction trades to adopt new practices, participants argued. A useful first step for advancing acceptance of these practices, they said, would be to evaluate whether the capital and operations and maintenance costs, quality, and performance of installed prefab modules exceeds that of homes assembled onsite. Barriers might include a difference between expected and actual consumer acceptance, and municipal permitting and inspection requirements. Prefab and modular building technologies could result in a wide range of efficiencies: process intensification for energy savings, reduced labor costs, shortened construction schedules, quality assurance through statistical sampling, and improvements in indoor air quality through precise control of materials.

3.5.2 Guarantee that new high-performance buildings don't result in durability consequences/issues

As modern buildings become more airtight and have higher insulation levels, the building envelope becomes more sensitive to unmanaged moisture. Moisture risk management must be conducted to ensure that energy efficient buildings do not experience shortened service life. By accounting for moisture conditions and moisture performance in during design, the buildings service life can exceed that of typical existing buildings. However, participants noted there is a lack of information about what combination of temperature and moisture content, and their duration, cause durability problems. There has been substantial research performed on mold, but other durability failure mechanisms such as wood rot, metal corrosion, and material dissolution have not been investigated, participants said. Participants pointed out that hygrothermal models exist that can fairly accurately predict the building temperature and moisture content, along with their duration above specific thresholds. Tools are needed, they said, that can interpret the data and translate model outputs into a durability risk metric that can provide guidance.

Participants felt that these data, tools, and guidance will help industry confidently identify and specify the cheapest high-R building assembly designs that are least likely to encounter moisture problems in each climate zone. They also expect these tools to provide a comprehensive and compelling basis for building codes to include requirements for high-performance, moisture-managed building envelopes that are both energy efficient and have moisture durability. Participants argued that such envelopes will eliminate the negative image of energy efficient buildings in terms of durability and maintenance.

In the near term, participants recommended that work in this area should include measures that develop builder and consumer confidence in durable energy efficient building envelopes. A first step in their minds would be to conduct a literature review, recruit industry partners whose products would be the focus of durability research (wood, insulation, steel, concrete, gypsum), and begin to develop a fundamental understanding of degradation processes. Small-scale laboratory tests would be performed to initiate the development of limit state data for potential failure mechanisms such as wood rot and mold growth, insulation R-value loss, metal corrosion, concrete freeze-thaw cycling, and gypsum dissolution. The objectives of this work, participants envisioned, would be to understand the state of the art, compile and coordinate lists of all stakeholders for each durability issue, attempt to quantify impacts by defining material classes, and collect data for the materials most representative of each class. They also asked for comprehensive reports describing and parameterizing each degradation process, sufficient to design experiments.

In the medium term, participants recommended developing algorithms for models and validating them in field experiments. Material property data relevant to moisture could be added to existing hygrothermal models. The models' output could be compared with experts' experience to verify their results are consistent with field observations. Large-scale system and subsystem laboratory testing could also be employed, participants thought, to validate the prediction algorithms. The improvements to moisture models should be widely disseminated so that the buildings audience is convinced of the robustness of this effort. Participants also said standards and codes organizations should be kept abreast of the research.

In the long term, additional validation and verification activities that demonstrate these algorithms accurately predict in-situ hygrothermal performance could be performed, participants said. These activities would also demonstrate these models could be part of the energy usage analysis performed on all high-performance buildings. This research would result, they predicted, in more complete understanding of the combinations of conditions that result in the various ways hygrothermal performance is degraded. Outcomes that participants characterized as possible "technical breakthroughs" would include an understanding of degradation mechanisms as a function of temperature, relative humidity, and time, and robust models to predict these durability consequences.

Stakeholders in this hypothetical project idea would include industry partners representing the wood, insulation, steel, concrete, and gypsum industries, each contributing their knowledge of the durability issues associated with their materials and products, and the national laboratories.

3.5.3 Develop vapor and moisture diodes (passive and/or active) that allow movement of water vapor and liquid in only one direction

Moisture, in either liquid or vapor phases, that accumulates in wall cavities can lead to many problems, such as mold growth, wood rot, corrosion, dissolution, and energy inefficiency. To prevent or manage these problems, wall assemblies include a water barrier and a vapor retarder. In the building code, vapor retarders are classified according to their permeance:

- Class I ≤ 0.1 perm (e.g., polyethylene)
- 0.1 perm < Class II ≤ 1 perm (e.g., kraft facing)
- 1 perm < Class III ≤ 10 (e.g., latex paint)

Building codes typically require wall assemblies to include either a Class I or II vapor retarder on one side of the wall cavity. The requirements vary by climate zone and the characteristics of the wall material assembly. All of the available vapor retarders are membranes that have the same vapor permeance in both directions; therefore, they provide the same resistance to vapor diffusion into and out of the wall cavity. Consequently, the side of the wall that does not include a Class I or II vapor retarder has materials with a high vapor permeance so the cavity can dry if moisture accumulates within it due to imperfections (e.g., water leaks). A weakness of this design, participants explained, is that the location of the high humidity source alternates between indoors and outdoors based on the season, occupant activities, and the extent to which the sun drives water vapor into the building envelope. Thus, moisture can potentially accumulate in the wall assembly. A possible solution could be to add vapor retarders to the interior and exterior sides of the wall assembly. However, participants did not recommended this because if moisture leaks into the envelope assembly through a construction defect, they explained, the trapped water vapor will not be able to easily diffuse out of the wall cavity.

Vapor retarder technologies could be improved in these, participants thought, by developing sheathing materials composed of membranes and surface modifications that have directional vapor permeance. These sheathing materials would have a low vapor permeance (i.e., ≤ 1 perm) in one direction that would significantly minimize vapor intrusion into wall assemblies. These membranes would also have a high vapor permeance (i.e., ≥ 10 perms) in the opposite direction to allow accumulated moisture to diffuse out of the cavity. Participants expected these new sheathing materials to significantly simplify building design because they could be installed on both sides of the wall cavity and thus could be used in all climate zones and all wall assemblies. Any material used in improved sheathing materials could also be used to optimize and improve the drying potential of all building envelope technologies, making them much more durable over a wider variety of interior and climate conditions. The overarching value proposition, they said, is that this material would offer designers another option for dealing with moisture control in difficult climate zones.

In the near term, participants recommended that work in this area should include a literature review of state of the art directional vapor permeance membranes. Ideally, in their professional opinion, it would also identify and quantify the performance attributes and market opportunity for moisture diodes, develop prototypes that exhibit the low and high vapor permeance attributes specified above, and solicit industry feedback on the prototypes.

In the medium term, participants said a manufacturing partner could be identified to produce moisture diode samples on a small scale. Small-scale laboratory tests can determine whether the samples possess the required material properties. Large-scale laboratory tests could validate the moisture diodes performance. It is important that manufacturers commit to developing and producing sufficient numbers of test samples so that wall system changes due to thermal, moisture, durability, and weathering effects could be evaluated.

In the long term, additional validation and verification efforts could demonstrate to builders and designers that moisture diodes improve the wall system durability, participants said. A cost analysis could be completed, and a manufacturer, they hoped, would be identified that would produce the moisture diodes.

If this technology is pursued, a new class of water-resistive materials and vapor barriers could be created, and the building community would have another potential solution for overcoming problems caused by hygrothermal phenomena, they said. The risks associated with this research include high manufacturing costs (resulting in insufficient return on investment) and materials not being durable enough. In addition, many building owners and operators, participants explained, are unaware of how water vapor movement affects the building envelope, need to be better educated about the relevant issues, as well as convinced that new vapor retarder technologies would be valuable.

Stakeholders suggested by participants include national laboratory researchers and industry partners representing the water-resistive barrier, air barrier, and vapor barrier industries.

3.5.4 Human-centered design of installation techniques of products and materials

The risks associated with unmanaged moisture is higher for modern energy efficient building envelopes because they do not dry out as easily as old, energy inefficient structures. The latest building energy codes (i.e., IECC 2009, 2012, and 2015) significantly increased airtightness and insulation levels. When envelopes are designed and components installed properly, these new requirements are cost effective and improve comfort and energy efficiency. However, design and installation problems persist throughout the industry, participants noted, leading to increased risk of failing to meet higher performance requirements or—worse yet—durability problems. Modern building envelope assemblies are much less tolerant of design and installation flaws.

Therefore workshop participants said these assemblies must be better designed and constructed to control thermal, air, and moisture flows in and out of the structure.

Materials with greater resilience to installer behavior and error are needed, participants advised, to reduce the effects of installation errors enhance safety, and reduce installation time, workmanship errors, and labor costs.

Further work in this area could include measures for developing materials with more tolerant installation requirements, participants said. In addition, information should be developed that helps stakeholders understand and quantify the benefits and value of improved installation practices; observe, collect, and analyze data of current installation techniques/problems; and perform anthropological studies and develop principles to create human-centric design installation methods. Near-term research efforts could potentially include performing a cost analysis of benefits and an energy analysis of performance compared to typical installations, they said. These research efforts, participants hoped, would produce comprehensive reports that identify problems, detail solutions, create new installation techniques, and develop builder training and installer certifications, as well as codes and standards provisions that align with new installation techniques. In addition, current installation methods could be compared to improved techniques and new installation methods. The risks associated with this research, they warned, include materials and methods not being cost effective, not producing significant reductions in installation error or improvements in installer behavior, and slow adoption by industry and installers.

Stakeholders in this project would include builders, raters, product manufacturers, academia (for their anthropological studies), and the national laboratories.

3.6 Education

3.6.1 Education/database development for better customer education of technology benefits

This area addresses what participants felt were insufficiencies in data and information dissemination to decision-makers—designers, builders, and building owners—concerning the role envelopes play in providing occupant comfort, occupant health, energy efficiency, and building durability. There are two challenges that workshop participants identified. Datasets that provide an empirical, quantitative basis for assessing the effect of the building envelope on occupant comfort, occupant health, energy efficiency, and durability should be developed, they said. Expounding further, they talked about information products that educate and enable decision makers to design and operate their buildings to account for these factors. Research activities, in these participants' eyes, could include testing and monitoring air barriers and envelope assemblies to characterize and quantify the impacts of design choices, construction deficiencies, and system degradation over time. Short-term measurement and long-term monitoring of components and assemblies in the laboratory and the field is required, they said. Performance data needs to be organized and distilled into useful information, such as performance rating and derating factors for energy efficiency, comfort, health, and durability. These data could also be used to improve building energy modeling software (e.g., EnergyPlus, OpenStudio), and inform codes and standards, particularly with respect to imputed envelope performance values. The resulting data and information would likely facilitate education, building energy modeling, economic analysis, and design specifications, participants said.

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