Project Information

DE-EE0003925

Southwall Technologies

"R10 Heat Mirror Technology with Optimized SHGC"

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Description:

The objective of this project is the development of a Heat Mirror (HM)-based R-10 window solution with improved solar heat gain coefficient (SHGC) performance for the residential window market. Heat Mirror, with multi-cavity window performance at an efficient form and weight factor, will support improved acceptance of high-performance glazing through lower cost of structural window frame components, reduced transportation cost, and easier installation.

Executive Summary:

This project developed a new high-performance R-10/high SHGC window design, reviewed market positioning and evaluated manufacturing solutions required for broad market adoption. The project objectives were accomplished by: identifying viable technical solutions based on modeling of modern and potential coating stacks and IGU designs; development of new coating material sets for HM thin film stacks, as well as improved HM IGU designs to accept multiple layers of HM films; matching promising new coating designs with new HM IGU designs to demonstrate performance gains; and assess the potential for high-volume manufacturing and cost efficiency of a HM-based R-10 window with improved solar heat gain characteristics. A broad view of available materials and design options was applied to achieve the desired improvements. Gated engineering methodologies were employed to guide the development process from concept generation to a window demonstration.

Goals/Accomplishment Comparison:

The objective of this project was the development of a Heat Mirror (HM)-based R-10 window solution with improved solar heat gain coefficient (SHGC) performance for the residential window market. Heat Mirror, with multi-cavity window performance at an efficient form and weight factor, supports improved acceptance of high-performance glazing through lower cost of structural window frame components, reduced transportation cost, and easier installation.

The project determined that a slightly de-rated window performance allows formulation of a path to achieve the desired cost reductions to support end consumer adoption.

Technical Report / Project Activities:

Task 1: The PMP was submitted, reviewed and approved. The Kick-Off meeting at DOE-NETL Pittsburgh was held on October 19, 2010.

Task 2.1: Since the launch of the thermal modeling was delayed due to resource constraints at the chosen contractor, a preliminary design screening was performed in-house using WINDOW5. Since the availability of high-performance frames and warm-edge spacers in the WINDOW5 materials library is limited, the focus was on Center-of-Glass performance. Figure 1 summarizes key findings ("180" denotes Cardinal Glass "LoE-180", a new single-silver low-e – coated glass aimed at passive house market; "88" denotes Heat Mirror 88; "366" denotes Cardinal Glass "LoE-366", a high-performance triple-silver low-e – coated glass). The study determined that a 3-cavity window design with Argon gas fill and a single-silver low-e coating in each cavity is necessary for u_{COG} of better an 0.2, and a SHGC of approximately 0.5. Such a design requires a Heat Mirror-based IGU design due to weight and form factor constraints.

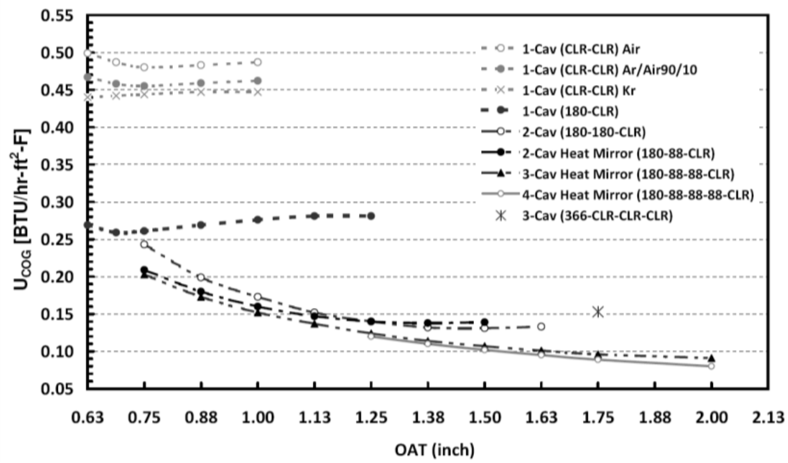

Figure 1: Preliminary WINDOW5 modeling of candidate IGU designs

For the more detailed thermal modeling of the entire window, the matrix of case scenarios to be modeled with THERM has been defined, and appropriate optics files in IGDB-format have been synthesized for the proposed high-T_{sol} low-e Heat Mirror coatings. A modeling consultant prepared a matrix of simulations that included baselines of best currently commercially available material options as well as explorations into different weightings on the u-value/SHGC trade-off. The modeling strategy took into account baselining, reverse-modeling and identification of the most influential variables.

Task 2.2: After it was determined by the glazing optics modeling consultant that a correct analysis of non-normal reflected color is impossible without detailed knowledge of all coating stacks (including commercially available low-e coated glass, the exact layer design of which is proprietary), analysis focused on modeling color changes for IGU designs determined in the WINDOW5 modeling exercise of Task 2.1. Key results are summarized in Figure 2. It was found that commercially available high-SHGC low-e coated glass (Cardinal loE-180, e.g.) at the required configuration (3 cavities) shifts the reflected color significantly into the green and blue spectrum, whereas substituting the inner glass panes with a Heat Mirror-based design effectively suppresses the green shift, which results in a more neutral reflected color appearance. Further studies (optical effects of tuned thin film stacks) suggested that the color shift can be further suppressed by fine-tuning the advanced stack design proposed for high-SHGC performance of Heat Mirror films. This would enable multi-cavity designs with less-noticeable color variations that should enhance customer acceptance.

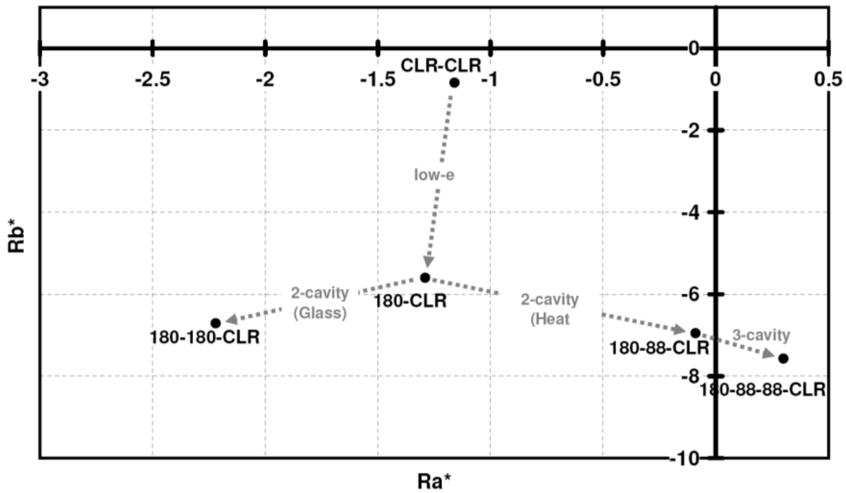

Figure 2: Preliminary modeling of normal reflected color of several IGU candidate designs

Task 2.3 (Economic Analysis): Cost models were developed that describe both the cost of thin-film coating operations (to produce the proposed new Heat Mirror film designs), as well as to determine the cost of manufacturing complete Heat Mirror IGUs.

The IGU manufacturing model was based on discrete-event modeling software (ExtendSim) that is particularly useful to analyze manufacturing sequences with high design variations such as the various sizes and design variant typical for residential window fabrication. This is particularly important when considering modern automated high-volume production scenarios that will be necessary to achieve the price points required for sufficient market acceptance. The cost models were set up to describe the manufacturing methodologies anticipated for this project, and were expanded and refined to represent the automated HM IGU assembly operations at Southwall Insulating Glass (SIG) in Chicago (currently in production ramp-up) as a test case, and were being expanded to cost capturing capability. Additional manufacturing options investigated in this project were also integrated into the discrete-event model as much as feasible.

In parallel, a spreadsheet-based IGU “cost and materials” model based on the bill of materials, expected labor requirements, depreciation cost of automated manufacturing equipment and projected production capacities and manufacturing efficiencies was developed. This model also allowed comparisons of case scenarios (different spacer types, glass variants, cavity count etc.) to assist in the identification of cost-effective product formats and manufacturing scenarios. The model was refined to adequately describe triple-cavity IGUs with the wide range of commercially available glass types and warm-edge spacers. Cost inputs were continuously updated with cost data from SIG operations and marketing input. The model was also expanded to derive an IGU cost target based on DOE consumer-cost target, which required some assumptions about the cost progression along the value chain that are beyond Southwall’s control and are notoriously difficult to obtain.

A similar “cost of materials”-based model has been developed to determine the production cost of the new/improved Heat Mirror films plus the anti-reflection coating.

Task 3.1+3.2: A new low-e coating stack for Heat Mirror was previously under development at Southwall, and prototype samples have been produced. The film shows a significant emissivity improvement over current HM film at a slight penalty in Tsol, but the trade-off is still advantageous in view of “Passive House” glazing design guidelines.

The material has been evaluated in a matrix of tests designed to examine the potential to integrate these new low-e films into the Heat Mirror architecture. Several long-term stability tests were performed to investigate the design’s viability. The test results generally have demonstrated a film that is compatible with classical Heat Mirror manufacturing methods, is sufficiently durable, and shows improved emissivity at the same or better T_{sol} compared to classic HM88 film, and thus supports the objectives of this project. Initial cost modeling indicated an attractive modeled production cost for the new coating to support an affordable future window solution in case the technical performance confirms to meet the project goals. A trade-off scenario comparison was conducted by analyzing the performance and production cost of an ambitious, superior low-e Heat Mirror coating concept. Samples from this Southwall product development effort to further reduce the emissivity of HM films have been obtained and have passed initial technical qualifications for HM integration, but further investigation determined that it will not meet current manufacturability and cost objectives for this program. However, the samples demonstrate that further performance improvements are technically possible.

Optical modeling has demonstrated that adding a broadband anti-reflection coating on the reverse side of a Heat Mirror film improves SHGC performance and can be used to improve reflected color aesthetics. Plans were developed to add an anti-reflection coating on the backside of this new Heat Mirror film in order to maximize T_{sol} for higher solar heat gain. Three approaches for the anti-reflection coating were considered; one approach was sourced from Southwall's manufacturing facility, the second approach was developed earlier conceptually on Southwall's laboratory roll coater (requiring retrofitting the coater with a new deposition technique), and a third approach was a new technique developed by an external systems provider that was screened for efficacy. Cost-benefit analysis was performed, with the result that the lab coater approach is currently most attractive. One option – a surface-structure-based technique – proved fragile and of high-haze, another option – stacks of high-rate high/low index multi-layer ARs showed mixed results (confirming high deposition rates but revealing compatibility issues with the low-e HM coating). The deposition approach in the laboratory coater was pursued for final product demonstration as it provided an attractive cost/performance balance and was deemed to be scalable. Sufficient quantities of this material could be produced to demonstrate integration into the assembly process at prototype production scale.

Southwall's lab coater was upgraded to produce prototype quantities of an evaporation-based anti-reflection coating on the backside of this new Heat Mirror film in order to maximize T_{sol} for higher solar heat gain.

Task 3.3: A scheduled Milestone review was held July 20, 2012. Heat Mirror coating stacks were specified for prototype assembly and economics review to be delivered in BP3. In addition the prototype assemblies, an innovative assembly workflow was identified based on prior studies that was evaluated for manufacturability and economical analysis. Because the workflow consisted of discrete processing steps that required capital-intensive hardware integration for a physical demonstration in a completed IGU, these more advanced manufacturing flows were examined in the form of a study but did not lend themselves for production for full-sized physical samples.

Task 3.4 (New Heat Mirror IGU) was pursued along several vectors. Based on the preliminary thermal modeling that determined the need for a triple-cavity IGU design with very good Edge-of-Glass performance, the conventional Heat Mirror suspension system needed to be modified to accommodate a more efficient thermal break.

Given the various design options, it was desirable to have the design of an improved suspension system guided by Finite Element Analysis (FEA). A suitable software extension for the already existing SolidWorks CAD software was purchased. Defining a FEA model required several fundamental material definitions that needed to be determined. Since the mechanics of the current HM suspension method were not very well understood and much is unknown about the mechanical properties of both the HM film as well as the suspension system, material analysis was conducted to analyze key mechanical parameters (Young's modulus, coefficient of thermal expansion, elastic and thermo-plastic properties). A materials testing consultant has been engaged to measure material properties. Evaluation of Heat Mirror film in various processing stages (uncoated, coated, tensioned) was performed. In an initial validation exercise, the classic Heat Mirror suspension system was modeled and vetted against experimental data before embarking on new suspension designs. The results of the vetting exercise were mixed, and although FEA could predict certain static IGU properties, it was determined that eventual fitness-for-use and concept/materials screening & qualification required prototype fabrication and testing, which was employed throughout the program wherever feasible.

The need for an improved thermal break initiated the search for alternatives to the classic galvanized steel spacer that is well-established for Heat Mirror. Historically, the structural requirement to reliably tension the film has limited the choices, but several modern box spacers (thin-wall stainless steel, stainless/polymer hybrids, in-situ-formed stainless (Intercept)) were of interest. Initial processing trials demonstrated that the bending quality of such warm-edge spacers was insufficient for high-quality Heat Mirror IGUs, and a cooperation with a large spacer bender manufacturer was initiated to develop improved tooling. Initial development focused on processing thin-wall stainless box spacers, better-performing hybrid (metal/polymer) box spacers are a viable option that was also considered. In addition to warm-edge box spacers, the incorporation of non-structural warm-edge spacers was consideration and was effectively prototyped with suitable IGU components and processes after the finite element modeling capability indicated promise of the approach.

A structural thin-wall stainless-steel (SST) spacer that is structurally compatible as a drop-in replacement for the conventional HM spacer was successfully integrated into the HM system, including production integration in the automated HM assembly line at SIG. A renowned vendor of IGU assembly equipment developed adequate automated high-volume spacer manufacturing capability that effectively demonstrates the adoptability and high-volume manufacturability of this approach for HM IGUs (Figure 3).

Another successful warm edge integration demonstration was the combination of structural spacers with a non-structural high-performance warm-edge spacer in a triple-cavity HM IGU prototype (Figure 4).

Extensive development focused on radically new HM suspension and IGU assembly concepts, primarily to integrate warm-edge spacers and to streamline the production of HM IGU. In-depth materials characterization of the HM film to determine mechanical and thermal properties that could serves as inputs into Finite Element Analysis (FEA) revealed a very complex and highly an-isotropic material behavior that proved to be too complicated to describe mathematically, and the hope to screen design candidates by FEA modeling had to be abandoned. The team developed several techniques to determine crucial materials behavior and design capabilities experimentally. Despite a very productive brainstorming session to identify novel suspension concepts, Southwall's in-depth knowledge of product characteristics, customer preferences, manufacturing constraints and competing production techniques quickly eliminated a large number of candidates through rapid design iterations. The investigations of this task proved more laborious and time-consuming than initially anticipated, but resulted in a couple of crucial concepts (both on IGU designs, assembly concepts, and manufacturing methods) that deserved further investigation without jeopardizing overall project progress.

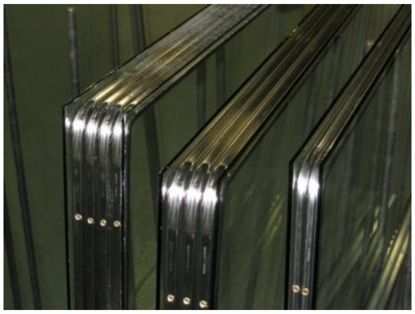
Figure 3: multi-film structural warm-edge HM IGUs prior to sealing


Figure 4: HM IGU with experimental polymer warm-edge spacer prior to sealing and tensioning

Studies to build patio-sized IGUs of down-selected new manufacturing methods were completed. Manufacturing flows, cost assessment and risk-benefit analyses were completed for several manufacturing options in preparation for Milestone review. The vendor of an innovative assembly process was requested to provide some work flow details, manufacturing capacity data and capital equipment costs to complement the economic analysis.

A Continuation Application including an updated Project Timeline for BP3 was filed in early May 2012, and approved in August 2013 to ensure continuation of project activities.

Task 3.6: The Milestone review was held on July 20. IGU configurations have been specified for prototype assembly, and cost reduction concepts have been down-selected for refined manufacturability and economics analysis during BP3.

Task 4.1 (New Film & New Spacer/IGU: Prototyping & Performance Analysis): Tests using advanced-performance HM films in the automated IGU assembly process were successful to demonstrate fundamental compatibility for integration with warm-edge spacer concepts in 3-cavity IGU designs. Additional quantities of advanced Heat Mirror film have been ordered, produced and received at production site for prototype assembly and detailed manufacturability studies. The manufacturing studies primarily evaluated the readiness (or technology gaps) for integrating the advanced films in the automated assembly process available at Southwall Insulating Glass (SIG, Chicago) as well as some new experimental assembly alternatives under investigation in Palo Alto. Latest prototype versions of low-cost/improved performance films completed initial testing for manufacturing integration, including automated assembly and final tensioning feasibility. Process parameters required refinement but were within general capabilities of automated IGU assembly hardware. Additional warm-edge concepts were under continued evaluation and a design parameter window has been identified to guide a set of refined tests at a vendor site. Alternative IGU assembly techniques have demonstrated fundamental mechanical feasibility.

Task 4.2 (Manufacturability & Economic Review): The down-selected IGU manufacturing paths underwent a more detailed workflow, time study, cost and capital expenditure analysis. The goal was an updated and realistic population of input data for the two cost analysis approaches developed under Tasks 3.2 and 3.5, as well as the coating cost analysis models developed in Task 2.3 and 3.2. The studies benefited from operational experience with the automated IGU manufacturing line at Southwall Insulating Glass (SIG) in Chicago. Earlier in the program, it was expected that some recently identified new spacer and subcomponent options that have become candidates for HM due to recent design improvements may get included in the studies as well. Physical prototype demonstration of respective materials and process options were successfully conducted to assess technical feasibility and potential for large-scale industrial adoption. Processing options for prototype assembly and cost-reduction opportunities identified in recent Milestone reviews were refined and converted into manufacturing model flows for capacity and cost analysis. Several process sequences and assembly techniques have been identified, expanding production volume/IGU cost options to address project's market adoption/end consumer cost objectives. Throughout the program, additional warm-edge concepts were under continued evaluation, CapEx and direct costs were obtained and integrated into cost models. Alternative IGU assembly techniques that have shown fundamental mechanical feasibility were investigated for assembly process/cost merits, but cost modeling established that they may not meet the capacity/CapEx requirements of the program.

While cost description of IGU manufacturing was well-defined due to the familiarity with materials, assembly processes and the development of the automated assembly process at Southwall Insulating Glass, cost modeling of the final end consumer price suffered from a lack of transparency of the cost contributions in the distribution channel from the finished IGU to the end consumer. The cost model took into consideration the potential cost contribution from a generic/fictitious window manufacturer (who might incur expenses for energy-efficient sash and framing profiles with adequate pocket depths) as well as a generic/fictitious distributor that facilitates installation and service as the end consumer contact. All cost inputs from these two distribution stages were speculative, but historical market insights were taken into consideration.

Final analysis of financial modeling showed that a window performance of u_w=0.1 / R10/SHGC>0.5 is unlikely to be obtained within the end consumer cost target of the program. Fundamental obstacles are the current expense and limited availability of certain high-performance glass options, and a performance-optimized cavity width that exceeds broadly accepted sash formats in the U.S. suitable for slider-type windows, e.g.

Moderately de-rating the thermal performance to approximately u_w=0.115 / R8.7/SHGC=0.44

opens a path to meet the program's end consumer cost target under the following assumptions:

- Automated high-volume/high-yield assembly (as demonstrated at Southwall Insulating Glass);
- High-volume production of the anti-reflection coating (as could be facilitated at Eastman Chemical Co's Martinsville coating plant), preferably on a thin-gauge PET substrate;
- Adoption of advanced warm-edge spacers that reduce CapEx and labor cost in high-volume manufacturing;
- Availability of clear and single-silver low-e coated mid-iron glass at a modest premium over standard float glass, and at a significant cost advantage over low-iron glass;
- The cost premium of the IGU does not scale linearly throughout the distribution channel, i.e. the cost increases of the post-IGU distribution channel are minimal at high-volume adoption, benefiting from light-weighting advantages of the Heat Mirror concept.

Task 4.3 (Milestone review – R10 Heat Mirror Feasibility): Milestone review was conducted January-10 2013, with conclusion to proceed with Task 4.4 (Sample Build), according to plan. Tasks 4.1 has qualified sufficiently capable materials and IGU designs that match scalable manufacturing concepts and realistic economic projections validated in Task 4.2 to move ahead with prototype film and IGU manufacturing at demonstrator scale.

Task 4.4 (External Review: Samples to Window Manufacturer, DOE): was initiated, per decision of the January-10 Milestone Review. The preparation of physical samples required obtaining modern window frames, depositing the necessary low-emissivity and anti-reflection coatings on the Heat Mirror film, and assembling the triple-cavity IGUs of suitable, specified components on Southwall's automated IGU assembly line. A window manufacturer was secured to provide frames/sash for demonstration window. Frames were received with assembly instructions; window manufacturer delivered additional frames/sash for demonstration windows. For the production of the project-specific Heat Mirror film, sputter-coated high-performance low-emissivity film was received from the Dresden production site. Coating runs to produce custom Heat Mirror film with anti-reflection coating for final demonstration units were completed at Palo Alto site, film was shipped to Chicago assembly site. Additional test runs for full IGU assembly at Chicago site with substitute Heat Mirror film to fine-tune assembly process and IGU quality were successfully performed. Test IGUs were shipped to Palo Alto and test-fitted in demonstration sash/frame. Custom Heat Mirror film for final demonstration units was received at Chicago assembly site. A final set of Heat Mirror IGUs (incorporating customized Heat Mirror film, warm-edge spacer and 3-cavity design) for the demonstration windows was produced in Chicago, and shipped to Palo Alto for fitting into frames/sashes.

Figure 3: Demonstration IGU being fitted into sample sash

Task 4.5 (Final Report): a final project team meeting was held June-28 2013 to gather latest findings on manufacturability assessments, cost modeling, market assessment and alignment for final report preparation. Findings from June-28 2013 review meeting were incorporated into the final internal technical report.

1. A description of any product produced or technology transfer activities accomplished during this reporting period, such as:

   No products, patents, or similar have been produced.

   A. Publications (list journal name, volume, issue); conference papers; or other public releases of results. Attach or send copies of public releases to the DOE Program Manager identified in Block 15 of the Assistance Agreement Cover Page.

   - Boman, Lee; Meade, John; Stoessel, Chris; Wipfler, Richard: **"Impact of Thin Film Coatings on the Performance of Highly Energy-Efficient Windows"**, 2011 Technical Conference Proceedings, Symposium on Coating Advances and Impact on the Future of Vacuum Coating Industry (November 16, 2011)
   - Wipfler, Richard; Meade, John; Stoessel, Chris; Boman, Lee: "**Design Options for Advanced Passive House Windows**", 9th International Conference of Coatings on Glass, Breda, The Netherlands, June 24-28, 2012

   B. Web site or other Internet sites that reflect the results of this project.

   N.A.

   C. Networks or collaborations fostered.

   Discussions with LBNL (Steve Selkowitz, Andre Anders), occasional status updates.

   Discussions with select U.S. window manufacturers continued, resulting in supply of frame/sash samples to install HM IGUs into high-performance window frames for delivery of project samples.

   D. Technologies/Techniques.

   Alternative techniques to attach Heat Mirror film to a spacer for tensioning.

   Automated assembly of thin-substrate Heat Mirror prototype film

   Integration of advanced structural warm-edge spacers into multi-cavity HM IGUs

   E. Inventions/Patent Applications

   N.A.

   F. Other products, such as data or databases, physical collections, audio or video, software or netware, models, educational aid or curricula, instruments or equipment.

   Assembly of a lab-scale-compliant HM IGU/window demonstrator .

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