Energy Research and Development Division
FINAL PROJECT REPORT

LOW–COST, ENERGY–SAVING, SOLID-STATE SMART WINDOWS

Prepared for: California Energy Commission
Prepared by: Soladigm, Inc.

AUGUST 2012
CEC-500-2013-026

SOLADIGM™

Prepared by:

Primary Author(s):
Robert Rozbicki, Principal Investigator

Soladigm, Inc.
195 S. Milpitas Blvd
Milpitas, CA 95035
408-263-9200
www.soladigm.com

Contract Number: PIR-10-049

Prepared for:

California Energy Commission

Dustin Davis
Contract Manager

Virginia Lew
Office Manager
Energy Efficiency Research Office

Laurie ten Hope
Deputy Director
RESEARCH AND DEVELOPMENT DIVISION

Robert P. Oglesby
Executive Director

ACKNOWLEDGEMENTS

This material is based upon work supported by the United States Department of Energy (DOE) under Award Number DE-EE0003908 and by the California Energy Commission, agreement PIR-10-049.

The project team gratefully acknowledges the hard work of the DOE and Energy Commission in developing and managing this project.

PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The Energy Research and Development Division strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

Energy Research and Development Division funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Low Cost Energy Saving Solid-State Smart Windows is the final report for Grant Number PIR-10-049, conducted by Applied Materials Incorporated. The information from this project contributes to Energy Research and Development Division's Buildings End-Use Energy Efficiency Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

Dynamic, electrochromic or "smart" windows can switch between a clear and tinted state on demand to block direct sunlight and radiant heat in the summer and n transmit radiant heat in the winter. These windows can transmit ambient light from indirect sunlight year-round to reduce energy use associated with lighting and air conditioning California buildings. Electrochromic windows darken when energized by an electrical current and turn clear when the voltage is taken away. Existing dynamic windows have fallen short of the cost, performance, and quality requirements needed for wide-scale market adoption.

The overall goal of this project was to develop a new approach to manufacturing electrochromic windows at a reduced cost using an all-vacuum in-line production process. An all-vacuum in-line production process requires only one vacuum step and is significantly less expensive than the traditional process.

The project accomplished its goals and resulted in a new manufacturing process that produces electrochromic windows at a substantially lower cost. These windows are now commercially available. Since commercial and residential buildings annually consume about 40 percent of the energy used in California, electrochromic windows could reduce the energy and cost associated with lighting, heating and cooling buildings. In existing commercial buildings, assuming a 10 percent market penetration, this technology could save California ratepayers more than 500 gigawatt hours (GWh) a year, which translates to more than $65 million annually in reduced lighting energy costs alone.

Keywords: Electrochromic windows, dynamic windows, smart windows, insulated glass units (IGUs), in-line manufacturing

Please use the following citation for this report:

Rozbicki, Robert (Soladigm, Inc.). 2012. ***Low–Cost, Energy–Saving, Solid-State Smart Windows***, California Energy Commission. Publication Number: CEC-500-2013-026.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The California Energy Commission provided cost-share funding to supplement Soladigm, Incorporated's (Soladigm) American Recovery and Reinvestment Act of 2009 (ARRA) award. The project conducted research and development of a new, more cost-effective process for manufacturing electrochromic windows. The Energy Commission's cost share assisted in the development and testing of a new manufacturing process to produce electrochromic windows at a reduced cost. The approved Department of Energy final report submitted by Soladigm is included in the appendix to supplement this report.

The project developed a revolutionary new process for fabricating electrochromic glass that will enable high-volume manufacturing at a lower cost than the conventional process. This project accomplished the goals of developing, fabricating, and testing the windows using a more cost-effective manufacturing process and resulted in these windows now being commercially available. Reduced cost of this technology will help address a major barrier to widespread adoption.

Widespread adoption of electrochromic windows could significantly reduce energy use associated with lighting, heating and air conditioning in California buildings. Compared to standard double-pane windows, a Lawrence Berkeley National Lab study shows electrochromic windows could reduce peak cooling loads by at least 19 percent and lighting loads by 48 percent, offering significant potential savings to California ratepayers. In existing commercial buildings, assuming a 10 percent market penetration, this technology could save California ratepayers more than 500 gigawatt hours (GWh) a year, which translates to more than $65 million annually in reduced lighting energy costs alone.

Energy Commission funding was critical to create and retain 12 jobs during a down economy at Soladigm's research and development facility in Milipitas, California. Also, Energy Commission funding expedited the development of the technology to successfully pass National Renewable Energy Laboratory's (NREL) reliability test almost six months ahead of schedule. The fact that this data was available much earlier than expected allowed the project team to pursue and win the company's first large-scale demonstration of Soladigm's electrochromic windows at the Marine Corps Air Station Miramar, in San Diego, attracting additional federal funding to California.

Appendix A contains a copy of the final report, *Low–Cost, Energy–Saving, Solid-State Smart Windows,* prepared by Soladigm for the U. S. Department of Energy under grant DE – EE0003908.

APPENDIX A:
Low–Cost, Energy–Saving, Solid-State Smart Windows, prepared by Soladigm for the U. S. Department of Energy under grant DE – EE0003908

Soladigm DOE Final Scientific/Technical Report

This Final Scientific/Technical Report describes the work of Soladigm, Inc., for its project supported by a Department of Energy grant from July 21, 2010 through December 31, 2011.

1. Project Identification

DOE Award Number DE-EE0003908, Soladigm, Inc., for "Low-Cost, High-Energy Savings, Solid State Dynamic Windows." Robert Rozbicki, Ph.D., Principal Investigator. No consortium or teaming members.

2. Distribution Limitation Notice

None.

3. Executive Summary

How the research adds to the understanding of the area investigated:

Soladigm's research has produced a fundamental improvement in the technology for dynamic windows by successfully transitioning a low-cost, high-performance dynamic glass fabrication process from a simple 2" research prototype into a full-scale manufacturing environment capable of producing commercial dynamic insulated glass units (IGUs), and developing and optimizing the production process to meet all specifications for mass commercial production.

The technology developed under this project is a revolutionary process for fabricating electrochromic glass that today exceeds DOE's 2020 performance and reliability targets at a compelling consumer price point. Before this project, we had demonstrated 2" prototypes using our deposition process that met these performance targets. The goal of this project was to prove that we could transition this lab-scale process to a scalable, "inline" manufacturing process, leveraging existing manufacturing tools capable of achieving a commercially attractive price-point in the near-term.

The technical effectiveness/economic feasibility of the methods or techniques investigated:

Under this project we demonstrated the technical effectiveness of our manufacturing process by achieving or exceeding all of our technical and performance targets for inline fabrication of electrochromic IGUs. These performance specifications exceed DOE's 2020 performance and reliability targets.

We also demonstrated the economic feasibility of our manufacturing process by reaching an initial production process that will achieve our target costs, which are compatible with mass adoption.

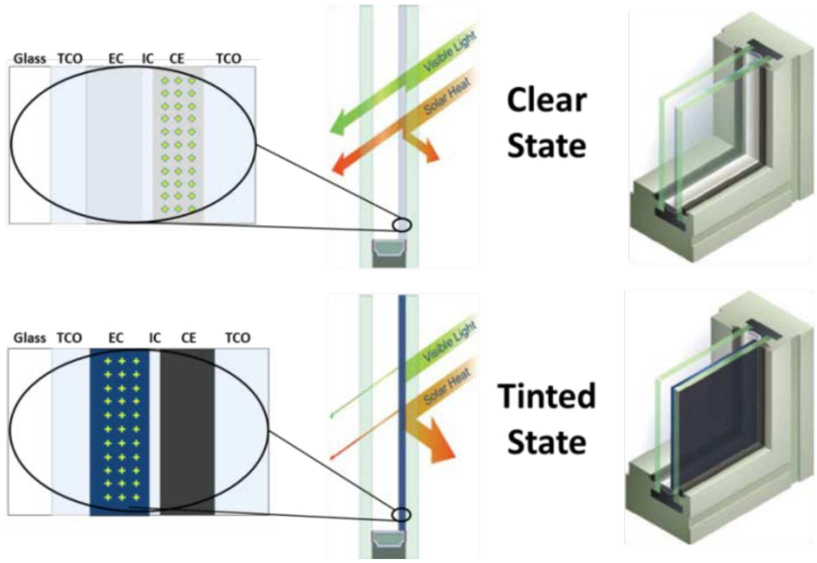

Figure 1: Electrochromic window configuration and optical characteristics

How the project is otherwise of benefit to the public:

Several categories of electrochromic glass already exist, based on different materials (organic vs. inorganic), ion types (proton vs. Li), and fabrication methods (vacuum vs. solution). Yet no previous approach has combined the performance, reliability and cost needed for broad adoption of dynamic windows. Our project has now achieved this long-sought combination, which will enable market acceptance.

This product will benefit builders and homeowners by making dynamic windows economically competitive. In addition, building managers and occupants will benefit from lower levels of building heating/air conditioning, and reduced glare due to sunlight, along with direct savings from lowered energy consumption. Our windows maximize exposure to natural daylight while providing a clear, unobstructed view. This benefit has been shown to improve worker health and productivity, decrease absenteeism, and reduce errors and manufacturing defects. Another direct benefit involves not having to clean or replace blinds and window curtains.

Lastly, the public will benefit both financially and environmentally from associated reductions in greenhouse gas impacts and pollutants.

4. Comparison of the Actual Accomplishments with Project Goals and Objectives

During this project, we met or exceeded all of our stated goals and objectives. The goal of this project was to transition our lab-scale process to a scalable, "inline" manufacturing process, leveraging existing manufacturing tools capable of achieving a commercially attractive price-point in the near-term. Each of our specific objectives and actual accomplishments are listed below:

Objective #1: Transfer and optimize our proven lab-scale process to a commercial deposition pilot line.
Actual #1: <u>We exceeded this objective</u>. We not only successfully transferred our lab-scale batch process onto our in-line pilot reactor; our progress was so rapid that we were also able to demonstrate this same level of performance on a full-scale manufacturing line. This step has taken this project beyond simply demonstrating that we could develop a process that was "compatible" with full-scale manufacturing tools, and demonstrated that we can actually run the process on these tools.

Objective #2: BuildIGUs meeting ASTM E-2141 durability standards.
Accomplishment #2: <u>We exceeded this objective.</u> We demonstrated IGUs that exceeded all ASTM E-2141 durability standards.

Objective #3: Show that the process can yield an attractive consumer price.
Accomplishment #3: <u>We exceeded this objective.</u> With the processes and device architecture developed under this program, we have projected that the cost based on operating the production line at scale will achieve the level below our initial targets.

Objective #4: Demonstrate a path to a price premium compatible with mass residential adoption.
Accomplishment #4: <u>We exceeded this objective.</u> Based on our current process, we project that we will reach this pricing target through a combination of identified improvements in manufacturing process efficiency as well as equipment efficiency as additional production lines are brought on line. We currently anticipate this level of improvement will be achieved within the first few years of production, well ahead of our target.

Figure 2: View from interior looking outside: Soladigm's low-cost dynamic windows installed in a standard curtain-wall façade and set to different levels of transparency: **A)** Top and left-side windows are set to "clear"; middle windows are set to "full tint"; and right-side windows are set to an intermediate state.

5. Summary of Project Activities for the entire period of funding

This project was divided into two phases. In Phase 1, we transitioned our process to an inline pilot manufacturing tool and fabricated prototype IGU units . In Phase 2, we further optimized our process to demonstrate operation over a larger glass-width. All devices exceeded DOE's 2020 goals for dynamic glass, with a process capable of yielding our target consumer price point.

<u>PHASE 1</u>

Phase 1 Scope of Work: In Phase 1, we brought up the pilot line and developed preliminary production characteristics, including mapping the impact of process changes. This allowed us to identify the optimum cost, quality, and time-of-production parameters. Key parameters included deposition rate, throughput, and material costs. The output of Phase 1 was a prototype IGU meeting the performance characteristics of our lab-prototype, but fabricated on our pilot line (See Table 1).

Phase 1 Tasks Performed:

Task 1.0: Project Management Plan

We completed all project management activities during both phases.

Task 2.0: Develop Device Models

<u>Goal of Task</u>: Develop film- and stack-models to generate inputs for Design of Experiments (DoE) optimization process, guide program decisions, and facilitate future development to hit price targets.

Key Steps:

1. *Develop and Validate Model –*

Using a commercial software program, MICROCAP, we constructed a hybrid device model for transient performance of our scaled device, including a combination of (a) a purely resistive model that predicts steady-state device uniformity as a function of TCO sheet resistance, stack resistivity and bus-bar geometry; and (b) a transient switching model with more complex impedance models for the electrochromic layers. We validated the model against our existing lab-prototype devices, as well as devices (and individual layers) fabricated in Tasks 3, 4, and 5 below.

2. *Deliver starting-point parameters to, and guide optimization in, Tasks 3 and 4 –*

The model we developed in the project's first quarter assumed a resistive network with a finite number of series resistors representing the TCO layers, sandwiching parallel resistors which represent electronic leakage paths. Using this model, we typically assumed good device uniformity and toggled four parameters (top TCO Rs, bottom TCO Rs, leakage path resistance, and applied voltage) to get resultant voltage profiles. We then translated these voltage profiles to expected coloration differences of an EC device. Specifying the allowable optical density non-uniformity of a device allowed for the determination of acceptable electronic leakage, TCO resistance and applied voltage.

The model was successfully developed and validated by comparing predicted voltage profiles to measured voltage profiles across multiple devices. The accuracy of the model was confirmed to be >95%. Based on this model, success criteria for TCO sheet resistance and leakage current were established to scale the technology to larger dimensions.

After validating the model in Q1 of the project, we used it to project optimum starting points for DoE on materials and process optimizations in Tasks 3 and 4. The model was also used to guide decision-making throughout the entire project.

At the start of the development period in Q2 of this project, the device model of Task 2 had been developed and experimentally validated. It was a useful tool in understanding the impact of leakage currents and TCO sheet resistance on device performance and scalability and enabled us to establish quantifiable goals for our final IGU deliverables.

Milestone:

1. **ACHIEVED -** Validated model; input parameters delivered to Tasks 3 & 4

Task 3.0: Develop and Optimize Thin Film Layer Processes

Goal of Task: Develop optimized deposition processes on the pilot line for each layer in the electrochromic stack that (i) meet the materials/uniformity characteristics from the model in Task 2, (ii) meet our Phase 1 performance targets, and (iii) provide device-data feedback to the model in Task 2.

Key Steps:

1. *Develop EC Layer* – Used pilot line to coat the EC layer. Did DoE optimization around the 2” prototype baseline process against pressure, heating, O_2 content, power, and deposition rate for substrates. Characterized the resulting coatings for thickness uniformity, microstructure, stoichiometry, and EC properties. Compared to 2” batch films and optimized to match.
2. *Develop IC Layer* – Repeated DoE described in (1) for the IC layer, maximizing ionic conductivity and electronic resistivity, with a sufficient breakdown voltage. Based on labs-scale results, layer thickness was optimized.
3. *Develop CE Layer* – Repeated DoE described in (1) for the CE layer. Characterized the coatings for thickness uniformity, microstructure, stoichiometry, and EC properties.

In Q1 of the project, single film development activities focused on optimization of the counter electrode (CE) and second TCO layers. Optimized single films were integrated into a working device and tested for dynamic range, switching speed, and defect performance. Dynamic range describes the maximum and minimum % transmission in the visible range (%Tvis) and is referred to as %Tbleach and %Tcolor, respectively. Switching speed is the time required to achieve 80% of the end state product specification, measured in optical density rather than %Tvis to align with what the eye sees. Defectivity is the density of visible defects in the colored state. For the CE layer, process pressure and gas composition were investigated. Single films were deposited and tested using standard wet chemistry techniques to evaluate charge capacity and reversibility. Two conditions were chosen based on their compatibility with the electrochromic film and which were believed to provide the best performance for large-scale manufacturing. Of the two CE films integrated into working devices, both showed acceptable performance in terms of dynamic range and switching speed. However, one condition outperformed the other in terms of defectivity, and was therefore selected.

The top TCO single layer was also a major development activity in Q1. As discussed in the device modeling section above, the TCO sheet resistance is a critical parameter for device scalability. Low in-plane resistance minimizes the voltage drop across the device, leading to faster and more uniform switching. The challenge becomes achieving low resistance while maintaining high transparency and integrating this layer directly onto the electrochromic device.

Milestone:

1. **ACHIEVED -** Optimized EC Layer process to achieve thickness variation targets;
2. **ACHIEVED -** Optimized IC Layer process
3. **ACHIEVED -** Optimized CE Layer to achieve surface thickness uniformity targets.

Task 4: Fabricate Electrochromic Device

Goal of Task: Fabricate and optimize complete device structure using the outputs of Tasks 2 and 3.

Key Steps:

1. Fabricate Stack – Starting with TCO-coated glass , fabricated stack structure with successive coatings of IC, IC, CE, and TCO. Used output from Task 3 as the starting point for DoE; used model from Task 2 to direct decisions.
2. Optimized Spectral and SHGC Parameters – Adjusted thickness and thickness ratio of CE and EC layers to optimize spectral characteristics and SHGC. Evaluated device performance with current-voltage measurements. Evaluated optical quality in bleached and dark state with a mapping spectrometer.
3. Optimized Switching Kinetics and Leakage Current – Adjusted thickness of IC layer to optimize electrical isolation, ionic conductivity, and switching speed in a uniform fashion across device.
4. Characterized and Minimized Defects – Characterized defect density, shape, and composition to understand root cause. Optimized process to reduce defect density, meeting our targets.

5. Optimized Sheet Resistance of Top and Bottom TCOs – Adjusted deposition parameters for top TCO layer to ensure uniformity of sheet resistance and optical performance across the device.
6. Fabricated IGU – Fabricated IGUs using standard two stage seal insulating glass method.

Beginning in Q2, we put a significant focus on scaling Soladigm's technology from our prototype size to our full-size target for Phase I. To that end, defectivity reduction played a key role as defects can both contribute to leakage current (e.g. electronic shorts in the device) and can appear in the form of visual defects. Since defects scale with device area, it's easy to see the importance of focus in this area.

Most of the defect reduction efforts involved handling, quality control and cleaning. Because electrochromic coatings are active electronic devices, they require higher standards than conventional low-E coatings, for example. Improvements in handling, storing, staging and pre-inspection of glass were all critical in driving down the defectivity levels.

Leakage current is the electronic leakage within the electrochromic window. Although it is easy to measure a bulk value, it has many potential sources that are difficult to de-convolute. However, one source that's easily characterized is particulate-induced defects which manifest themselves into electronic shorts and localized areas of poor or non-coloration. These defects can come from the incoming glass or during the deposition of the electrochromic coatings during the fabrication process. This source of leakage is of particular interest because not only does it contribute to a leakage current increase that impacts scalability, it creates visual non-uniformities in the window that significantly impact quality and yield. As such, a considerable amount of time and effort in Q2 was spent on particulate-related defect characterization and reduction in order to achieve leakage current goals for Phase I.

To this end, glass quality continued to be an area of focus for defect reduction. Some of the improvements put in place included better handling protocols, evaluating alternative vendors processing, and improving documentation and training on all steps of glass processing. These improvements not only led to a reduction in particulate-induced defects, but also a reduction in the frequency of chips, cracks and scratches that impacted yield.

The second area of defect reduction was on the fabrication process – specifically, on the sequence of deposition processes used to apply the electrochromic stack to the glass substrate. Particulate defectivity can have many sources within a deposition system. These include buildup of deposition materials on shields and chamber walls, re-deposition on target surfaces, and unintentional erosion of chamber components. These sources can be liberated and transported to the substrate during the fabrication process due to mechanical motion, thermal non-equilibrium, and plasma processing. Once on the substrate, they often become incorporated into the electrochromic stack and become "active" within the electrical circuit of the device. Because these defects are conductive, they allow electrons to flow across the ion conductor layer, resulting in both an increase in leakage current (impacting scalability) and often creating areas of poor or non-coloration due to the localized voltage drop.

During Q2, many samples collected from the substrate were compared to potential defects sources within the deposition system. Based on this work, theories were developed on the different locations within the system that the defects were originating from, as well as mechanisms for how these defects were being transported to the glass substrate during processing. Corrective actions were designed and tested, often individually, to confirm a particular defect source was reduced or eliminated. Although this methodology was quite time-consuming and laborious, it provided a systematic and quantifiable technique for defect reduction and led to robust improvements in leakage current.

Within Task 4, other areas of progress were made in optimization of switching kinetics and IGU fabrication. IGUs were fabricated which passed the ASTM-2190 testing protocol for Argon retention and seal integrity. This milestone is of paramount importance as electrochromic windows are expected to last at least 30 years.

With our improved glass handling and cleaning protocols in place, along with our defect reduction efforts of the fabrication process, a large number of EC lites were fabricated. These lites were subsequently built into EC IGUs using the ASTM validated procedure and these windows provided the sample set for 'Test and Evaluation of the IGU Prototypes' (Task 5). Each IGU was characterized for performance (e.g. switching speed, dynamic range, cycle to cycle repeatability) as well as quality (e.g. defect density, uniformity). Selected windows were used for an onsite installation in order to evaluate side by side performance and longer term stability.

In Q3 of the project, a majority of the effort in Task 4 focused on improving %T bleach and reducing defectivity. One area of the window performance that required improvement was the %Tvis in the “bleached” or clear state. By the end of Q3, we were able to meet our %T color requirement.

Electrochromic windows utilize ions, usually protons or Li ions, to control the optical state of the window through application of an external voltage. When the voltage is applied in a negative polarity, the ions move from the counter electrode to the electrochromic film and the window colors. When the polarity is reversed, the ions move back to the counter electrode and the window bleaches. Precise control over the film characteristics and thickness ratios is required to achieve the desired range of coloration and bleaching.

As a result, a significant amount of the development effort to expand the dynamic range of the EC glass to meet our product specifications focused on the Li process relative to the thicknesses of the electrochromic and counter electrode layers. The first step was to map out the response of device performance to the amount of Li in the device. It was observed that when the device was under-lithiated, coloration was impacted. Eventually, we established an approximate process window for the degree of lithiation.

Optimization of the Li process itself included evaluating the process parameters which impacted rate and uniformity. The latter was important to ensure that all areas of the window performed similarly in dynamic range. For example, in certain cases, it was possible to over-lithiate one area of the window while under-lithiating another, creating non-uniform coloration and bleaching. By adjusting Li parameters, we achieved a process which was uniform and with a rate that was in line with our goals.

This enabled us to achieve our Phase 1 goal of producing dynamic IGUs that met the needed product specifications.

<u>Milestone</u>:

1. **ACHIEVED -** Optimized process meeting Phase 1 performance, throughput, and price projection targets
2. **ACHIEVED -** Data delivered to Task 2 to refine and finalize model for future development efforts
3. **ACHIEVED -** Prototype IGUs delivered for testing and evaluation in Task 5

Task 5.0: Test and Evaluate Dynamic IGUs

Goal of Task: Test and evaluate the IGU prototypes from Task 4.

Key Steps:

1. Test IGUs – Evaluated performance and operation of prototype IGUs, including limited ASTM E-2141 reliability test (5,000 cycles), to ensure color, switching speed, and appearance meet expectations.

As stated above, a large number of EC lites were fabricated using a copy methodology. and these windows provided the sample set for this task. Each IGU was characterized for performance (e.g. switching speed, dynamic range, cycle to cycle repeatability) as well as quality (e.g. defect density, uniformity). Selected IGUs were used for an onsite installation in order to evaluate side by side performance and longer term stability. Overall, the quality and consistency of the 30" prototypes improved considerably due to these efforts.

Milestone: **ACHIEVED -** IGU prototypes met all Phase 1 performance targets.

Check-Point: At this point in the program, and based on our success in achieving all Phase 1 milestones, DOE approved moving to Phase 2.

PHASE 2

Phase 2 Scope of Work: Run full 50,000-cycle ASTM E-2141 reliability tests on standard IGUs. Demonstrate EC operation with 60" substrate widths. The output of Phase 2 is a field-tested IGU product prototype meeting Phase 2 performance targets in Table 1.

Phase 2 Tasks to Be Performed:

Task 6.0: Reliability Testing

Goal of Task: Pass full NREL ASTM E-2141

Key Steps:

1. Fabricated Samples – Fabricate IGUs using the baseline process developed in Phase 1
2. Ran NREL Tests – Completed 50,000 cycles using ASTM E-2141 testing criteria.

In Q5, Task 6 specified fabrication of samples and testing of samples under the ASTM-2141 standard at NREL. Samples were submitted to NREL in November, 2010 to begin testing (almost two quarters ahead of schedule).

During Q3, coating durability continued to be a key focus for us, even becoming an area where we performed ahead of schedule. Namely, Task 6 specified fabrication of samples and testing of samples under the ASTM-2141 standard at NREL. By the end of Q4, samples testing at NREL had successfully completed the first check at 20,000 cycles. In addition, internal "look ahead" samples that were started in 2010 had completed the entire test, exceeding 50,000 cycles.

As of the end of Q5, samples testing at NREL had successfully completed the second check at 43,500 cycles; and by the end of Q6 of the project, we completed NREL ASTM E2141-6 Electrochromic Durability Testing. These tests involved standard solar cycling (1 sun) at 85degC for 50,000 cycles, with a goal to maintain at least a %Tbleach > 50%, %Tcolor < 12.5% (PTR>4) with no visual degradation. Our windows significantly exceeded all of these requirements under NREL testing. Soladigm is only the second dynamic glass to have ever passed these tests.

Milestone:

1. **ACHIEVED -** Passed ASTM E-2141 certification.

Task 7.0: Build Test Stand for Commercial Scale Substrates

Goal of Task: Verify coating for commercial size substrates.

Key Steps:

1. Build Test Stand - we built a test stand system with production style deposition to cover the full area for commercial sized substrates.
2. Verify Deposition Performance – We ran films using the test stand and demonstrated we can achieve our pilot line film performance scaled up to full size.

By the project's fourth quarter, it was time to address the fact that our pilot line hardware did not match the specific details of our planned production line hardware. To address this, we designed and built two (2) offline deposition systems. The first system (pilot test stand or PTS) matched the *design* of the production deposition system but *not* the dimension (i.e. it will have the same hardware as the production system but at a size that matches the pilot line). The second system (large test stand or LTS) matched *both* the design and dimension of the production coater. The need for two systems reflects the importance of transferring process across both design and dimensional differences between the pilot line and the production line. In order to achieve the objectives of full-size scalability (Task 8), we needed to confirm that the same film properties for each coating of the electrochromic stack could be achieved across all three platforms. This improved our confidence that the technology developed on the pilot line was scalable to our production line.

In Q5 of the project, a significant amount of effort was put into the design of the PTS, procurement of hardware, and fabrication of the deposition system. The system consisted of a deposition chamber along with a load lock to transfer the glass substrate between atmosphere and vacuum. It included numerous onboard diagnostic tools to monitor the "health" of the deposition system (e.g. vacuum levels), as well as provide in situ monitoring of the glass substrate during the deposition process. Initially, it was configured with the same hardware as the pilot line to confirm we could achieve the same process on both platforms and "qualify" the PTS deposition system. This was successfully completed which allowed the PTS to be upgraded with hardware that matched the design of the production system. At the close of Q6, a total of two (2) of the processes used to fabricate the electrochromic coatings on the pilot line had been tested on the PTS outfitted with the production hardware. The results were very encouraging, with key performance metrics within a few percentage points of one another when comparing the data on the individual films. The initial data suggested that the hardware differences between the pilot line and production line were low risk to the process transfer and scale up. However, it was important to arrive at a similar conclusion for all coating processes and so we continued comparing pilot line hardware to production line hardware on PTS.

In Q8, the PTS was expanded from one (1) zone to three (3) zones. This was an extensive upgrade to the PTS and it required integration of more hardware and new software development to enable the flexibility required for R&D, or this expansion enabled accurate experiments to study interactions between steps. A key driver for this expansion was the ability to look for cross-step interactions, which we determined to be critical to device operation in Task 4. The qualification tests run on PTS show that the cross-step interactions observed on the pilot tool are also observed on the PTS, which suggests that the single step and cross-step knowledge from the PTS are directly applicable for process transfer.

The second major focus on PTS was qualification of the different hardware sub-assemblies that would be used on the production coater. A more extended design of experiments was undertaken on PTS to look at all the interactions between the process conditions to determine the optimum space for the deposition process.

While the PTS offered the ability to test out some of the hardware sub-assemblies, there were many sub-assemblies that could not be tested on the PTS due to size limitations. This required the use of the second test system – the large test stand system (LTS). As stated above, the large test stand system (LTS) was built to match *both* the design and dimension of the production coater. In Q5, most of the effort on LTS was in the design and procurement of hardware. In Q6 and Q7, this system was constructed. The design of the LTS was intended to be as similar to the production coater as possible. Two standalone LTS systems were developed, which allowed us to study two material systems in parallel. In Q8, both LTS systems were constructed and installed; and initial experiments were started on one system while the second system underwent the final checks.

The LTS system was designed to match the production coater in key hardware sub-assemblies. As a result, we gained knowledge about the interactions between these sub-systems as the LTS systems were being brought online. In addition, a lot of the debugging knowledge gained from the LTS startup can be applied to the production coater since there are similarities between software control systems. After the hardware checks were complete, the LTS system was used for the initial tests. This was a key data point, as it significantly de-risked the configuration and process space that would be used in the production coater. Multiple films were run to characterize the deposition process. In our initial assessment, the deposition was acceptable to meet the target manufacturing metrics on the production coater. However, this was dependent on the LTS films matching the pilot line film and meeting all the single film metrics. At that point, the single film characterization was undertaken.

By the project's final quarter, the test stands in Olive Branch, MS had been custom-built by Soladigm in order to test scalability. Each test stand had the capability of depositing a thin film coating across full-size commercial glass.

Milestone:

1. **ACHIEVED -** Test stand provides full-size substrate deposition performance.

Task 8.0: Scale to Full-Width Devices

Goal of Task: Prove scaled performance.

Key Steps:

1. Baseline Full-Size Performance: Characterize the performance of the full-width devices.
2. Optimize devices to achieve full-size objectives: Using the procedures from Task 4, we will characterize defects, identify route causes and optimize to meet performance specification.
3. Test Final Full-Width Devices: Evaluate all performance metrics after optimization.

In Q6, we built full-width windows to evaluate the operation of our dynamic windows at commercial size. In this configuration, these windows met all of our standard performance requirements, but they required more than our target time to complete the transition between bleached and colored states. This represented our baseline for Task 8. We then began a complete design of experiments on our pilot line to optimize film characteristics to improve transition time, as well as further improve our overall performance characteristics.

After completing this DoE in Q7, we re-tested the full-width design using the optimized dynamic glass. This involved experimentation, development and validation across multiple platforms including our pilot line (Milpitas, CA) as well as offline test stands and our manufacturing line (Olive Branch, MS). Multiple platforms were required to complete Task 8.

For the purposes of Task 8, single films were deposited on the test stands with the objective of matching the materials properties to the single films that comprised the electrochromic devices on the pilot line. Process parameters were optimized and the resulting films were analyzed across a full-width distance. The challenge became not only to match the film properties at a single location, but to achieve the desired film properties across the entire surface with good uniformity. We used optimization of process parameters to tune the basic films properties. We placed extra focus on the TCO layers since the sheet resistance strongly impacts scalability. Through iterative cycles of development, we confirmed that the single films on the test stand matched the single films of the pilot line.

Milestone:

1. **ACHIEVED -** Full-size IGU with performance characteristics meeting the Phase 2 targets.
2. **EXCEEDED –** Demonstrated that process can be transferred onto a full-scale production line (this milestone goes beyond the scope of this project)

Task 9.0: Field Testing of IGU

Goal of Task: Setup and perform complete field testing of IGUs.

Key Steps:

1. Field Trial Setup - Placed IGUs in a southwest facing rack and continuously cycled them for a period of 10-14 weeks.
2. Evaluate performance (weekly) – Measured effects of environmental exposure on optical and electrical performance. Made visual inspections and documented aesthetic changes.

In order to evaluate the operation of our dynamic windows in real life conditions, we installed our windows on the roof of our Pilot facility in Milpitas, CA in October, 2011. The windows were exposed to environmental conditions (solar and humidity exposure, thermal cycling through the day, etc.). The windows were held in conditions to simulate actual application (e.g. held in the dark state during the day). Multiple windows were run in these conditions for varying lengths of time between 70 – 100 days to collect statistical data for this test. All windows showed excellent performance stability. No degradation was observed during the test. This data aligned with the reliability of the devices as observed in Task 6.

Milestone:

1. **ACHIEVED -** Field test and evaluation of IGUs.

Problems encountered and departure from planned methodology, and an assessment of their impact on the project results:

In Phase 2, we experienced a delay in meeting our goal to complete the transition to full inline manufacturing by Oct. 31, 2011. This was due to a longer than expected period to optimize the manufacturing process to achieve our full-width process objectives. As a result, we were granted a short two-month extension until Dec. 31, 2011 to complete the testing of full-width devices. This modification had no substantive impact on our ability to reach the stated goals in our original hypotheses.

If applicable, include any facts, figures, analyses, and assumptions used during the life of the project to support the conclusions:

All values were measured and confirmed by NREL through the two ASTM tests described above. All cost projections are based on robust manufacturing models for the full-volume production plant in Mississippi. The results of this project are now being demonstrated in real-world installation in the San Diego area. This demonstration project, funded under the DOD's ESTCP program, will commence in mid 2012. Images of the site are included below.

<u>MCAS - Miramar</u>
San Diego,CA
Views of Building 6311

Figure 4: Marine Corps Air Station Building 6311 – New demonstration site of Soladigm's electrochromic windows.

6. Products Developed Under the Award and Technology Transfer Activities, such as:

a. Publications, conference papers or other public releases of results: None.

b. Web sites that reflect the results of this project: None.

c. Networks or collaborations fostered: None.

d. Technologies/Techniques: Through this research effort, we developed and optimized our technology for a scalable, "inline" process to manufacture commercial size dynamic windows.

We will apply our electrochromic coating before assembling dual-pane IGUs into standard form factor IGUs, which will allow seamless integration into new and retrofit construction. As our price point decreases over time, we will enter certain markets in the following order, based on price sensitivity and the cost-savings potential of our windows: new commercial buildings; commercial retrofits; new residential buildings; and finally, residential retrofits.

e. Inventions/Patent Applications, licensing agreements: None.

f. Other products, such as data or databases, physical collections, audio or video, software or netware, models, educational aid or curricula, instruments or equipment: None.

7. For Projects Involving Computer Modeling, provide the following information:

a. Model description, key assumptions, version, source and intended use: In Task 2.0 (to Develop Device Models), we used commercial MICROCAP software to construct a hybrid device model for transient performance of our scaled device. This included a combination of (a) a purely resistive model that predicts steady-state device uniformity as a function of TCO sheet resistance, stack resistivity and bus-bar geometry; and (b) a transient switching model with more complex impedance models for the electrochromic layers *b. Performance criteria for the model related to intended use*: The performance criteria for the model is to accurately predict the effective voltage for the device at any point across the substrate.

c. Test results to demonstrate the model performance criteria were met (e.g. code verification/validation, sensitivity analyses, history matching with lab or field data, as appropriate): We validated our model against our initial lab-prototype devices, as well as devices and individual layers developed in Task 3 (Develop and Optimize Thin Film Layer Processes), Task 4 (to Fabricate Electrochromic Device) and Task 5 (to Test and Evaluate IGUs).

We also delivered starting point parameters to Tasks 3 and 4, and guided optimization to project optimum starting points for DOE on materials and process optimizations in Task 3 and Task 4. The model was used to guide decision-making throughout the entire project.

d. Theory behind the model, expressed in non-mathematical terms: The model theory is based on thin-film resistor network modeling coupled with capacitance within device modeling.

e. Mathematics to be used, including formulas and calculation methods: The formula and calculation methods can be found in the following reference: “Modelling switching of electrochromic devices – a route to successful large area device design”, J.M. Bell, J.P. Matthews, I.L. Skryabin, Solid State Ionics 152-153 (2002) 853-860.

f. Whether or not the theory and mathematical algorithms were peer-reviewed, and if so, include a summary of theoretical strengths and weaknesses: The theory and mathematical algorithms were peer reviewed as shown in the following same reference: “Modelling switching of electrochromic devices – a route to successful large area device design”, J.M. Bell, J.P. Matthews, I.L. Skryabin, Solid State Ionics 152-153 (2002) 853-860.

g. Hardware requirements: None

h. Documentation (e.g. user’s guide, model code): http://www.spectrum-soft.com/down/rm.pdf