Tuesday, 30 September 2008

TO: Joel Chaddock
NETL Project Officer
National Energy Technology Laboratory
3610 Collins Ferry Road, PO Box 880
Morgantown, WV 26507-0880

CC: Dietrich Bertram (Philips), Holger Schwab (Philips), Keith Cook (Philips), W. Ken Weidner (DCC), Doug Freitag (Bayside Materials Technology)

SUBJECT: Thin Film Packaging Solutions for High Efficiency OLED Lighting Products (Subcontract No. DE-FC26-05NT42344)

Dear Joel,

Philips Lighting and Dow Corning Corporation are pleased to submit this third and final budget period report for your review and consideration. Please direct questions regarding this report to Brian Marinik – contact information is provided below for your convenience:

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Sincerely,

Brian J. Marinik
Government Contracts Program Manager
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PO Box 994
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EXECUTIVE SUMMARY

The objective of the *Thin Film Packaging Solutions for High Efficiency OLED Lighting Products* project is to demonstrate thin film packaging solutions based on SiC hermetic coatings that, when applied to glass and plastic substrates, support OLED lighting devices by providing longer life with greater efficiency at lower cost than is currently available.

- Phase I Objective: Demonstrate thin film encapsulated working phosphorescent OLED devices on optical glass with lifetime of 1,000 hour life, CRI greater than 75, and 15 lm/W.
- Phase II Objective: Demonstrate thin film encapsulated working phosphorescent OLED devices on plastic or glass composite with 25 lm/W, 5,000 hours life, and CRI greater than 80.
- Phase III Objective: Demonstrate 2 x 2 ft^2 thin film encapsulated working phosphorescent OLED with 40 lm/W, 10,000 hour life, and CRI greater than 85.

This report details the efforts of Phase III (Budget Period Three), a fourteen month collaborative effort that focused on optimization of high-efficiency phosphorescent OLED devices and thin-film encapsulation of said devices. The report further details the conclusions and recommendations of the project team that have foundation in all three budget periods for the program.

During the conduct of the Thin Film Packaging Solutions for High Efficiency OLED Lighting Products program, including budget period three, the project team completed and delivered the following achievements:

1) a three-year marketing effort that characterized the near-term and longer-term OLED market, identified customer and consumer lighting needs, and suggested prototype product concepts and niche OLED applications lighting that will give rise to broader market acceptance as a source for wide area illumination and energy conservation;

2) a thin film encapsulation technology with a lifetime of nearly 15,000 hours, tested by calcium coupons, while stored at 16°C and 40% relative humidity (“RH”). This encapsulation technology was characterized as having less than 10% change in transmission during the 15,000 hour test period;

3) demonstrated thin film encapsulation of a phosphorescent OLED device with 1,500 hours of lifetime at 60°C and 80% RH;

4) demonstrated that a thin film laminate encapsulation, in addition to the direct thin film deposition process, of a polymer OLED device was another feasible packaging strategy for OLED lighting. The thin film laminate strategy was developed to mitigate defects, demonstrate roll-to-roll process capability for high volume throughput (reduce costs) and to support a potential commercial pathway that is less dependent upon integrated manufacturing since the laminate could be sold as a rolled good;

5) demonstrated that low cost “blue” glass substrates could be coated with a siloxane barrier layer for planarization and ion-protection and used in the fabrication of a polymer OLED lighting device. This study further demonstrated that the substrate cost has potential for huge cost reductions from the white borosilicate glass substrate currently used by the OLED lighting industry;

6) delivered four-square feet of white phosphorescent OLED technology, including novel high efficiency devices with 82 CRI, greater than 50 lm/W efficiency, and more than 1,000 hours lifetime in a product concept model shelf;

7) presented and or published more than twenty internal studies (for private use), three external presentations (OLED workshop – for public use), and five technology-related external presentations (industry conferences – for public use); and

8) issued five patent applications, which are in various maturity stages at time of publication.

Delivery of thin film encapsulated white phosphorescent OLED lighting technology remains a challenging technical achievement, and it seems that commercial availability of thin, bright, white OLED light that meets market requirements will continue to require research and development effort. However, there will be glass encapsulated white OLED lighting products commercialized in niche markets during the 2008 calendar year. This commercialization effort, the project team believes, will lead to increasing market attention and broader demand for more efficient, wide area general purpose white OLED lighting in the coming years.

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PROGRAM OBJECTIVES

The objective of the project is to demonstrate thin film packaging solutions based on SiC hermetic coatings that, when applied to glass and plastic substrates, support organic light emitting diode (OLED) lighting devices by providing longer life with greater efficiency at lower cost than is currently available.

- Phase I Objective: Demonstrate thin film encapsulated working phosphorescent OLED devices on optical glass with lifetime of 1,000 hour life, CRI greater than 75, and 15 lm/W.
- Phase II Objective: Demonstrate thin film encapsulated working phosphorescent OLED devices on plastic or glass composite with 25 lm/W, 5,000 hours life, and CRI greater than 80.
- Phase III Objective: Demonstrate 2 x 2 ft^2 thin film encapsulated working phosphorescent OLED with 40 lm/W, 10,000 hour life, and CRI greater than 85.

In order to achieve these objectives, Dow Corning is working with Philips Lighting for high-efficiency phosphorescent OLED fabrication and testing, and for support of OLED lighting market research.

PROGRAM ACCOMPLISHMENTS

During the conduct of the *Thin Film Packaging Solutions for High Efficiency OLED Lighting Products* program, including budget period three, the project team completed and delivered the following achievements:

- A three-year marketing effort that characterized the near-term and longer-term OLED market, identified customer and consumer lighting needs, and suggested prototype product concepts and niche OLED lighting applications that will give rise to broader market acceptance as a source for wide area illumination and energy conservation.
- A thin film encapsulation technology with a lifetime of nearly 15,000 hours, tested by calcium coupons, while stored at 16°C and 40% relative humidity ("RH"). This encapsulation technology was characterized as having less than 10% change in transmission during the 15,000 hour test period.
- Demonstrated thin film encapsulation of a phosphorescent OLED device with 1,500 hours of lifetime at 60°C and 80% RH.
- Demonstrated that a thin film laminate encapsulation, in addition to the direct thin film deposition process, of a polymer OLED device was another feasible packaging strategy for OLED lighting. The thin film laminate strategy was developed to mitigate defects, demonstrate roll-to-roll process capability for high volume throughput (reduce costs) and to support a potential commercial pathway that is less dependent upon integrated manufacturing since the laminate could be sold as a rolled good.

- Demonstrated that low cost "blue" glass substrates could be coated with a siloxane barrier layer for planarization and ion-protection and used in the fabrication of a polymer OLED lighting device. This study further demonstrated that the substrate cost has potential for huge cost reductions from the white borosilicate glass substrate currently used by the OLED lighting industry.
- Delivered four-square feet of white phosphorescent OLED technology, including novel high efficiency devices with 82 CRI, greater than 50 lm/W efficiency, and more than 1,000 hours lifetime in a product concept model shelf.
- Presented and or published more than twenty internal studies (for private use), three external presentations (OLED workshop – for public use), and five technology-related external presentations (industry conferences – for public use).
- Issued five patent applications, which are in various maturity stages at time of publication.

Goals and accomplishments per our *Solid State Lighting Program Management Plan* ("Management Plan") schedule are listed in Table 1. The Management Plan was utilized by the project team and the leadership at NETL as a semi-formal roadmap for technology development and provided all parties with a common set of detailed milestones, compared with the contract budget period objectives, to measure progress.

Table 1 – Management Plan Milestone Summary

Metric	Planned Timing	Actual Timing	Status
Deliver report of general market research, application screen, and definition of lighting requirements.	30 Nov 2005	30 Nov 2005	Completed
Deliver (5) monochrome OLED samples targeting 15 lm/W, 5,000 hours lifetime, CRI greater than 75 and device dimensions of two square inches.	30 Nov 2005	15 Feb 2006	Completed
Deliver final report of materials and process developments for low cost substrate (glass and composite) test data targeting transparency of greater than 85%, RMS less than 10nm and spikes less than 20nm.	31 May 2006	15 May 2006	Completed
Deliver (5) OLED devices on alternate substrate(s) for demonstration, including targets for 5,000 hour lifetime at ambient conditions and processing temperatures less than 80C.	30 Nov 2006	PLED Devices	Incomplete
Deliver (5) monochrome OLED samples targeting 25 lm/W, 5,000 hour lifetime, CRI greater than 80 and device dimensions of two square inches.	30 Nov 2006	31 July 2007	Completed
Deliver report of cost and performance criteria for store-display illumination application and report on application downselection with increased definition of requirements.	30 Nov 2006	14 Nov 2006	Completed
Deliver monochrome OLED samples; target 25 lm/W, 5,000 hour lifetime, CRI greater than 80 and device dimensions of six square inches.	28 Feb 2007	Device Area $<6in^2$	Incomplete
Deliver report including application downselection with increased definition of requirements.	31 May 2007	15 May 2007	Completed
Deliver a report on scaled process that enables a six inch square OLED device on alternative substrates with greater than 50% efficiency yield.	31 Aug 2007	-	Incomplete
Deliver white OLED devices for demonstration; target 40 lm/W, 10,000 hour lifetime, CRI greater than 85 and device dimensions of two square feet.	31 Aug 2007	23 Jun 2008	Completed

The Management Plan milestone completion rate was 70%. The remaining milestones marked "incomplete" were either accomplished using an alternate technology pathway, for example demonstration of encapsulation using a polymer OLED rather than a phosphorescent OLED, or were not attempted due to changes in the strategies that would support the project team's ultimate objective of delivering a white phosphorescent OLED demonstration unit with the given efficiency, lifetime and color rendering index performance metrics. All changes and or incomplete milestones were discussed with NETL program management and were jointly determined to be of a lower priority at given budget period and interim reviews.

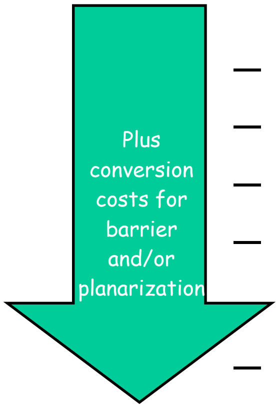
CONCLUSIONS

The project team was very pleased with the final outcome and status of the challenging technical and market objectives researched during this program. Most of the budget period and Management Plan milestones were delivered successfully; of those original milestones that were not delivered as written, alternate achievements were demonstrated, as dictated by good science or marketing intelligence, in an effort to keep the program relevant and on target with commercial goals for OLED lighting over the roughly four year period.

Delivery of thin film encapsulated white phosphorescent OLED lighting technology remains a challenging technical achievement, and it seems that commercial availability of thin, bright, white OLED light that meets market requirements will continue to require research and development effort. However, there will be glass encapsulated white OLED lighting products commercialized in niche markets during the 2008 calendar year. This commercialization effort, the project team believes, will lead to increasing market attention and broader demand for more efficient, wide area, lower cost, general purpose white OLED lighting in the coming years.

Solid State Lighting Economic Evaluation

Mass market acceptance and adoption of OLED lighting will require broad cost reductions to the OLED lighting device from the substrate through to the encapsulation layer. Current substrate economics are unfavorable to the OLED lighting manufacturer. Economic modeling, and internal and external market projections (Fuji Chimera Research Institute, *Flat Panel Display Materials: Trends and Forecasts*, 2006) suggest that even the use of low cost, lower quality blue glass (soda lime) will not deliver the necessary cost reductions currently sought by industry, nor will this pathway achieve the goal outlined in the Multi-Year Program Plan ("MYPP", see citation) for substrate cost less than $3 per square meter (*Multi-Year Program Plan FY'09-FY'14 Solid-State Lighting Research and Development*, Navigant Consulting, March 2008, p.83). Indeed, unconverted blue glass, which is unsuitable for use in OLED lighting as a raw material, is projected to cost between two and three times the cost target issued in the MYPP. Figure 1 outlines variable raw material and conversion costs for OLED lighting substrates.



<u>Un-converted substrates / cover slips</u>:

- PET $ 1 /m^2 for liner grade – $ 3 /m^2 for display grade
- Glass $ 6 /m^2 for soda lime – $ 50 /m^2 for display grade
- 430 SS $ 9 /m^2 for 2 mil – $18 /m^2 for 4 mil
- Al foil $ 0.9 /m^2 for 2 mil – $1.8 /m^2 for 4 mil

<u>Relative costs for substrates / cover slips</u>:

- Coated Aluminum foils $$
- Low cost glass $$$$
- Coated Stainless Steel foils $$$$
- Barrier coated films $$$$$$

Figure 1 – Substrate Economics

Further, similar models project that direct thin film encapsulation solutions will not achieve the given encapsulation cost target, less than $3 per square meter (*Multi-Year Program Plan FY'09-FY'14 Solid-State Lighting Research and Development*, Navigant Consulting, March 2008, p.83). Raw materials for encapsulation may be pushed down to target levels over the next five to ten years, but the novel engineering and capital intensity of encapsulation processes that are foreseeable push the cost well above the given target. It should be noted here, that aggressive goals outlined in the MYPP have merit; however, the goals are not realistic and therefore have an adverse effect within industrial organizations with regard to future investment. If industrial organizations cannot project reasonable returns for research and development investments, they will not authorize continued resource allocation. In this instance, despite the merits of OLED lighting, the substrate and encapsulation cost targets make continued investment in OLED product development a nearly impossible argument in the prioritization of limited research dollars across broad development portfolios.

In addition to lowering component costs, OLED adoption will require improved lifetime; lifetime may be characterized by both emitter lifetime – blue is still the limiting reagent – and device lifetime, which is driven largely by the encapsulation technology. Further, device efficiency gains must push to performance that is two or three times the current levels being reported (~50lm/W).

Finally, OLED adoption will be driven by the process technology. Production yield will directly impact the economics of OLED lighting, but it will also drive the availability, device size and device form factor of OLED lighting so that market needs can be adequately met. Yield is influenced by several factors; in this program the yield was dominated by emitting layer deposition (i.e. new process equipment took time and resource to optimize) and encapsulation. Direct thin film encapsulation is still defect/black spot contaminated and scaling to wider area device sizes will require significant improvement in process technology, if it is possible at all. Future acquisitions by the DOE should consider programs that encourage a core team led by a significant lighting manufacturer who has the commercial clout to negotiate both public and private collaboration with a large scale process equipment manufacturer and significant materials developers, to have meaningful, successful impact on the process technology. The team members must have complementary economic and commercial goals; currently, many of the known organizations are working on at least two of the three pieces despite their expertise, or lack thereof, and it may be detrimental to the progress of OLED lighting.

Solid State Lighting Commercialization

Barriers to market for OLED lighting remain challenging. Cost has been addressed, but it should also be noted that the initial investment, brand equity, and supply chain presence, including, but not limited to channels to market, customer teams and operating income sufficient to sustain early market setbacks are critical to the success of OLED lighting product launches. These same challenges are huge hurdles for competition, and therefore the leading OLED lighting manufacturers have significant competitive advantages over smaller and newer OLED lighting organizations in mass market adoption and usage. However, at the current level of OLED lighting interest and adoption, niche market applications remain relatively open to competition though larger lighting companies maintain some of their advantages.

Within the calendar year of 2008, it appears that at least one major lighting manufacturer will be launching an OLED lighting product. The project team perceives this launch as a significant step in a favorable direction for OLED lighting; it is clear that niche markets with special needs for novel lighting devices, novel lighting form factors, low lighting thermal signatures or other unique OLED benefits will dominate demand, in low volumes, for the near term. During this period, it will be critical to continue to deliver higher performing products to those markets willing to adopt OLED technology in an effort to reassure current buyers and to stimulate new buyers and new market applications. Product development and general market acceptance of wide area OLED lighting devices is still many years away; in fact, the project team feels that large scale production of wide area OLED lighting products for commercial use is perhaps as much as twenty years away. In order to realize OLED lighting's potential cost and energy savings in the United States, the government and industry must improve the trust relationship with the markets through continuously better technology. Continued collaboration and investment will ensure that OLED lighting products eventually compete with traditional lighting sources in office spaces, i.e. fluorescence, and ultimately homes, i.e. incandescent.

PROGRAM ADMINISTRATION

Program Task Description

The project was originally planned for 36 months, but took 42 months to complete. A detailed description for Budget Period 3 tasks is provided for reference, following:

Task 1 – Establish a Benchmark

The Recipient shall complete the detailed requirements definitions initiated in Phase II and shall define the final commercialization product.

Task 2 – Develop OLED Lighting Encapsulation and Barrier System

The Recipient shall scale the materials and processes developed in earlier phases to enable the demonstration of a 2 ft x 2 ft OLED lighting module.

Task 3 - Develop Composite Substrate Structures

Task 3 was only slated for budget period, or phase, II.

Task 4 – Develop Phosphorescent OLEDs

Materials and processes developed in Phases I and II shall be scaled up to accommodate a module demonstration with dimensions of 2 ft x 2 ft. square. Optimum OLED device structures shall be defined based upon past modeling and experimental results. Test methods shall be scaled to permit the characterization of the full size module against the benchmarks identified in Task 1 - Establish a Benchmark with goals of 40 lm/W, 10,000 hours at ambient conditions, and CRI greater than 85.

Program Work Schedule

ID	WBS	Task Name	Start	Finish
1	1	**Establish a Benchmark**	**Wed Dec 1, '04**	**Mon May 28, '07**
2	1.1	Market research and Application Screening	Wed Dec 1, '04	Fri Jul 29, '05
3	1.2	Define lighting requirements	Mon Aug 1, '05	Fri Dec 30, '05
4	1.3	Establish cost and performance criteria	Mon Jan 2, '06	Fri Sep 29, '06
5	1.4	Downselection with increased definition of requ	Mon Oct 2, '06	Fri Mar 2, '07
6	1.5	Product definition	Mon Mar 5, '07	Mon May 28, '07
7	2	**Develop OLED Lighting System Encapsulation a**	**Wed Dec 1, '04**	**Mon Dec 10, '07**
8	2.1	**Standard Glass with CVD only encapsulatio**	**Wed Dec 1, '04**	**Tue Jun 7, '05**
13	2.2	**Interfacial layer addition to CVD process on**	**Wed Jun 8, '05**	**Wed Mar 8, '06**
18	2.3	**Alternative substrate testing**	**Mon May 15, '06**	**Fri Dec 8, '06**
23	2.4	**Production tool design**	**Tue Oct 9, '07**	**Mon Dec 10, '07**
25	3	**Develop Composite Substrate Structures**	**Wed Dec 1, '04**	**Fri Nov 30, '07**
26	3.1	**Glass Composite Substrate**	**Wed Dec 1, '04**	**Fri May 5, '06**
31	3.2	**Plastic Composite Substrate**	**Wed Dec 1, '04**	**Fri Apr 28, '06**
36	3.3	Down selection of composite substrate	Mon May 1, '06	Fri May 12, '06
37	3.4	Composite Substrate Scaleup	Mon Jun 4, '07	Fri Nov 30, '07
38	4	**Develop Phosophorscent OLEDs**	**Wed Dec 1, '04**	**Fri Nov 30, '07**
39	4.1	**Research and development of high efficienc**	**Wed Dec 1, '04**	**Mon Dec 5, '05**
44	4.2	**Development of advanced PhOLED structur**	**Tue Dec 6, '05**	**Mon Dec 4, '06**
49	4.3	Optical modeling of PhOLED on composite gla	Mon Jun 6, '05	Fri Feb 9, '07
50	4.4	**Scaleup of improved PhOLEDs on plastic su**	**Wed Dec 1, '04**	**Mon Oct 8, '07**
55	4.5	Benchmark assessment	Tue Oct 9, '07	Fri Nov 30, '07

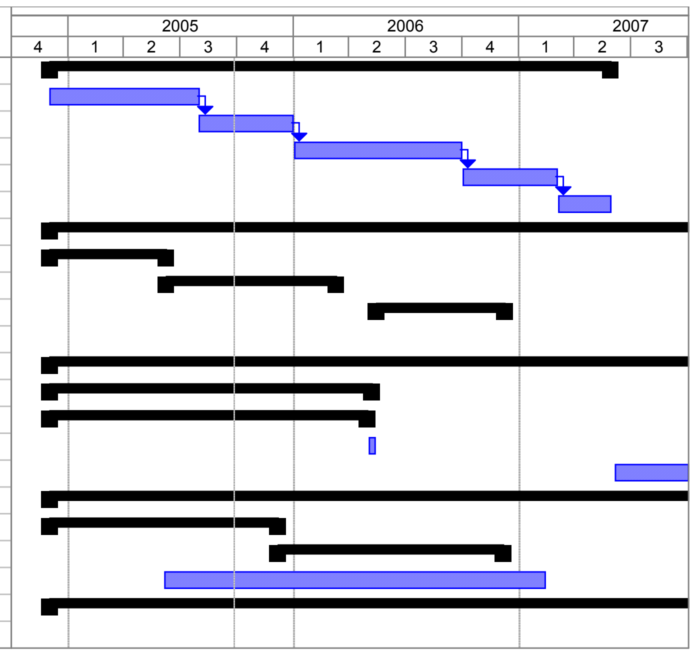


Figure 2 – Original Project Schedule/WBS

PROGRAM RESULTS

Please note that several individuals have contributed to the work and output of the program and this report. While the content of the report has been edited to present the information as if it were written by a single author, the actual body of work was contributed by many and at no time has the editor changed the message they wished to present to the reader, but rather attempted to massage the language for consistency.

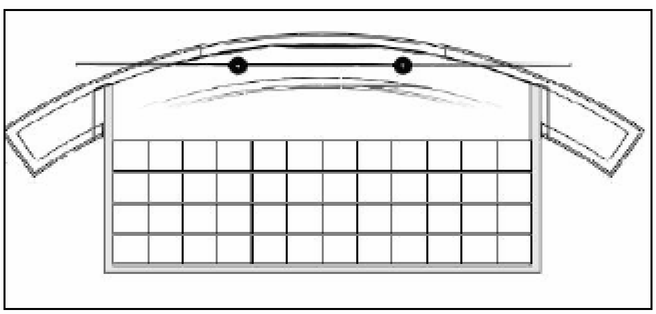
Task 1 – Establish a Benchmark

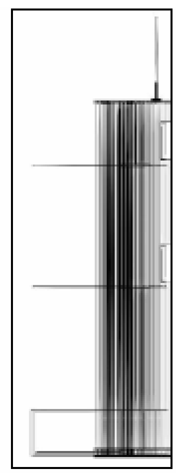
During the course of this program, the project team sought to screen various lighting applications suitable for OLEDs, identify potential lighting requirements for those candidate applications, and conduct an initial analysis of cost and performance benefits required for OLED lighting to be successfully adopted. Further, the project team used a completed analysis of cost and performance requirements to select the most promising candidate applications and developed detailed market requirements to define the final commercialization product concept. The following details are a summary of the cumulative market research with specific attention to the data and activities cultivated during the final budget period.

Product Concept – Prototype Lighting Integrated Display Shelf

Based on the team's market screen and target market segment in retail shopping, the project team ultimately chose to design and build a lighting product prototype for lighting integrated furniture that could feasibly be used in fashion shops. The concept was tailored to the needs of the target lighting customers in the fashion store segment and consists of a shelf lighting application with OLED lamps that demonstrate the added value of this new technology in the retail environment.

To realize the prototype display shelf and deliver a mock-product for the program, a display and shop designer was involved in the project process. In an effort to build an appealing shelf lighting solution with OLED lighting it was determined to use a demonstrator with white finish, which reflects design trends in the fashion segment, and a smooth, curved backplane in order to achieve maximum stability without a side framework, which provides a frameless appearance (figure at left is an architectural sketch of the horizontal cross-section, and the figure at right is an architectural sketch of the vertical cross-section). Notably, the curvature of the backplane additionally provides a feminine quality, which is also an identified fashion display trend.





The prototype has two white shelves that are equipped with rows of white OLEDs; each OLED has a 4 by 3 centimeter lighted area. The shelves are meant to create homogeneous light over the whole shelf area and illuminate apparel or other fashion wares. The concept system is modular and enables the user flexibility to add or reduce the number of OLEDs per shelf according to the shelf dimensions. The delivered unit has shelves that are 53 cm wide, 27 cm deep and 4 mm thick. In an effort to make the maintenance of the unit easy, each shelf can be pulled out of the bent backplane and replaced. Individual OLEDs may be replaced in a given shelf by loosening the aluminum frame, removing the glass plate, and selecting a given OLED for easy removal and replacement. The electrical connection of individual OLEDs is created by pushing the OLED in its placeholder against a spring contact. The shelf back wall is concave and provides space for the transformers and the converter.

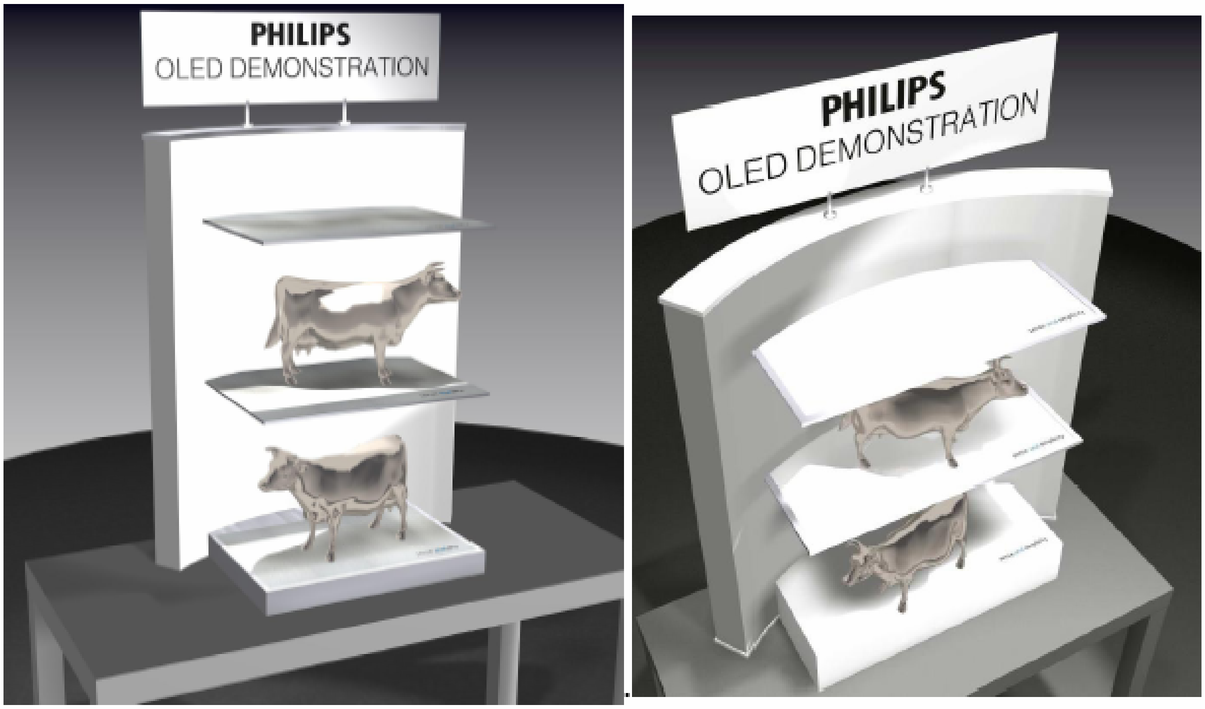


Figure 3 – Prototype Product Concept – High-end Fashion Lighting Integrated Shelf with OLED Lamps.

The benchmark demonstration, using the OLED lighting integrated shelf, delivers features that solve many of the unmet needs identified for, and by, high-end fashion store lighting designers, shop owners, architects and interior designers. At this early stage of technology development, there is not a perfect match of OLEDs to unmet needs, however the apparent value of integrating OLED lighting into shelves, and other furniture, is clear. Design and light effects are achieved and the desired flat, frameless look is realized with a shelf thickness of 4 mm. The curved backplane stabilizes the shelf with added support and shows how OLEDs can realize a thin, sleek appearance – no other lighting solution can provide such a thin integrated system. The design is elegant and pure picking up on the trend toward black and white; the light is homogeneously distributed over the whole shelf area. Use of OLEDs delivers a CRI of over 80, providing the best color rendering available and eliminating the emission of UV light, which is provides a non-bleaching light source to the fashion industry. Further, OLED lighting provides illumination with out shadows, and brightness that can be adjusted by current control. Thus, the identified 1,400 cd/m² brightness is feasible and maintains a reasonable lifetime of about 8,000 hours, which comparable with fluorescent solutions.

Easy system installation, adjustments and replacement prevail for shop owner and employee needs; this prototype has plug and play OLEDs and shelves and replacement is arguably faster than screwing a light bulb in and out. Another advantage of the OLED lighting technology is digital basis making modifications to lighting and integration with multimedia far easier than incumbent light systems. Customization is fulfilled through this prototype since the OLED elements are used to distribute the light over the whole area of the shelf. Conceptually, there is no limit to the addition or reduction of OLEDs in the shelf, and the color and the intensity of the OLEDs may be modified at will. Variable colors were not given in the demonstration delivered, but the solution does exist.

The product concept cost and eco-compatibility is still maturing, though it's clear that OLED technology has both performance and cost of ownership advantages for lighting users. Further, the environmental impact of widespread OLED lighting will benefit users and the general public through reduced energy consumption and reduced carbon emissions. Initial OLED lifetime of 8,000 hours is still brightness dependent however technological developments put lifetime improvements as doubling every three years. One of the key advantages of OLEDs is low heat dissipation as well as the low wattage needed for driving. These features, included in the prototype unit, will strongly influence adoption as restrictions, and cost, on energy consumption in the United States and the trends in Europe significantly limit incumbent lighting designs. Energy efficiency still requires a great deal of development. Indeed, white OLEDs achieve only about 50 lumens per Watt today, but with investment future efficiencies are expected to triple every two years and thus prospects are brilliant for the near future.

	Design	**CRI**	**Light output**	**Plug & play**	**Customizability**
Requirements	Thin, frameless, elegant, Integrated solution, (White, Curved shapes)	> 85	Homogeneous, shadow free, color consistency	Easy installation, usage, replacement Integrated system, Digital lighting	Modular lighting solution Different dimensions, dimmable color variability
OLED Demonstrator	+++	++	+++	++	++

Figure 4 – Product Concept Demonstration Unit Performance against Target Market Requirements

Market Benchmarking Conclusion

In summary, the project team sought to deliver the best possible OLED lighting marketing intelligence available through an initially broad view on the lighting market and then scaling to the minute details of a given target market fashion retail stores. The study was based not only on traditional market intelligence, but field research and direct contact with lighting users, designers and specifiers in an effort to deliver a product concept founded in real unmet needs.

The completion of this study and the program culminates in an identified product application that is feasible at this point in time and using given technology and yet demonstrates both the significant growth potential as well as a development road map for future OLED adoption and development, respectively. The demonstration OLED lighting integrated shelf is well positioned to target the fashion segment as an entry point and should provide valuable market feedback for future development.

As market players increasingly seek differentiation from competition it is anticipated that the OLED lighting integrated shelf concept will become an important marketing tool and drive adoption. The project team believes strongly that as technology matures and costs decrease, the performance, fit, and benefits of OLED lighting will continue to deliver solutions for unmet needs in the retail segment, which will then translate to broader retail adoption and ultimately broad adoption of OLED lighting in commercial markets.

Task 2 – Develop OLED Encapsulation and Barrier System

Two approaches were under development for encapsulation of high efficient white OLED devices:

1. a direct thin film encapsulation, and
2. a laminated cover slip encapsulation

Direct Thin Film Encapsulation

The direct thin film encapsulation is a multilayer barrier stack as presented in the previous budget periods, and includes two graded amorphous silicon carbide ("a-SiC:H") barrier layers separated by a siloxane resin interfacial layer ("IFL"). The a-SiC:H barrier layers are deposited by plasma enhanced chemical vapor deposition proecess ("PECVD") using organosilicon precursors graded to manage the stress at the interface to the device and prevent mechanical damage. The siloxane resin interfacial layer was deposited by spincoating and patterned to dimensions inside the second barrier layers such that the second barrier layer encapsulates the edge of the IFL layer. Two primary development activities occurred during budget period three have included studies on the PECVD processes in an attempt to alleviate aged delamination issues occurring with the OLEDs, and deposition development of the IFL layer to identify a printing method more appropriate for large area deposition.

Phosphorescent OLED encapsulation with the multilayer barrier stacked discussed above has been plagued with seemingly apparent random delamination occurring when aged at 60 ºC and 80% RH; this delamination does not occur on samples aged in the lab ambient conditions. Figure 5 shows delamination occurring on OLEDs across a six inch square substrate. The nature and occurrence of the delamination appears random, even across a single six inch substrate, and did not trend with any of the experimental variables. Aside from delamination occurring under accelerated conditions, the thin film encapsulated OLEDs has generally failed in specific defect locations leading to black spot formation and growth. Again, these defects are quite random, across a single substrate, as shown in Figure 6, and from substrate to substrate. This random generation of defect locations leads to the suspicion of particle contamination, which may be reduced or eliminated in a more disciplined, production environment. It has also been observed over the years that there is a variation in defect formation based on the fabrication source of the OLED, which may suggest the quality of the metal cathode surface is imposing defects. It seems that successful development of a thin film encapsulation and fabrication of a long lasting, high efficient OLED device depends on integration of device fabrication and encapsulation processing in the same lab, and including a high level of process control and cleanliness. Developing an integrated interface between the cathode and the barrier layer will also aid in the successful design and fabrication of thin film encapsulated OLED lights.

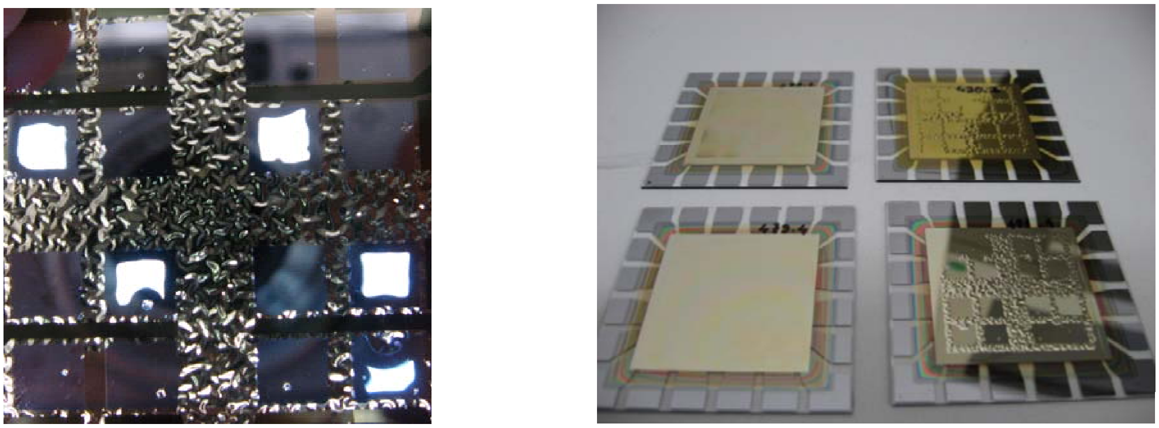


Figure 5 – Delamination of thin film encapsulated OLED devices across a six inch square substrate.

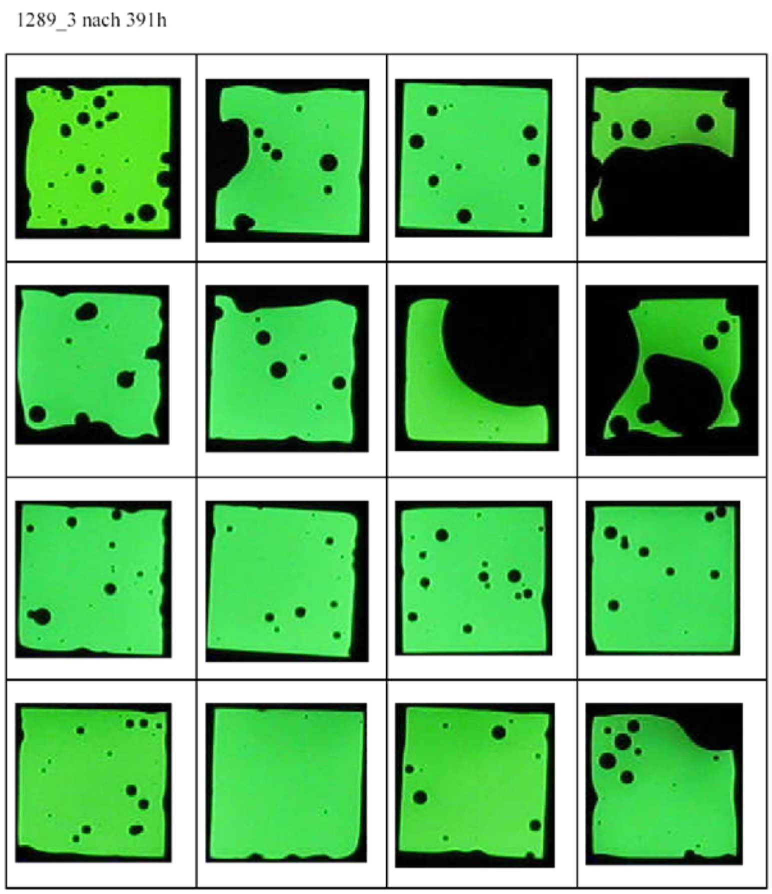


Figure 6 – Random black spot formation and growth occurring in defects on thin film encapsulated OLEDs.

The concept of a direct thin film encapsulation seems appealing since the addition of the process could be performed, potentially, through the addition of extra chamber at the end of an in-line fabrication tool. This addition could lead to a truly low cost encapsulation solution as compared to the incumbent approach, which includes use of a milled glass cavity, lined with desiccant, and perimeter sealed with an adhesive. Several aspects of the thin film encapsulation being developed prevent this idealized concept from being realized; the deposition of barrier layers is relatively slow and there is a huge stretch to meet the target tact times for an in-line OLED manufacturing process.

In addition, the chamber is typically cleaned between each barrier deposition, which further increases the tack time through the barrier processing chamber. One solution to this slow tack time for barrier depositions could be to split off several encapsulation chambers for each OLED line. Since no institution has demonstrated a single barrier encapsulation to meet OLED requirements, multilayer barrier stacks are being developed, which adds to the complexity of the barrier encapsulation equipment. Direct thin film encapsulation quickly becomes much more expensive when it requires multiple chambers for each encapsulation, and multiple encapsulation lines for each OLED line. One other concern for using a direct thin film encapsulation is potential yield loss. Barrier layers have shown to be highly sensitive to particles and defect formation, which could plague a reactor at anytime during manufacturing; it would be quite expensive to take a yield hit at the end of an OLED manufacturing process due to a barrier chamber loosing particle control. Timeliness in identifying this lack of control and loss of barrier properties would be imperative for in-line processing.

A final comment regarding the complexity of commercializing a direct thin film encapsulation, especially for large area rigid manufacturing lines (generation four glass size, and up), is the limited number of equipment manufacturers that provide equipment into this market, and the willingness (or lack of) for them to adopt a thin film approach. The “flexible” roll-to-roll manufacturing approach is more disruptive and more willing equipment manufacturing partners may be identified; yet this OLED manufacturing approach is further out than current high efficiency white OLED development currently being pursued.

Laminated Cover Slip Encapsulation

A second encapsulation approach under development is a laminated cover slip. This approach utilizes a barrier coated film cover slip that is laminated directly to the OLED device using an adhesive solution. Development activities during BP3 included evaluation of adhesive currently available on the market or under the development by leading manufactures, tailoring an adhesive solution in house to meet specific needs, development of a lamination process, and evaluation on OLED devices.

An assortment of adhesives designed for OLED encapsulation were collected and measured for water vapor transport rates (“WVTR”) using a calcium degradation test. This method of assessing WVTR was described in more detail in the BP2 report, which consisted of a moisture sensitive calcium thin film that was encapsulated between two layers of glass held together with the adhesive material under evaluation. The baseline adhesive was a UV cured adhesive that has been the standard for this type of testing. WVTR of the baseline compared to an assortment of the adhesive collected is shown in Table 2 below. Most of the adhesive materials have fairly comparable WVTR values, with the exception of the hot melt adhesive that has WVTR an order of magnitude higher.

Table 2 – Comparison of water vapor transport rates of adhesive resins used for OLED encapsulation

Adhesive	WVTR @ 38 °/ 80% RH g/(m² day)
Baseline	**4.9×10^{-4}**
Hot Melt	**4.2×10^{-3}**
Thermal Cure	**1.7×10^{-4}**
UV cure 1	**1.1×10^{-4}**
UV cure 2	**4.7×10^{-4}**
UV cure 3	**1.4×10^{-4}**

It was determined that an adhesive solution needed to be tailored for the specific application of laminating the barrier coated film ("BCF") to the OLED device due, in part, to the unique properties of the a-SiC:H barrier on the BCF. Requirements for the adhesive solution included low WVTR, good adhesive force, a high degree of compliancy, and compatibility with the OLED as a blanket coating over the device. Achieving these requirements involved combining several components together into a solution which consisted of an adhesive resin, coupling agents, surface modifiers, and cure initiators.

To begin this work a broad range of adhesive resins were investigated including:
- Epoxy – the baseline
- Aromatic Urethane
- Aliphatic Urethane
- Monomeric resin
- Butadiene Acrylate

In order to achieve a quality blanket coating and attain good adhesion the surface tension of the solution must be less than the surface energy of the substrate. Dow Corning produced a surface tension modifier for liquids, Z990, an acrylate functionalized silicone, which can be added to liquids to reduce surface tension. Another approach was to increase the surface energy of the substrate, accomplished through plasma treatments or the addition of a priming layer. Dow Corning produces a series of silane priming agents that hydrolyze on the surface of the substrate to increase surface energy and improve wetting and adhesion of subsequent coatings. Figure 6 is a list of these various priming agents available from Dow Corning, and demonstrates how they will change the surface chemistry. The surface tensions and surface energy values measured during various experimental trials included the baseline resin solution and BCF substrate, listed in Table 3. There is a variety of solutions that meet the requirement for providing lower surface tension of the liquid as compared to the surface energy of the substrate. It can be seen that the baseline epoxy resin solution has surface tension much higher than the untreated BCF substrate, 50 dynes/cm compared to 37 dynes/cm – this suggests the starting baseline values failed to achieve good coatings and any adhesion.

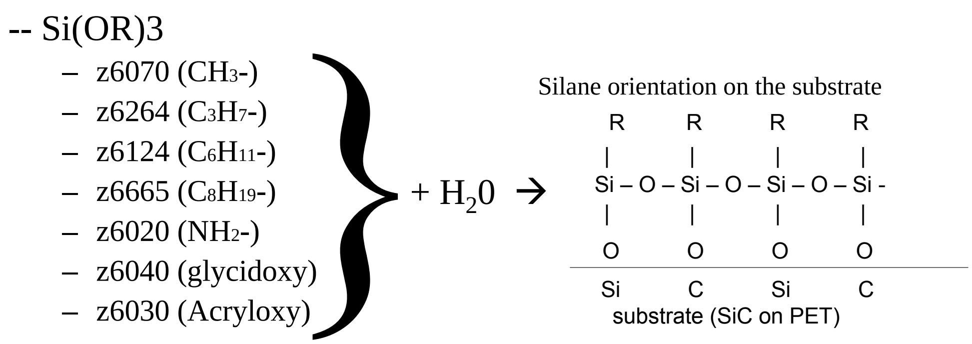
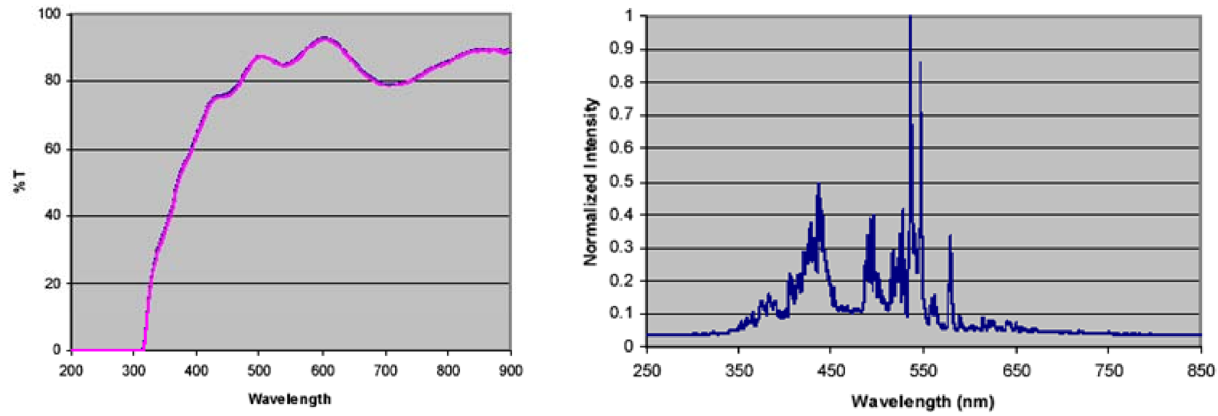


Figure 7 – various silane surface primers offered by Dow Corning and their impact to the surface chemistry of the a-SiC:H barrier coating.

Table 3 – Surface tension and surface energy of various experimental solutions

Liquid surface tension	(Dynes/cm)
– Epoxy -- Baseline	50
– Aromatic Urethane	32
– Aliphatic Urethane	37
– Monomeric resin	41
– Abrasion Resistant Coating	42
Substrate surface energy	
– BCF	39
– Soda lime glass	47
– 6070/BCF	37
– 6020/BCF	48

After tailoring surface wetting and adhesion, the team sought to establish the appropriate cure initiators. Since OLEDs only allow a low thermal budget for encapsulation, targeted to be less than 80 ºC, UV cure initiators are evaluated. This was complicated by PET, which blocks much of the UV, and further so by the addition of the a-SiC:H barrier layer. Figure 8a is a transmittance spectrum of the BCF, which shows complete cut off of the UV below 315 nm. A UV-V lamp was chosen for the UV source; it had a higher wavelength than the other UV sources, as shown in the optical emission spectra of Figure 8b. In addition, a UV cure initiator was identified, Irgacure 2022, that was initiated at a wavelength of 435 nm. This was a good match when compared with the transmittance spectra of the BCF and the emission spectra of the UV-V source.



(a) ***(b)***

Figure 8 – (a) Transmittance spectra for the BCF – a-SiC:H barrier film on PET, and (b) the optical emission spectra for a UV-V lamp.

Experimental trials were conducted with various adhesive resins, surface tension / energy modifiers, and the cure initiator to identify a resin with good functionality for the UV catalyzed cross linking and providing adequate adhesion. BCF laminates were constructed, and a peel adhesion test was performed to determine the adhesive strength. In addition, the calcium degradation test was performed to identify the water permeability of the adhesive solutions. Figure 9 is a plot of the results showing adhesive force and WVTR of the adhesive solutions. Much like the evaluation of the commercially available adhesive, most of these adhesive solution also showed similar WVTR values in the 1 to 5 X 10^{-4} g/(m^2 day) range. A couple of the adhesive solutions, solution A and solution B, stand out as having superior adhesive strength with the BCF laminate.

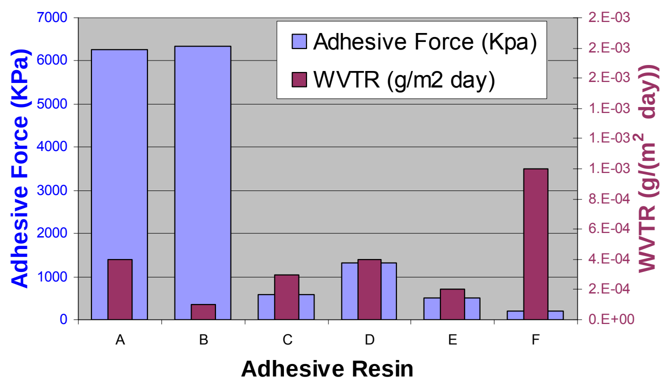


Figure 9 – Adhesive force and WVTR of the various resin solutions tailored for the BCF laminate.

One other criterion for the adhesive solution was potential to be compliant. Compliancy should improve the mechanical characteristics of joining this thin film laminate structures together, as well as allow a degree of flexibility. The cost modeling at the beginning of this report highlights flexible substrate and flexible encapsulation technologies, combined with roll-to-roll manufacturing, as ultimately being the most likely to reach low cost targets required for OLED lighting to be adopted into the general lighting market. To assess the compliancy, nanoindentation was performed on selected adhesive solutions, and the results are shown in Figure 10. The resin solution A (appears as sample 4 in the plots), shows a much lower load versus depth of indentation, which results in a lower modulus of the film. A lower modulus is defined as a higher amount of strain versus applied force, and translates into a higher degree of compliancy.

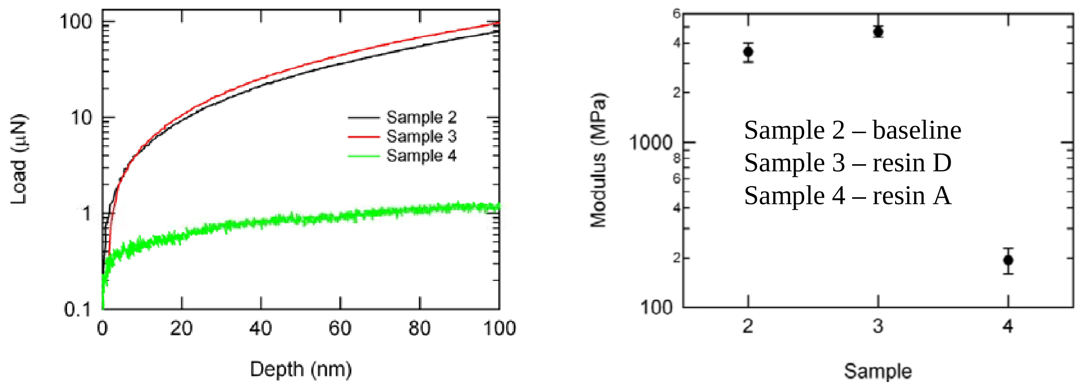
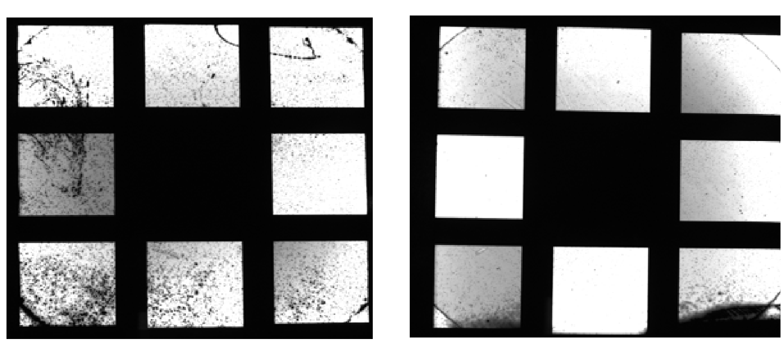


Figure 10 – Nanoindentation results of selected adhesive resins as cured on a glass substrate.

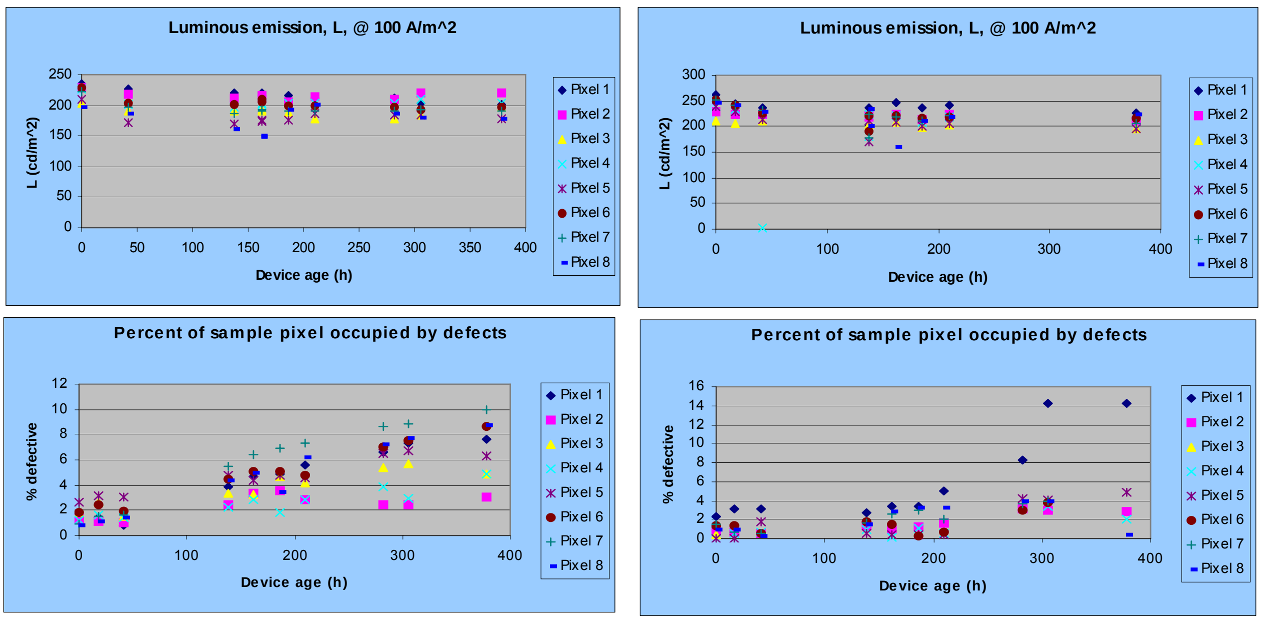
Of the resin solutions evaluated, adhesive solution A showed the best adhesive force, WVTR, and compliancy. OLED encapsulation studies were therefore conducted using this preferred adhesive solution. The OLED device structure and testing capabilities was developed in prior years at Dow Corning, and described in further details in the BP2 report. The device is fabricated using Summation 1301 green LEP, Baytron P HTL, ITO anode, and a Ca/Al cathode. The PLEDs were encapsulated using the lamination process, a blanket adhesive coating using adhesive solution A, and either a barrier coated film (BCF) or thin glass cover slip. Images of aged OLEDs for these devices is shown in Figure 11, which indicates some black spot growth occurring with both types of cover slips, but more so with the BCF. It was determined later that much of the initial black spot formation was due to moisture remaining in the adhesive solution, and steps have been taken since to dry these adhesives prior use. It is not unexpected that the BCF cover slip would provide less protection than the glass, since the BCF currently has a WVTR on the order of 10^{-4} g/(m^2 day), which does not meet the current OLED requirements for barrier protection. None of the black spot formation and growth was determined caused by side ingression of the water through the adhesive during these tests.



(a) ***(b)***

Figure 11 – Images of PLED aged 378 hrs at 38 ºC/ 80% RH encapsulated with a laminated (a) BCF cover slip, and (b) thin glass cover slip.

Figure 12 shows the other measured results acquired over the aged period of time, which is the change in luminous intensity at constant current and an increase in defective area, as calculated by the imaging and algorithm approach discussed in BP2 report. The increase in defective area for the BCF cover slip is measurable by this approach, but is not significant enough for the glass cover slip to be measured except with pixel 1 (bottom right corner in Figure 9b). There is no obvious change in luminous intensity over the period, which does not correlate with the increase in black spot growth as with the BCF cover slip sample. This has been observed in other samples as well, and it's determined that even though the intentions are to retain constant current density, as black spots form and ceases to conduct current, the current density in the active regions is effectively increasing, and therefore increasing the luminous output in those regions respectively. This increase in active regions is canceled by the black spot growth for the gross luminous intensity measurement, therefore providing a constant average luminous intensity measurement over time.



(a) ***(b)***

Figure 12 – change in luminous intensity and defective black spot area of PLEDs when aged at 38 ºC/ 80% RH and encapsulated with a laminated (a) BCF cover slip, and (b) thin glass cover slip.

There are concerns that mechanical mismatches and thermal heating during operation of an OLED will lead to a destructive failure. To test for this, a PLED, encapsulated with a thin glass cover slip and a blanket layer of adhesive solution A, was characterized for continuous operation at 100 cd/m^2 for over 1300 hours in a lab environment. Imaging results and L-V plots from t=0 hrs to t=1,320 hours is shown in Figure 13, and does not show any degradation in performance, except for some black spot growth which can be expected from the non-continuous operation as described above.

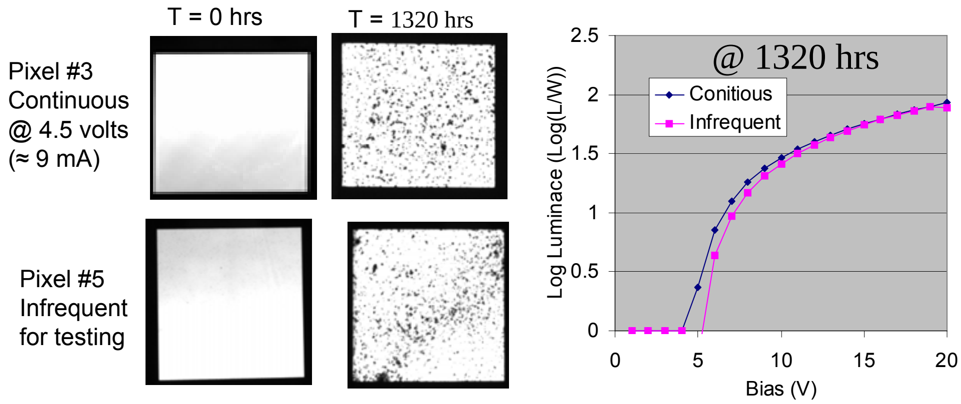


Figure 13 – imaging and L-V results from aging a PLED, encapsulated by laminating a thin glass cover slip with adhesive A, under continuous operation at 100 cd/m^2 for 1,320 hours.

A summary of key results observed for laminated cover slip encapsulation development during BP3 included:

- "The Best" of current low WVTR adhesives compare at around 10^{-4} g/(m^2 day)
- A compliant adhesive solution was identified that could cure through the a-SiC:H barrier coated films, with good adhesion and permeability around 10^{-4} g/(m^2 day).
- No adverse degradation of a PLED device when under continuous illumination at 100cd/m^2 for greater than 1,300 hours.
- Some black spot growth observed; more so with the BCF cover slip compared to a glass cover slip.

The desired approach to reach the long term vision of 100% roll-to-roll manufacturing of low cost OLED lighting requires better performance from the BCF cover slip. Development efforts continue to improve the barrier performance of the BCF as discussed in further sections of this report, but a reduction in water permeability acceptable for OLEDs still requires a significant breakthrough. Another method to possibly realize this approach may be to include a single thin film barrier directly on the device in addition to the laminated BCF cover slip. Applying the single thin film barrier may be more easily and affordably integrated into a production line than the complicated multilayer thin film encapsulation discussed in the previous selection, and provide enough protection to fully encapsulate the device when combined with the laminated cover slip.

Task 3 – Develop Composite Substrate Structures

Two approaches are under development for composite substrate structures to be used for high efficient white OLED devices:

1. a low cost "blue" glass, and
2. a barrier coated plastic film

Low Cost Glass

There were no significant development activities occurring with the low cost glass during BP3. Reefer to BP1 and BP2 reports for development progress of this technology.

Barrier Coated Films (BCF)

Barrier technology, similar to the technology developed for the direct thin film encapsulation, was developed in roll-to-roll equipment to produce barrier coated plastics. The approach was, and is, a unique and proprietary PECVD processes to produce the a-SiC:H layers with high barrier performance to moisture and oxygen on flexible plastic films. Polyethylene Teraphthalate (PET) has been the plastic of choice due to the availability of high quality films at reasonably low costs. Development activities occurring during BP3 include mitigating defects to improve barrier performance and process optimization to solve a recently observed adhesion issue with the a-SiC:H barrier layers on the PET.

It has been highlighted in previous budget period reports that failure of the BCF to block moisture and oxygen occurs through specific defect locations. Two approaches were identified to reduce the level of defects during the previous budget period: 1) web cleaning to remove particles, and 2) web planarization to planarize scratches and spikes in the plastic.

A web cleaning tool developed by WSI/Shinko ("Shinko") using ultrasonic air knives was identified as the preferred web cleaning tool, which is a non contact cleaning approach that will remove particles down to 0.5 μm in size. Details on the mechanics of operation for the ultrasonic air knives are documented in the BP2 report. During BP3, this technology was integrated into a web winding system, installed at DCC, measurement methods developed, and the cleaning approach evaluated for effectiveness. An image of the final web winding tool with the web cleaning capabilities, as installed at DCC, is shown in Figure 14. This web winding system incorporates two of the air knives so that both sides of the web can be cleaned in one pass. It will handle web width from 6" to 12" wide, and run flexible substrate materials varying from plastics to silicone resin films to metal foils.

Figure 14 – web cleaning line installed at DCC utilizing dual ultrasonic air knives

A method to count particles on the surface of flexible web was developed utilizing an ultrasonic bath and a liquid particle counter; a diagram of this approach is shown in Figure 15. Methylisobutylketone ("MIBK") was used as the carrier media in the ultrasonic bath, in which the flexible web samples are placed in and agitated for a given time to remove particles from the film. Care was taken not to place the cut ends of the sample into the bath, since the cutting process will create particles itself. The liquid particle counter was then used to measure the number of particles for a given volume of the MIBK / particle solution. A series of tests showed that that PET material in stock provided a measured particle count of 25.5 particles / cm^2. After cleaning the web using the dual air knife web cleaner, particles counts were reduced to a range from 2.8 to 7.3 particles / cm^2, validating the removal of particles. This finding was in agreement with the testing performed at Shinko when demonstrating the equipment.

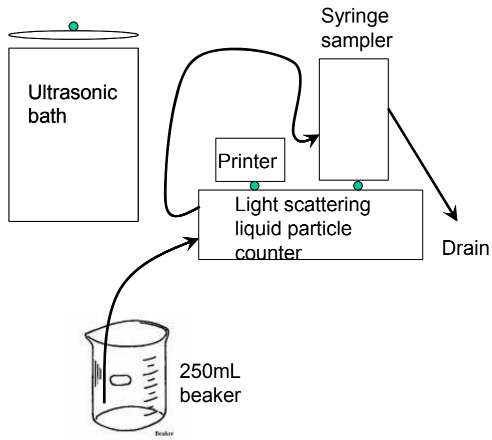
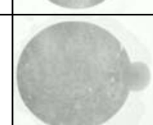
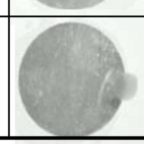


Figure 15 – schematic of particle counting method for flexible web samples.

The impact on web cleaning was then evaluated by cleaning a section of web, leaving a portion uncleaned, and then cleaning more of the web. Barrier was evaluated using the Mocon permatran units as well as calcium degradation testing. Results from these tests are shown in Table 4, which does not indicate any improvement gained by the web cleaning. The images from the calcium degradation continue to indicate defect locations in the barrier, which must be dominated by scratches and spikes in the plastic. It is also noted that the web is fairly high grade, and reasonably clean to begin with, so repeat studies with lower cost, dirtier plastic web are planned to try and realize impact of web cleaning.

Table 4 – Surface tension and surface energy of various experimental solutions

	Mocon g/(m^2 day)	Ca Degradation g/(m^2 day)	Ca - 77 hr
Beginning section of web pre-cleaned	0.034	0.017	
Middle section of web not pre-cleaned	0.032	0.018	
Ending section of web pre-cleaned	0.042	0.016	

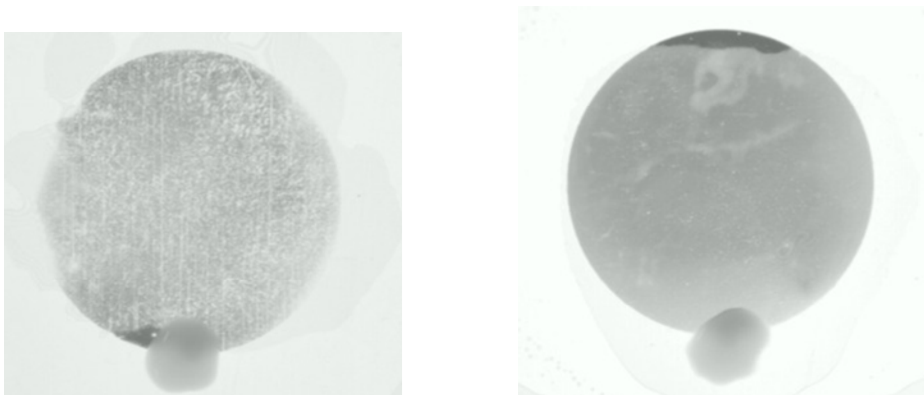
Another piece of equipment added to the suite of web winding and roll to roll tools at DCC is a web splicer, shown in Figure 16. The roll-to-roll PECVD barrier deposition tool requires a large amount of web material to effectively run. To cost effectively study treatments or coatings on web, such as planarizing coatings, or to study new advanced substrate materials, smaller lengths are required. This web splicer tool offers the capability to splice these smaller R&D web samples into the larger roll.

Figure 16 – Web slicer tool.

Planarizing the web prior barrier deposition was demonstrated on a lab scale with batch operations during BP2 and indicated an improved performance as documented in the BP2 final report. During BP3, planarized PET was acquired from a commercial manufacturer and evaluated for any improvements in barrier performance in a larger scale roll to roll process; the web splicing tool mentioned above was integral in performing these experiments. The RMS surface roughness of the PET was 4.37 nm before planarizing and 1.06 nm after planarizing. These films were each exposed to four different PECVD barrier deposition processes, and the results tabulated in Table 5 below, which show significant improvement in barrier performance for the planarized PET. Figure 17 is the calcium results for samples that show defects in the non-planarized samples occurring from scratches in the PET; these defects do not occur in the planarized PET. This study supported the need to have a smooth substrate in order to attain high barrier performance, and validates a planarization approach offered by a commercial PET supplier.

Table 5 – WVTR measured at 38 ºC and 100% RH for the PET planarization study

Barrier Deposition Process	Non planarized WVTR (g/m² day)	Planarized WVTR (g/m² day)
Process 1	0.02	< 0.005
Process 2	0.03	< 0.005
Process 3	0.02	< 0.005
Process 4	0.03	0.006



(a) *(b)*

Figure 17 – Ca degradation of barrier films on (a) non planarized PET, and (b) planarized PET.

During BP3, the BCF material was sampled to potential customers across various industries; feedback from this exercise highlighted a potential issue with the durability of the barrier film. When aged in damp heat, the barrier layers would crack and delaminate from the PET. Figure 18 has images of a BCF sample, aged in an 80 ºC / 85 % RH environment, which shows the rather quick deterioration of the barrier layers within three days.

1 day 2 days 3 days

Figure 18 – A baseline BCF sample from early BP3 time period aged in at 80 ºC / 85% RH.

An extensive study was initiated to understand and solve this delamination issue with the barrier layers on the PET film. A tape peel test was established, based on ASTM D3359, which used a cross hatch scribed through the barrier layer creating a 3 mm spaced grid. After applying and peeling a specified tape over the grid, the number of squares removed from the grid were counted. This provided a quantifiable measure of the adhesion – either as a classification in the ASTM standard, or a percent failure. Figure 19 shows an example from the ASTM standard, and as applied to a BCF sample aged over 100 hours.

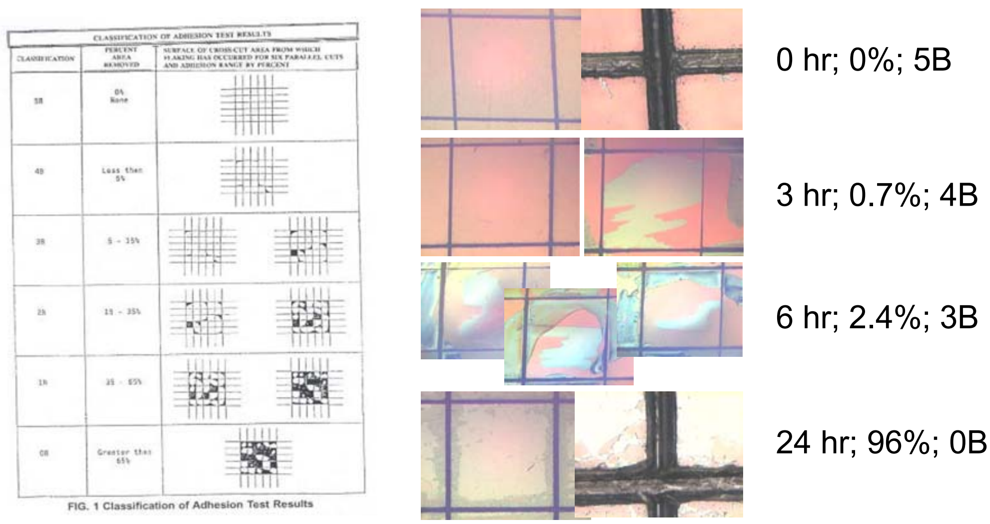


Figure 19 – A baseline BCF sample from early BP3 time period aged in at 80 ºC / 85% RH.

The desired result from the tape and peel adhesion test was to provide 0% failure after 1,000 hours of aging in an 80 ºC and 85% RH environment. A broad test matrix including various surface pretreatments of the PET and PECVD barrier deposition processes was conducted over several months. The variables included film thickness, plasma power settings, levels and types of inert and oxidizing gases, while trimethylsilane as the silicon carbide precursor remained constant. The failure rate varies quite dramatically for the different trials, from complete (100%) failure with in the first couple days, to minimal failure out to 42 days (1,000 hours), shown in Figure 20. Ultimately, conditions were identified that provide 0% failure when aged over 1,000 hours at 80 ºC and 85% RH conditions; these trials have since been repeated, and the new process conditions adopted as the baseline BCF process.

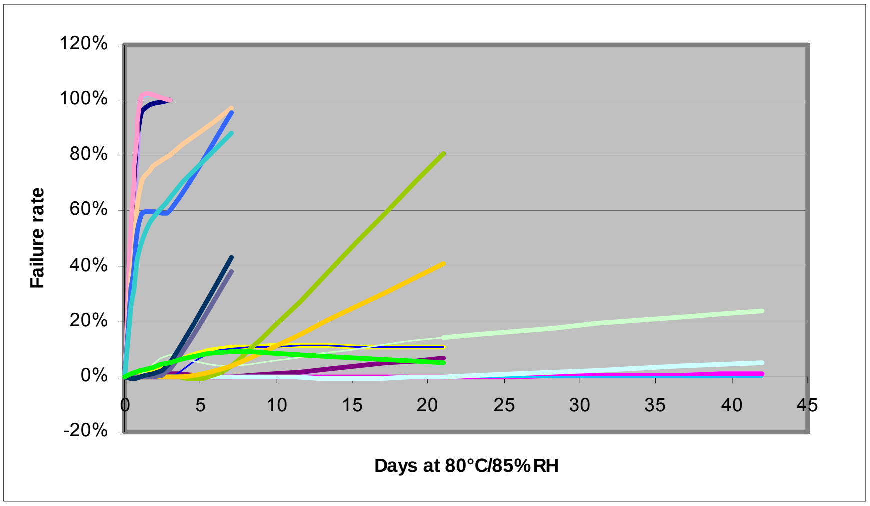


Figure 20 – Results of an aged adhesion study of barrier coated films with varying surface pretreatments and PECVD barrier processes.

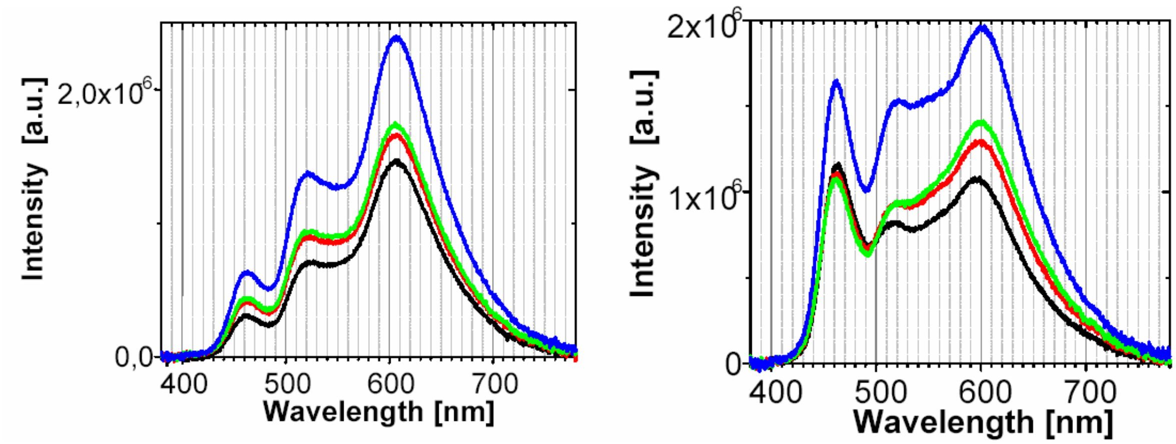
In a separate effort, a few samples of high barrier film produced externally to Dow Corning were acquired for a comparison. These materials were exposed to the same series of tests, including transmittance, water permeability, adhesion, and stability. Table 6 summarizes the results from this characterization; none of the samples measured for low water permeability as per their claims except for the SiOC:H produced by Dow Corning. Adhesion and stability were also issues with a couple of the samples. There are other barrier coated film technologies that were not available to Dow Corning for characterization, but this early comparison sheds some insight that the technology developed at Dow Corning has some technical merit.

Table 6 – Comparison of high barrier films available for sampling to Dow Corning.

	Dow Corning	Company A	Company B	Company C
Material	SiOC:H on PEN	SiON:H on PEN	SiON:H on PEN	AlO–SiC on PC
Transmittance @ 470nm (%)	79	80	83	89
Roughness (nm)	6.8	2.5	3.55	0.6
Permeance ($g/m^2/d$)	<5E-4	0.53–1.158	0.032-0.047	0.044-0.054
Adhesion	Pass	Pass	Pass	Delam./crack
Thermal / Hydro Stability	All pass	Pass	Delam./crack	Pass
Overall Ranking	1st	3rd	4th	2nd

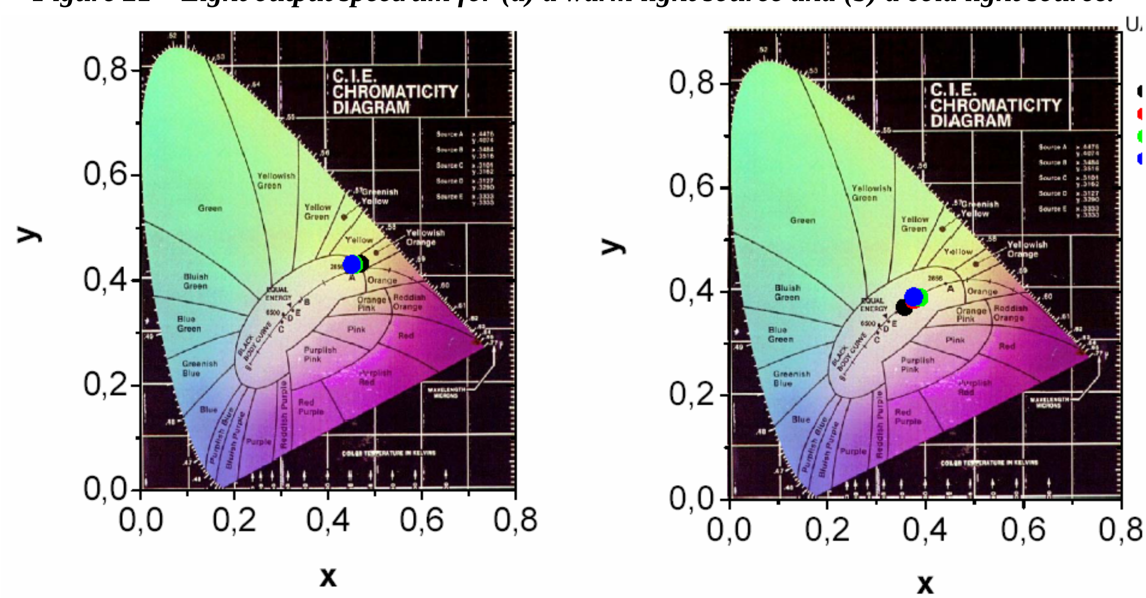
Task 4 – Develop Phosphorescent OLEDs

Philips lighting has developed a multilayer hybrid OLED technology to produce the high efficient white light. The multilayer approach utilizes a fluorescent blue light emitting material combined with phosphorescent red and green light emitting materials. Efficiency has also been improved by enhancing the charge injection via a p-i-n structure in which a n-doped insulating layer is incorporated between the cathode and electron transport material and a p-doped insulating layer between the anode and hole transport layer. Both a warm and cold light source has been developed with this structure; the light output spectrum and chromaticity plots for these sources are shown in Figures 21 and 22, respectively, while the performance data is listed in Table 7.



(a) *(b)*

Figure 21 – Light output spectrum for (a) a warm light source and (b) a cold light source.



(a) *(b)*

Figure 22 – Chromaticity plots for (a) a warm light source and (b) a cold light source.

Table 7 – Performance data for warm and cold white light sources.

	Warm White	Cold White
Efficacy w/ light extraction (lm/W)	45	46-50
Efficacy w/o light extraction (lm/W)	30	31
Color Temp (K)	2850	20
Color Rendering Index	85	86
Lifetime (h)	2000	5000

PROGRAM MANAGEMENT

The *Thin Film Packaging Solutions for High Efficiency OLED Lighting Products* program was initiated on 01 December 2004 and was slated for three 12-month budget periods ending on 30 November 2007. Execution of the program led to two time extensions in an effort to ensure that the specific budget period objectives were fully researched and reported, or delivered, on fulfilling the original program goals; budget period two was extended seven months from 30 November 2006 to 30 June 2007, and budget period three was extended two weeks, starting on 15 May 2007 and ending 30 June 2008. The time extensions, moving the program from a 36-month effort to a 43-month effort, afforded the project team sufficient room to ultimately deliver on the program goals, as reported herein, but did generate some budget overruns, which the project team organizations included as their sole cost taking on a greater ratio of cost share than outlined in the original agreement.

Financial Status

Overall, the final program investment exceeded the original budget plan, $4,762,973, by approximately thirteen percent and totaled $5,394,997. The budget was adversely impacted by the complexity of the program goals, two time extensions, unfavorable exchange rates for the U.S. dollar (particularly during BP3), and the increased need for travel, freight and duty related to collaborations for work performance. The following tables illustrate the program investments per budget period and overall, including cost share by organization.

The original program investment details, as defined in the Financial Assistance Agreement DE-FC26-05NT42344, are listed in Table F-1. The table outlines each budget period, cost share responsibility (in USDs) and percent of Prime Contractor cost share.

Table F-1 – Original Program Investment Details

	Budget Period 1		Budget Period 2		Budget Period 3		Total	
	Govt. Funding	Cost Share	Govt. Funding	Cost Share	Govt. Funding	Cost Share	Govt. Funding	Cost Share
Prime Recipient	$465,280	$511,260	$870,762	$772,400	$454,338	$440,793	$1,790,380	$1,724,453
Team Member	$174,889	$174,889	$244,302	$244,302	$204,879	$204,879	$624,070	$624,070

Total:	$640,169	$686,149	$1,115,064	$1,016,702	$659,217	$645,672	$2,414,450	$2,348,523
Cost Sharing (%):		51.7%		47.7%		49.5%		49.3%

Table F-2 details the projected final budget details, including final estimates for Budget Period 3, which is nearly final and therefore a reasonably accurate estimation. Please note that although the budget periods and cost sharing, as a percentage, are adjusted from time period to time period, the overall investment and cost sharing rate is unchanged.

Table F-2. – Final Program Investment Details

BP2 Update	Budget Period 1		Budget Period 2		Budget Period 3		Total	
	Govt. Funding	Cost Share	Govt. Funding	Cost Share	Govt. Funding	Cost Share	Govt. Funding	Cost Share
Prime Recipient	$329,267	$292,606	$733,282	$857,435	$689,955	$978,138	$1,752,504	$2,218,179
Team Member	$0	$0	$388,059	$388,059	$267,222	$478,076	$655,281	$866,135
Total:	$329,267	$292,606	$1,121,341	$1,245,494	$957,177	$1,456,214	$2,407,785	$2,994,314
Cost Sharing (%):		47.05%		52.62%		60.34%		55.43%
Actual Investment	$621,873		$2,366,835		$2,413,391		$5,402,099	
Planned Investment	$1,326,318		$2,131,766		$1,304,889		$4,762,973	
Variance	$704,445		($235,069)		($1,108,502)		($639,126)	