PROJECT DESCRIPTION**1. Project Title:**

Development of Advanced Manufacturing Methods for Warm White LEDs for General Lighting (DE-EE0003232)

2. Performer:

GE Lighting Solutions

3. Principal Investigator:

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4. Other Team Members:

Boris Kolodin, Cherian Jacob, Ashfaquul Chowdhury, Glenn Kuenzler, Karen Sater, Danny Aesram, Steven Glaettli, Brian Gallagher, Paul Langer (Contract Engineer) – all at GE Lighting Solutions.

Anant Setlur (GE - Research), Bill Beers (GE - Lighting) – advisory role

5. Technology Focus:

The focus of this program is Manufacturing

6. Relevant Subtask Priority Area:

M.L3 Test and Inspection Equipment

M.L6 LED Packaging

M.L7 Phosphor manufacturing and Application

7. Schedule/Budget Overview:

Budget overview as per the program management plan.

	Start Date	End Date	Government Share	Performer Share	Total
Budget Period 1	(04/01/10)	(03/31/11)	\$330,721.04	\$330,721.04	\$661,442.08
Budget Period 2	(04/01/11)	(03/31/12)	\$218,102.55	\$218,102.55	\$436,205.1
Total	(04/01/10)	(03/31/12)	\$548,823.59	\$548,823.59	\$1,097,647.18

Discussion of variances

The summary of DOE funds committed and invoiced to date (6/29/2012) is attached below.

Date 6/29/2012		
DOE Funds Total	DOE funds Committed	DOE funds Invoiced
\$548,824.00	\$499,321.19	\$499,321.19

Table-1 Summary of funding profile updated on 6/29/2012.

A detailed breakdown of the expenditures to date is included below.

		GE Manpower + Contract Mech Engr. - Plan	Invoiced	Supplies / Purchased services - Plan	Invoiced	Consult Task-5	Invoiced
	Apr	\$2,198.67	\$2,198.67				
	May	\$3,930.28	\$3,930.28				
	Jun	\$3,229.83	\$3,229.83				
	Jul	\$3,463.30	\$3,463.30				
	Aug	\$3,677.32	\$3,677.32				
	Sept	\$8,123.79	\$8,123.79	\$9,980.80	\$9,980.80		
	Oct	\$8,122.00	\$8,357.00	\$6,000.00	\$6,221.00		
	Nov	\$8,122.00	\$7,812.42	\$5,000.00	\$6,300.00		
2010	Dec	\$8,122.00	\$5,968.49	\$4,121.63	\$3,691.50		
	Jan	\$8,122.00	\$8,201.61	\$4,000.00	\$890.00		
	Feb	\$8,122.00	\$7,540.08	\$4,000.00	\$3,639.00		
	Mar	\$8,122.00	\$7,945.87	\$4,000.00	\$5,646.67		
	Apr	\$8,122.00	\$7,673.53	\$4,000.00	\$9,795.80		
	May	\$8,122.00	\$8,062.64	\$4,000.00	\$5,124.60		
	June	\$8,122.00	\$5,774.65	\$4,000.00	\$3,547.50		
	July	\$8,122.00	\$7,420.76	\$4,000.00	\$1,797.81		
	Aug	\$8,122.00	\$7,517.86	\$4,000.00	\$1,450.00		
	Sept	\$8,122.00	\$7,725.50	\$4,000.00	\$5,801.71		
	Oct	\$7,323.07	\$6,908.29	\$4,416.54	\$1,632.61		
	Nov	\$7,122.00	\$7,102.91	\$3,000.00	\$1,080.00	\$4,000.00	\$5,160.00
2011	Dec	\$7,122.00	\$6,402.45	\$2,461.83	\$2,816.15	\$4,000.00	\$0.00
	Jan	\$7,122.00	\$6,052.24	\$1,145.57	\$1,070.00	\$4,000.00	\$0.00
	Feb	\$7,122.00	\$5,740.94	\$1,000.00	\$0.00	\$4,000.00	\$0.00
2012	Mar	\$3,000.00	\$1,790.03	\$1,000.00	\$661.36	\$4,835.43	\$9,600.00
	Apr		\$350.22		\$6,737.30		
	May						
	Jun		\$836.63		\$788.80		
2012 - No cost extn							
	Total	\$160,898.26	\$149,807.31	\$74,126.37	\$78,672.61	\$20,835.43	\$14,760.00

Bigger Eqpt & Expense items	Plan	Actual PO amount	Date PO planned	Date PO issued	Amount Invoiced	Date latest PO Invoiced
Sphere / Spectro	\$20,695.00	\$20,695.00	10/25/2010	10/28/2010	\$20,695.00	3/28/2011
HTHH chamber	\$23,280.00	\$23,280.00	11/15/2010	11/15/2010	\$23,280.00	4/15/2011
HTHH Install	\$2,481.75	\$2,481.75	3/25/2011	4/15/2011	\$2,481.80	7/21/2011
LM-80 test EQPT (Prototype)	\$29,950.00	\$29,950.00	2/15/2010	3/31/2011	\$29,950.00	6/21/2011
Scale up Task-3 (Tooling, supplies etc)	\$32,560.23	\$25,064.32			\$25,064.32	1/31/2012
Task-4 Tester 4 software etc.	\$7,927.50	\$7,927.50	4/14/2011	4/14/2011	\$7,927.55	10/31/2011
Task-4 WP - Custom software support	\$9,747.50	\$7,217.50	1/11/2012	1/11/2012	\$7,217.54	2/29/2012
Task-4 Eqpt build and effort	\$141,465.00	\$139,465.20	4/15/2010	3/28/2011	\$139,465.06	12/20/2011
Total	\$268,106.98	\$256,081.27			\$256,081.27	
Savings due to competitive bidding etc.	\$49,502.81					

Table-2 Detailed funding profile & associated to date savings due to competitive bidding etc.

As discussed in the project continuation report in March 2011 and also in an intermediate accomplishments report (in Aug. 2011), GE Lighting Solutions has been able to achieve savings due to competitive bidding by suppliers on purchased equipments. These savings were

production will be *well within the ANSI bins and as low as a 4-step MacAdam ellipse* centered on the black body curve. Achievement of both of these objectives will be demonstrated while meeting a performance target of > 75 lm/W for a warm-white LED and a reliability target of $<30\%$ lumen drop / <2 -step MacAdam ellipse shift, estimated over 50,000 hrs.

The project objectives are in line with the MYPP (July2011) Manufacturing R&D priority tasks.

Table 1. LED Manufacturing R&D Priority Tasks

⇒	M.L1. Luminaire/Module Manufacturing Support for the development of flexible manufacturing of state of the art LED modules, light engines, and luminaires.
⇒	M.L3. Test and Inspection Equipment Support for the development of high-speed, high-resolution, non-destructive test equipment with standardized test procedures and appropriate metrics.

9. Technical Approach and Work Plan:

The following schematic describes the Technical Approach and Work Plan.

Figure-2 Technical approach and work plan

Task 1 - Project management

GE Lighting Solutions has developed and will maintain a Project Management Plan (PMP) throughout the course of the project. The initial PMP was submitted to the DOE Project Officer within 60 days of award. GE Lighting Solutions will review and update the PMP at the end of each Budget Period and resubmit as a part of the budget period continuation application. The PMP also has provisions for modifications on an ad hoc basis to reflect significant changes or

deviations of planning.

Phase 1

Task 2- Develop techniques for improved phosphors utilization in Vio™ LEDs

The patented “remote phosphor” configuration of Vio™ LEDs offers several benefits to color quality and control. However, a major manufacturing cost is excessive phosphor materials usage in the process to produce the remote phosphor component. Reducing this cost significantly while retaining the efficacy, color, and reliability properties of the product will accelerate market penetration of general illumination products using Vio™. In order to address this issue, we are developing and evaluating integration methods involving either reduction in phosphor usage during phosphor coating or synthesizing monolithic phosphor containing parts. Our initial experiments are based on the current phosphors used in the Vio™ LED to help downselect the phosphor incorporation method. The downselected method is also being applied to the new phosphors developed in the ongoing DOE-sponsored program related to phosphor development. Key criteria in the downselection process will be the ability to reduce color variation in LEDs and ability to reduce phosphor material usage costs in remote phosphor packages. Both of these criteria will contribute to the achievement of project objectives of reduced package cost and tighter control over color variation (4 step MacAdam ellipse).

Task 3 – Demonstrate compatibility of phosphor incorporation techniques at larger scales and with Vio™ pilot line production. This task will focus upon transitioning the small-scale processes developed in Task 2 towards larger-scale production in order to understand the process sensitivities and yield. This involves prototyping and testing of larger numbers of LEDs that use the phosphor incorporation methods developed in Task 2. Other significant group of activity in this task includes extended reliability testing of components manufactured using the downselected phosphor incorporation method. The reliability protocol includes testing under various ambient conditions (temperature, ambient humidity) and adherence to IES testing protocols (such as LM-80). It is anticipated that the costs savings and reduced color variation observed in task 2 (small scale laboratory experiments) will be reproduced in these pilot line production trials thus confirming these savings for future large-scale production.

Task 4- Develop high-speed characterization of phosphor domes and LED Packages

One of the advantages for the Vio™ platform of LEDs is its ability to precisely target specific CCTs and CRIs while maintaining color uniformity and stability over life. Flexible manufacturing processes should complement the precision offered by such technology. These would serve to minimize production line modifications and allow for rapid switching between various CCT and CRI SKUs. It would also account for any variation in LED chip wavelength and intensity, which are among the leading causes of white LED color variation. A high-speed characterization tool will enable real-time process adjustments during manufacturing of the remote phosphor components. This is targeted to improve yield and reduce color variation of the white LEDs. This automated high-speed characterization equipment will also serve to reduce the labor content in the process. This labor content reduction will contribute to the anticipated cost savings as highlighted in the project objectives.

Phase 2

Task 5- Design and simulation testing of automated, large-scale manufacturing line - In order to fully leverage the impact of the above tasks on the market, the technology to make LEDs using remote phosphor domes that has been developed in this program must be transitioned to low-cost, large-scale production. This requires the development of appropriate tooling and manufacturing process steps. Any design changes due to limitations in large-scale production (tooling, EHS, etc.) must be simulated / tested to assure that technical and cost requirements are met for future

Vio™ light-engines. The deliverable of this task is a production / manufacturing plan for large scale manufacturing of remote phosphor Vio™ LED packages. It is anticipated that this task will provide a plan for further possible costs reductions in these remote phosphor packages thus contributing to costs reductions highlighted in the objectives section.

As highlighted in Task 2, the remote phosphor incorporation techniques developed would also be applied to the new phosphors developed in on going DOE supported project at GE. This includes work on phosphors excited by Blue LEDs (450nm excitation). It is anticipated that the LPW target highlighted in the objectives section could be met using the Blue platform. Progress towards achievement of this goal would also be discussed as part of Task 2.

10. Summary of progress / accomplishments :

The progress update for various tasks -

Task 1 - Project management

Task-1 is on-going project management. As a part of task-1 we tracked the progress on other technical tasks and associated milestones.

Various milestones, their planned and actual accomplishment dates have been summarized in Table-3.

Task #	Milestone #	PMP Planned	Actual
	associated with task	accomplishment date	accomplishment date
	completion		
1	None - ongoing task	None	None
2	1	1/31/2011	1/31/2011
3	2	2/28/2012	2/28/2012
4	3 - intermediate milestone	6/30/2011	6/30/2011
	4 - final milestone	11/30/2011	11/30/2011
5	5	3/31/2012	3/31/2012

Table-3 Summary of tasks, associated milestones and accomplishment dates

As can be seen from this summary, all the tasks have been completed and associated milestones have been accomplished on schedule per the PMP.

Intellectual Property (IP) was generated during the course of project work in 2010 and 2011. Two invention disclosures were submitted by the team. GE LS is currently pursuing patent filings associated with these disclosures.

A 2010 yearly report (Dec. 2010), a peer review report / presentation (Jan. 2011), project continuation report / presentation (March 2011), an intermediate accomplishments report / summary (August 2011), a yearly report (Dec. 2011) and this final report (June 2012) have been used to document technical progress on the various tasks. These reports have been in addition to the monthly reports submitted through the course of 2010, 2011 and 2012.

A detailed project budget overview has been completed in section 7. As can be seen from the description in section 7, we have been able to save \$49,502.81 (DOE funds) through competitive bidding from equipment suppliers.

As a part of task-1, we maintained a monthly billing / invoicing cycle with our vendors and with DOE. The invoice to the DOE included details about effort at GE LS (hours spent daily by each team member with activity details) along with details about PO / invoice received from suppliers and payments released by GE.

As a part of task-1, we attended DOE LED Manufacturing Workshops (April 2010, April 2011 and June 2012). We presented progress update presentations at these workshops. Also contributed to focused discussions that enable the modifications of the DOE MYPP document.

Finally as a part of task-1, we looked at the overall technical developments accomplished in this project and ways by which these accomplishments could be leveraged to further develop energy efficient lighting products.

Task 2 - Develop techniques for improved phosphors utilization in Vio™ LEDs

Two experimental methods were evaluated as new techniques for improved phosphor utilization in Vio™ LED packages. The focus was on being able to minimize phosphor waste through reutilizing the overcoat (Slurry Coating) and through metered dosage of phosphor (Phosphor Molding) in the remote phosphor LED products. The technical progress in both of these areas has been discussed in detail in the monthly reports in 2010.

In summary -

Slurry coating: Experiments were conducted initially using different types of carrier media in the slurry coating process. These included Polyethylene oxide (polyox) based slurries with different additives, Nitrocellulose lacquer (NcL) based slurries and Hydroxyethyl cellulose (HeC) based slurries.

The Polyox based slurries initially showed significant promise due to the relative ease with which the overcoat could be reused. However we ran into significant issues with air entrapment and froth formation in the slurry feedstock due to the surfactant nature of the carrier media. We also could not easily control the ‘pooling’ of the slurry at the bottom of the remote phosphor dome due to poor adhesion to glass.

We were successfully able to control the properties of the NcL slurry to get a uniform coat on the glass domes. We solved the problem of poor adhesion and slurry pooling. Additionally we could also reuse the phosphor in the overcoat by dissolving the overspray with solvents such as Tert. Butyl Acetate and reclaiming the phosphor. However the photometry results obtained for samples coated with NcL slurry were significantly lower. We saw as high as 40% lower lumens in NcL slurry coated LEDs as compared to standard production LEDs. HeC based slurries also provided

good phosphor adhesion in test LEDs. However they also suffered from similar lower photometry performance as the NcL slurries. The lower lumens pointed towards significant light absorption by these slurry media.

Given the inability to control lumen loss and the relatively difficult manufacturing process set up to reclaim phosphor, efforts around trying to develop slurry coating process further were stopped. Resources were devoted to the development of the Phosphor Injection Molding process that was being developed in parallel.

Phosphor Molding: Phosphor molding involved mixing a metered / carefully controlled amount of LED grade phosphor with an injection moldable carrier medium (such as Silicone). This feedstock would then be injection molded into a cavity that would resemble the shape of the remote phosphor component in the GE LED product. We saw some significant advantages in the injection molding process, some of which are highlighted below –

1. Ability to carefully control the phosphor amount – therefore eliminating waste.
2. Ability to design runners, gates etc. in the injection molding process to minimize feedstock (and therefore phosphor) waste.
3. Ability to attain reproducible color point / lumens in LEDs due to extremely well controlled thickness / phosphor content in the remote phosphor component.

Through structured Design of Experiments, we were able to understand the effects of key process input variables that affected the photometry performance and initial reliability of these molded remote phosphor components. These experiments have been discussed in detail in monthly reports for 2010.

Given the above advantages and the success that we had in tailoring photometry performance, phosphor molding was selected as the preferred method for phosphor incorporation in LED packages. The results supporting this selection (reported at Milestone - 1) have been summarized below.

Milestone-1

1. Photometry –

Criteria established in the PMP -

Definition - Test group (either Phosphor molding or Slurry coating samples), Control group (existing Vio™ design).

- Variables measured include CCT, Lumens, CRI, CIE ccx, ccy (or u' , v').

- Success criteria will be demonstrated ability in Test group to achieve the various CCT, CRI, and LPW combinations as in our existing Vio™ product portfolio.

- Statistical 2 sample T-test comparison between Test and Control (min 30 samples) for 3 representative CCT-CRI combinations from the existing product portfolio.

- Success criteria will be Test better than or comparable to Control (i.e. in 2 sample T-test, with alternative hypothesis being “not equal” the p value is greater than 0.05).

Results

Table-4 summarizes the photometry results obtained at milestone-1. The results have been obtained for 405nm excitation (near UV platform) and 450nm excitation (Blue platform).

Test group: Vio™ LEDs with injection molded remote phosphor component

Ctrl group: Vio™ LEDs with spray coated remote phosphor component

2700K						
	Lm		CCT		CRI	
	Mean	Std dev	Mean	Std dev	Mean	Std dev
Test	185.2	1.77	2819	4.02	89.08	0.11
Control	154.6	16.6	2765	156	75.6	2.52
P (2 sample T-test)	0.086		0.61		0.01	
Test comparable to Ctrl	Yes		Yes		No	
Test Mean, Std dev better than Ctrl	Yes		Yes		Yes	
Test Mean, Std dev better than historic results	Yes		Yes		Yes	
3000K						
	Lm		CCT		CRI	
	Mean	Std dev	Mean	Std dev	Mean	Std dev
Test	269.5	3.66	3160	18.6	89.6	0.51
Control	248.9	4.01	3039	95.1	83.7	2.34
P (2 sample T-test)	0		0.028		0.0017	
Test comparable to Ctrl	No		No		No	
Test Mean, Std dev better than Ctrl	Yes		Yes		Yes	
Test Mean, Std dev better than historic results	Yes		Yes		Yes	
3500K						
	Lm		CCT		CRI	
	Mean	Std dev	Mean	Std dev	Mean	Std dev
Test	190.2	11.9	3471	27.6	82	2.83
Control	157.8	3.17	3185	7.5	81.4	0.05
P (2 sample T-test)	0.16		0.044		0.83	
Test comparable to Ctrl	Yes		No		Yes	
Test Mean, Std dev better than Ctrl	Yes		Yes		Yes	
Test Mean, Std dev better than historic results	Yes		Yes		Yes	
4100K						
	Lm		CCT		CRI	
	Mean	Std dev	Mean	Std dev	Mean	Std dev
Test	378.9	1.98	3845	105	90.2	0.5
Control	325.4	12.7	4025	111	81	5.29
P (2 sample T-test)	0.019		0.096		0.095	
Test comparable to Ctrl	No		Yes		Yes	
Test Mean, Std dev better than Ctrl	Yes		Yes		Yes	
Test Mean, Std dev better than historic results	Yes		Yes		Yes	
Prototype samples using Blue Phosphor						
2700K						
	Lm		CCT		CRI	
	Mean	Std dev	Mean	Std dev	Mean	Std dev
Test	298.8	7.4	2744	54	89.4	0.7
Control	287.1	12	2892	55	85.6	1.14
P (2 sample T-test)	0.1		0.0012		0.001	
Test comparable to Ctrl	Yes		No		No	
Test Mean, Std dev better than Ctrl	Yes		Yes		Yes	
Test Mean, Std dev better than historic results (Vio)	Yes		Yes		Yes	

Table-4 Summarized photometry results obtained for various prototype samples at Milestone #1

As can be seen from this table various CCTs ranging from 2700K to 4100K can be achieved in the test groups (near UV excitation) while using phosphor molding process. CRI ranging from lower end (80) to higher end (90+) can also be achieved in the test group. Also as can be seen from table-4, in all of these prototype samples the test group is comparable or better than the control group samples. These results also demonstrate the possibility of using the phosphor molding process in a Blue platform (450nm excitation) LEDs light engine. *The criteria for success established in the PMP have been met for photometry testing at milestone-1.*

2. Reliability –

Criteria established in the PMP -

- 500hrs screening reliability test in LED devices in RTOL conditions (25C, ambient humidity) and HTHH (60C, 90% rel humidity)
- Success criteria will be Lumen maintenance, CCT shift, CIE ccx, ccy (or u' , v') shift in Test is comparable to Control for 3 representative CCT-CRI combinations from existing product portfolio.

Results

Table-5 summarizes the early reliability (500h) results obtained at Milestone # 1. The results have been obtained using room temperature testing condition (RTOL) and high temperature, high humidity testing conditions (HTHH).

RTOL testing										
(Room temperature operating reliability)										
	delta Lumens		delta CCX		delta CCY		delta CCT		delta CRI	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
Test (delta between time T = 0h to T = 500h for Test group samples)	0.75	1.13	0.0014	0.0001	0.0012	0.0002	-12	2	-0.2	0.4
Ctrl (delta between time T = 0h to T = 500h for Ctrl group samples)	6.03	4.48	0.0017	0.0004	0.0016	0.0005	-23	19	-0.3	0.6
P value (2 sample -T test)	0.18		0.38		0.31		0.41		0.74	
Statistically Test group comparable to Ctrl group	Yes		Yes		Yes		Yes*		Yes	
Test Mean, Std. Deviation better than Ctrl group	Yes		Yes		Yes		Yes*		Yes	
Test Mean, Std. Deviation better than historic results	Yes		Yes		Yes		Yes*		Yes	
HTHH testing										
(High temperature (60C), High Humidity (90%RH) operating reliability)										
	delta Lumens		delta CCX		delta CCY		delta CCT		delta CRI	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
Test (delta between time T = 0h to T = 500h for Test group samples)	3.68	2.08	0.0003	0.0001	0.0018	0.0003	9	3	-0.9	0.3
Ctrl (delta between time T = 0h to T = 500h for Ctrl group samples)	3.17	3.25	0.0003	0.0006	0.0010	0.0015	3	3	-0.3	0.5
P value (2 sample -T test)	0.79		0.95		0.31		0.021		0.073	
Statistically Test group comparable to Ctrl group	Yes		Yes		Yes		No*		Yes	
Test Mean, Std. Deviation better than Ctrl group	Yes		Yes		Yes		No*		Yes	
Test Mean, Std. Deviation better than historic results	Yes		Yes		Yes		Yes*		Yes	

Table-5 Reliability results obtained at Milestone # 1. The results include change (delta) in Lumens, CCX, CCY, CCT and CRI after 500hrs testing in RTOL and HTHH conditions.

As can be seen from Table-5, the delta in all of the measured parameters appears to be comparable or smaller in the test group as compared to the control group. This result signifies that the LED packages (with molded remote phosphor domes) have comparable early reliability performance with the control group. The results obtained for delta CCT during HTHH testing are in line with historic measurements. These have been discussed in greater detail in the reliability data files provided to DOE on 2/4/2011. *The criteria for success established in the PMP have been met for reliability testing at milestone-1.*

3. Manufacturing costs –

Criteria established in the PMP -

- Calculation of total phosphor material usage and labor time in the existing process and comparison with the actual phosphor material usage and labor time in the downselected process.
- Success criteria will be demonstrated reduction of average 30% in overall phosphor materials usage cost and 10% reduction in labor cost. Manufacturing costs data will be reported in a format similar to that used in the proposal document.

Results

Result reported at the peer review -

Improved efficiency of phosphor usage demonstrated: The current production process (spray coating method) is extremely wasteful. The process utilizes as high as 0.8 grams of phosphor to manufacture one remote phosphor dome. A significant portion of this material (>70%) is waste. Phosphor molding has been a phosphor incorporation method that has been evaluated in this program. Phosphor molding involves the injection molding of phosphor powders using carrier medium (such as Silicones) into remote phosphor hemispherical shapes. This process uses less than 0.1 grams of phosphor to make the injection molded part as well as the associated sprues and runners in the injection molding process. The change from spray coating to injection molding represents a greater than 80% reduction in the phosphor usage costs and is inline with the manufacturing costs targets highlighted in the objectives section.

Figure-3 Manuf. costs in current production and while using phosphor molding process

The use of phosphor molding process allows for labor cost reduction. Initial experiments in Task-2 confirm the 10% cost reduction possible due to the use of molded components

The use of phosphor molding process also allows for a much tighter control in CCX, CCY during manufacturing as highlighted at the peer review. This allows for reduced yield losses. A manufacturing cost reduction of 5 units (due to reduced yield losses) can also be attributed to the development of phosphor molding process.

The criteria for success established in the PMP have been met for manufacturing costs reduction at milestone-1.

Based on these encouraging results phosphor molding was selected as the preferred method for phosphor incorporation in the remote phosphor Vio™ LED packages.

Task-2 reached a conclusion with the achievement of Milestone # 1 (1/30/2011).

Task-3 – Demonstrate compatibility of phosphor incorporation techniques at larger scales and with Vio™ pilot line production.

Partner (based in Ohio) selected for scale up of phosphor molding process: As discussed in the yearly report submitted in 2010, the initial mold design and molding technique were selected at the end of last year. A search for manufacturing partners capable of executing this molding technique pointed us towards a partner based in Berlin, Ohio. In 2011, we have worked closely with this partner. GE has provided molded component design details, phosphor blend materials and phosphor loading levels. The partner has worked on manufacturing process settings (such as molding pressures, temperatures etc.) to optimize the molding process. The photometry and reliability performances results discussed in this report are for molded components obtained from the scale up partner. The reliability / performance tests have been completed at GE.

Photometry performance objectives (as highlighted in proposal) achieved: The original proposal had included our intentions to develop 75+ LPW products in the warm-white CCT (<4000K) regime in the remote phosphor Vio™ footprint. The phosphor molding process developed under this project in conjunction with the proprietary phosphor blend(s) developed at GE can enable this performance. The accomplishment of this goal has been highlighted below. Phosphor molding equipment was built in 1st quarter of 2011. Some initial phosphor molding trials were conducted in April-May 2011. Lower cost phosphor blends (designed for 70CRI, 4000K CCT) were used in these initial process screening trials. After gaining some confidence in the process settings being used at the partner location, we decided to initiate molding activity using the production grade (high cost) phosphors. Additionally some tests were completed in-house to ascertain the CRI, CCT, Lumens entitlements possible using the production grade phosphors. The results obtained for these tests (while varying the LED peak wavelength and phosphor coating thickness) are summarized in Table-6

Trial	PART			I(mA)	Vf	Iv (Lm)	Wd	Wp	CCX	CCY	CTEMP	CRI
1	1	Chip Wp = 450	Thick < 0.25mm	350	18.93	370.05	585.41	631.03	0.4431	0.3941	2816	92
2	2	Chip Wp = 450	Thick ~ 0.25mm	350	18.92	363.55	584.08	631.03	0.4568	0.4095	2735	91
3	3	Chip Wp = 450	Thick > 0.25mm	350	18.99	362.07	583.24	631.03	0.4717	0.4247	2648	89
4	4	Chip Wp = 443	Thick ~ 0.25mm	350	17.897	400.76	587.10	631.05	0.4661	0.3973	2512	89
4	5	Chip Wp = 443	Thick ~ 0.25mm	350	17.79	391.05	586.72	631.05	0.4698	0.4012	2495	88

Table-6 Summary of 4 trials using a high CRI based blend. (The phosphor blend was designed for 440-450nm excitation).

It was noted early - to improve the Lumens entitlement in the Vio™ footprint devices, we would have to use 450nm excitation LEDs. As can be seen from results compiled in Table-6, a high CRI (90+), Warm White CCT product was possible using the production grade phosphor blend. The LPW recorded in these experiments was low (~65LPW). Also the phosphor coating thickness used was ~ 0.25mm.

The production version of the phosphor molded component planned to use 0.5mm thick phosphor coating. Additional DoEs (Design of Experiments) were conducted in July-August 2011 to further improve performance in the 0.5mm thick phosphor molded inserts. A result obtained in one of these trials has been highlighted below.

I(mA)	Vf	isd	Iv (Lm)	Wd	Wp	CCX	CCY	CTEMP	CRI
350	18.4	Insert4	471.6	597	631	0.4137	0.3483	2921	91.3

Table-7 Flash photometry results obtained for 0.5mm thick molded insert using phosphor blend designed for Blue LED excitation (Wp ~ 448 nm). The CCT is less than 3000K with CRI higher than 90. LPW calculation ($471 / (18.4 * 0.35)$) yields a number of **73.3**

The result in Table-7 demonstrated an improvement as compared to the previous trials. The Design of Experiments approach helped us map the possible design space and identify areas for improvement. Details about the various input variables in these experiments and their interrelationships have been described in the proprietary and confidential report submitted in Aug. 2011.

The Department of Energy has also supported phosphors development at GE (Research) through DOE contract # DE-EE0003251. Our colleagues at GE (Research) have been working on the Red Line Emitting (RLE) phosphors. One of their objectives has been to improve the reliability and photometry performance of the RLE phosphor. An improved version of the RLE phosphor was available for manufacturing development at GE LS. This phosphor was used in combination with

high efficacy yellow phosphor in molding trials. A representative result obtained in one of these trials has been summarized in Table-8

I(mA)	Vf	Iv (Lm)	Wd	Wp	CCX	CCY	CTEMP	CRI	LPW
350	18.27	604.1	579.6	631.0	0.3968	0.3895	3684	83	94.5

Table-8 Photometry results obtained using the modified RLE phosphor. This result demonstrates the accomplishment of 75+ LPW in a remote phosphor product.

The demonstration of 94 LPW in a warm white (<4000K) CCT in a Vio™ footprint device underscores the accomplishment of one of the objectives of this manufacturing research program.

It is also worth mentioning that these results have been obtained using Blue (450nm excitation LEDs) with ~43% WPE (Wall Plug Efficiency, $WPE = \text{Blue Radiometric Power} / \text{Electrical Power}$). There is line of sight from Blue LED manufacturers to obtain WPE in excess of 57%. This represents an approx. 30% improvement (over the current baseline) in Blue LED efficiency. This could translate to 125+ LPW in a warm white remote phosphor LED device. The expected photometry results and (manufacturing costs) in this program are in line with the metrics discussed in July 2011 SSL MYPP roadmap document (table-5 in the report).

Transfer functions developed to control color point during manufacturing: As discussed in monthly reports in 2011, there appears to be a need to use phosphor molded insert in combination with a clear glass dome (hemisphere). This combination appears to provide improved thermal derating performance as compared to the standalone phosphor molded inserts. We have noticed a systematic shift in the color point before and after inserts attachment to these clear glass domes. Additionally the color point (ccx, ccy) in these molded insert can be varied by changing the phosphor blend, phosphor loading level, phosphor molded component thickness etc. In order to achieve high manufacturing yields, it is necessary to be able to map and understand these various relationships that can lead to color point shifts. The manufacturing goal is to control these various contributors to color point shift so as to achieve a distribution within 4 step MacAdam ellipse. The development of transfer functions that govern these color point shifts has been attempted and is complete. Figure-4 summarizes the results obtained during DoE iterations that led to the development of transfer functions. These transfer functions have been provided to DOE in a proprietary and confidential report submitted in August 2011.

Figure-4 Results of 6 DoE iterations plotted in CIE color space. These iterations were intended to derive the transfer functions governing the color point during manufacturing. Please note the systematic color point shift between molded inserts (I) and inserts attached to glass domes (I+G). Please note based on these transfer functions, we now have the ability to achieve color points within 3 step MacAdam ellipse near the 3000K and 2700K CCT color points.

The selection of the scale up partner, phosphor blend and LED dies modification efforts and manufacturing transfer functions development effort supported the scale up activity intended in task-3. These activities along with reliability testing (parallel effort) allowed for the accomplishment of milestone # 2 per the PMP.

Per the program management plan -

Milestone -2

Title: Scale up of selected phosphor incorporation technique in larger scale in pilot line production

Planned Date: 2/28/2012

Description & Verification Method: At the milestone # 1, either the Slurry coating or Phosphor molding will be selected as the final method for phosphor incorporation into the remote phosphor geometry. The selected method needs to be scaled up in a pilot line manufacturing environment to understand and resolve any large scale manufacturing issues that may arise due to these design and process changes. Also need to complete extended reliability testing to support screening reliability data obtained during work on milestone # 1.

Quantitative verification methods will involve –

1. Photometry –

- Demonstration of 100 pieces or larger batch size for each product combination being successfully built at the tollgate vendor.

The capability to build larger batches has now been established at the toll vendor. An example of samples obtained in batch run (with a batch size of about 100 parts) has been depicted in figure-5.

Figure-5 Phosphor molded parts loaded in a tray obtained in a batch run at the toll vendor (some rows have been left intentionally empty to distinguish parts from modified settings in the same batch). Inset – close up of molded parts before cleaning / flash removal and attachment to glass domes.

The batch size can be increased and the only limiting factor is the pot life of the phosphor plus silicone injection molding feedstock. As has been discussed previously a “cold-deck” injection molding process has been developed at the toll vendor to significantly increase the pot life of the molding feedstock.

- Demonstrated ability to meet the CCT, CRI, LPW etc. claims established for 18 products listed in current VioTM catalog using the new successful phosphor incorporation method.

Detailed transfer functions that would allow the prediction of photometry parameters (such as CCT, CRI, Distance from black body and Lumens) were developed in 2011. These were reported in a GE Confidential and Proprietary report submitted in Aug. 2011. Manufacturing scale up has relied on these transfer functions. We have been able to reproduce the results obtained during initial experiments (Aug. 2011) in our manufacturing scale up trials.

As a part of manufacturing scale up, the design space defined by these transfer functions has been mapped. Process settings based on these mapping tables have been established. Table-9 below is an example of a process settings exercise.

CCT	CRI	Dbb	Lm	Factor1	Factor2
2760.9	89.855	-0.04765	417.87	80	55
2766.97	89.251	-0.04299	418.776	79	55
2773.04	88.647	-0.03833	419.682	78	55
2779.11	88.043	-0.03367	420.588	77	55
2785.18	87.439	-0.02901	421.494	76	55
2791.25	86.835	-0.02435	422.4	75	55
2797.32	86.231	-0.01969	423.306	74	55
2803.39	85.627	-0.01503	424.212	73	55
2809.46	85.023	-0.01037	425.118	72	55
2815.53	84.419	-0.00571	426.024	71	55
2821.6	83.815	-0.00105	426.93	70	55
2827.67	83.211	0.00361	427.836	69	55
2833.74	82.607	0.00827	428.742	68	55
2839.81	82.003	0.01293	429.648	67	55
2845.88	81.399	0.01759	430.554	66	55
2851.95	80.795	0.02225	431.46	65	55
2858.02	80.191	0.02691	432.366	64	55
2864.09	79.587	0.03157	433.272	63	55
2870.16	78.983	0.03623	434.178	62	55
2876.23	78.379	0.04089	435.084	61	55
2882.3	77.775	0.04555	435.99	60	55

Table-9 Photometry results expected during manufacturing when using previously developed transfer functions to define process settings. Factors have been defined in the GE Proprietary and Confidential report submitted in Aug. 2011.

The intended goal in this exercise was to achieve 3000K CCT with CRI approaching 85, dbb close to 0 and highest possible Lumens. We know from our previous experiences that we should expect a CCT shift (systematic shift) of 200K after the phosphor molded dome is attached to the glass caps (for molded domes with CCT in the vicinity of 3000K or higher). Consequently our process settings target was 2800K while maintaining the other photometry objectives. As can be

seen from this table, we are able to define a process setting that would allow for 3000K CCT, 85CRI product with 425+ Lumens

Similarly the transfer function can be used to define manufacturing process settings for 4100K, 70 CRI products (the other end of product spectrum).

CCT	CRI	Dbb	Lm	Factor1	Factor2
3873.195	72.2855	0.007465	504.306	56.5	33.5

Table-10 Photometry results expected during manufacturing (when using previously developed transfer functions to define process settings) – intended photometry target is 4100K, 70CRI product.

As a part of this effort we are also evaluating the introduction of high CRI (85+), warm white (2700K CCT) product. The manufacturing settings for this product are shown in Table-11.

CCT	CRI	Dbb	Lm	Factor1	Factor2
2452.132	87.6658	-0.00233	399.9156	74.4	62.6

Table-11 Photometry results expected during manufacturing (when using previously developed transfer functions to define process settings) – intended photometry target is 2700K, 85+CRI product (expect to see about 250K CCT shift after attachment of the remote phosphor molded dome to the glass hemisphere).

The availability of transfer functions that enable manufacturing setting to attain the required photometry characteristics in the final product demonstrates the achievement of the objective laid out in the PMP.

- Demonstration that each of the product types has color point centered within the ANSI bins, with color variation within less than 4 steps MacAdam ellipses.

Figure-6a is a plot of color points obtained in a batch run. Overlaid on these results are 4 step MacAdam ellipses. The process setting for this batch was such that a product with 2700K CCT was intended to be manufactured. 3 Step MacAdam ellipses near 3000K CCT color point are also included in this figure for reference. Figure-6b is a plot of these same color points with the ANSI bin for 2700K CCT (per C78.377-2008) overlaid.

As can be seen from Fig-6a the process allows us to reproducibly manufacture remote phosphor molded domes with color variation less than 4 step MacAdam ellipses. The manufacturing process established at the partner would essentially be same for all the different product types. Consequently a manufacturing variation of less than 4 steps would be expected for different product types.

As can be seen from figure-6b the color points fall within the ANSI Bin for 2700K. Moreover based on further fine tuning the manufacturing transfer functions (while taking into account LED die bins etc.), we expect to reproducibly attain the center of the ANSI bins for different production runs.

Figure-6a Color point plot for one production batch run (2700K, 85+CRI) – overlaid are the 4 step MacAdam ellipses

Figure-6b Color point plot for one production batch run (2700K, 85+CRI) – same batch as depicted in Fig-6a. 7 step MacAdam Ellipses ANSI bin is overlaid for reference.

2. Reliability –

- Approx. 6000hrs test in RTOL, HTHH conditions. This extended test to be performed on 3 representative samples.

- Success criteria will be Lumen maintenance, CCT shift, CIE ccx, ccy (or u' , v') shift in Test is comparable to Control samples for 3 representative CCT-CRI combinations from existing product portfolio.

Reliability tests were started in two 3000K - 85+CRI products (1 LED, 3 LEDs versions) and one 3500K - 85CRI product (high lumens – intended new offering – 6 LEDs).

Results for the 3000K - 85CRI product (3 LEDs version) that has reached 6000+ hours in reliability testing have been summarized in figures-7 and 8

Figure-7 summarizes the L70 projection obtained for test data (based on 6061 hrs). The model predicts a L70 of greater than 50,000 hours. The datasheet claims for Control data (spray coated phosphors) is L70 = 50,000 hours. Based on these results it can be concluded that Lumen Maintenance for Test (with molded remote phosphor components) is comparable or better than Control (spray coated phosphors).

Figure-7 Lumen Maintenance projected for test samples (3000K, 85+CRI product). Projected L70 is greater than 50K hrs (green arrow). Control samples data (based on datasheet), projected L70 is 50K hrs (brown arrow). Lumen Maintenance projection in Test (molded remote phosphor samples) is better than Controls.

Figure-8 below summarizes the color point shift observed in Test samples. As can be inferred from this data, the color point shift after 6000 hours of testing is less than 1 step MacAdam ellipse in the Test samples. Using a predictive model, we can expect a color shift of less than 2 step MacAdam ellipse after 50,000 hours in the Test population. This result is comparable or better than the historic results obtained for control samples (with CCT shift less than 200K or less than 3 step MacAdam ellipses).

Figure-8 Color point plot for Test samples during reliability testing to time = 6061 hours.

Similar results have been obtained for the 3000K – 85 CRI product (1 LED version) during reliability testing. These have not been reproduced here for brevity.

Reliability tests were started in 3500K CCT – 85CRI product. This was intended to be a high lumen, high CRI new product offering – based on GE proprietary red line emitting (RLE) phosphor and Blue LEDs (450nm). 2000 hours of reliability testing has been completed in this new product embodiment. The results obtained have been summarized in figures-9,10

Figure-9 Lumen Maint. results after 2000 hrs of testing. Lumen Maint - 100% after 2000 hrs

Figure-10 Color point plot for samples in reliability testing (3500K – 85CRI – high lumen packages). Less than 1 step MacAdam ellipse color shift observed after 2000 hours.

Based on results discussed in this section, it can be concluded that the Test samples (with molded remote phosphor components) demonstrate comparable or better long term reliability performance as compared with the Control group samples (with spray coated remote phosphor domes).

- Start LM-80 testing on 2 representative samples. Gather data till the planned completion date for milestone #2. Develop lumen depreciation model based on available data at the completion of milestone # 2. If 6000hrs are not complete, continue test beyond milestone # 2 while reporting the available LM-80 data on 2/28/2012.

As discussed in the report for Aug 2011, LM-80 prototype equipment build was completed in 2011. Reliability test using molded remote phosphor components was initiated while using this prototype reliability equipment. The LM-80 test is being conducted with ambient temp. at 85°C. So far about 2250 hours of testing has been completed with no LED device failures. The Lumen maintenance curve recorded in this LM-80 test is shown in figure-11

Figure-11 Lumen Maintenance curve obtained after 2250 hours in LM-80 test (85°C ambient).

Using an exponential model for reliability prediction a L70 of 50,739 hours can be calculated based on this data. This Lumen maintenance result appears to be comparable to life predictions obtained for Control samples (using spray coated remote phosphor domes).

Figure-12 Color points plot for samples in LM-80 test.

Figure-12 is a color points plot for samples being test under LM-80 conditions. Less than 1 step MacAdam ellipse color shift is observed in these samples after about 2250 hours of reliability testing.

As discussed in the PMP, we plan to continue our testing under LM-80 conditions to 6000+ hours. This data will be used during internal reviews prior to a possible product launch in 2012.

The long term reliability testing results have been promising and validate the use of phosphor molding as a reliable technology for Lighting applications.

In summary, results presented in this section include - manufacturing process set up to attain the required photometry characteristics in products, demonstrated control over the manufacturing process to attain products that meet specifications, successful scale up of phosphor molding process at the partner location, demonstrated reliability results that meet the product long term performance objectives and the demonstrated ability to produce high lumen, high CRI, warm white LED products in the Vio™ footprint that start approaching the DOE SSL MYPP 2012 performance targets.

Task-3 reached a conclusion with the achievement of Milestone-2 (2/28/2012).

Task-4 Development of automated (photometry and electrical) characterization equipment for the remote phosphor Vio™ packages.

As has been highlighted in the proposal, the objective of this task was to automate the manual LED characterization process. By automating the process, we intended to increase the characterization speed as well as reduce the manual labor content in the manufacturing process. The LED characterization process involves the measurement of photometry parameters for the LED (color point, CCT, CRI, lumens) and electrical parameters (forward voltage – V_f). In addition the process also calls for categorization of LED products into appropriate bins based on these sets of measurements.

The manual measurement system included the use of an integrating sphere, spectrometer and software that allowed the categorization of LEDs into bins - all of these components being handled by a dedicated operator. This system was slow, inefficient and prone to human error. Moreover this system could not be economically scaled up to handle larger volumes as the pilot line production was projected to increase.

A system design was conceived at the start of the project. The basic elements in the system have been highlighted in the schematic in figure-13.

Figure-13 an initial concept that highlights the different components of the automated LED characterization machine.

The automated system concept included two major elements –

1. A **mechanical platform** that would enable the handling of LEDs during the characterization process. This includes managing warm up etc. cycle of LEDs, translating them into and out of the measurement station, marking the parts (laser marking based on appropriate bins), disposing parts

into appropriate physical bins based on results received from the binning software. Managing communication with the binning software.

2. **Sphere, spectrometer and associated binning software** that would complete the measurement of photometry / electrical parameters of the LED and provide results to the mechanical platform to complete physical binning of the measured LEDs.

After concept generation, we took on the task of developing a detailed technical specification document. This document included a detailed design description of GE Vio™ LED products and remote phosphor domes, the characterization requirements pertaining to each of the product types and the expected characterization machine working protocol / rate requirements. Information was also included for the possible high CRI, high lumen Blue LED based products that could be launched in the near future (based on Vio™ footprint).

The specification document along with our concept for the complete system were provided to multiple Mechanical Integration companies (MI) and Sphere/Spectrometer/Binning software (SSBS) manufacturers. Quotes and machine design concepts were received from these companies. The final selection process for both of these system elements was started. This selection process involved a team review of the designs / products available from 5 MI companies and 3 SSBS manufacturers. Based on these reviews and discussions with the suppliers, Pugh Matrices were created for the SSBS and MI company selection. Figures-14 and 15 are examples of Pugh matrices that were used to compare the leading SSBS and MI company candidates.

Pugh Concept Selection Matrix Vio Photometry equipment		Concepts	
<div><div>Concept Selection Legend</div><div>Better + Same S Worse -</div></div>		Supplier-1 Photometry Equipment	Supplier-2 Photometry Equipment
Criteria, Note: baseline system is the current manual lab system.	Criteria Weighting		
1 Ease of implementation, software, hardware, etc...	5	-	+
2 Photometry Requirements, does the system deliver the photometry requirements	5	S	S
3 Capital Requirements, what does equipment cost?	5	-	+
4 Product Quality, does system meet specifications	5	S	S
5 Process repeatability, ability of system to produce output within spec. limits	5	+	+
6 Ease of Maintenance/Trouble Shooting, robust equipment proved in production	4	-	+
7 Reliability of Operation	4	S	S
8 Components Defined, does system identify the components needed for the process	4	-	+
9 Process parameters, does the system monitor the parameters required to bin product	4	S	S
10 System history log, does it collect & log process parameters for history analysis	4	S	S
11 Does the system have the capability to stop the process if parameters are not maintained	4	S	S
12 Tact time, does the equipment meet (machine cycle time + manual load time+ manual unload time)	4	S	S
13 System production and delivery schedule, can they meet expected time lines?	4	S	S
14 System supplier Capability, has supplier been successful in delivering to GE in the past	3	S	+
15 After sales support and service, do they supply training and support & at what cost.	3	-	+
16 Detection of misload, will the process detect a loading error & prevent the process from starting	3	S	S
17 Flexibility of Operation	2	S	S
18 Cross Contamination Possibilities	2	S	S
19 Additional Hardware or software	2	S	+
20 Are there adjustments that the operator must make. Can the adjustments effect quality?	2	S	S
21 Foot print constraints	1	S	S
22 If sphere is used inverted (poles reversed) can dropped parts be retrieved?	1	S	S
Sum of Positives		1	8
Sum of Negatives		5	0
Sum of Sames		14	12
Weighted Sum of Positives		5	31
Weighted Sum of Negatives		-21	0
Overall Weighted Score		-16	31

Figure-14 Pugh Matrix highlighting the criteria used in selection of the final supplier for SSBS.

<div>Concept Selection Legend</div> <div>Better + Same S Worse -</div>			Sup 1	Sup 2
Criteria, Note: baseline system is manual lab system.	Criteria Weighting			
Product Quality, does system meet specifications?	0	S	S	
Process repeatability, ability of system to produce output within spec. limits? EVP 1&2.	0			
Safety	0	S	S	
Lock-out Tag-out: are there provisions to isolate energy sources?	0	S	S	
Process parameters, does the system monitor the parameters required to bin product?	0	S	S	
System history log, does it collect & log process parameters for history analysis?	0	S	S	
How are parts marked after characterized? Inkjet(-) or laser jet(+)? (Both have CO2 & YAG samples.)	0	+	+	
Guarding & shielding of unwanted light around test area & class 1 guarding of laser addressed?	0			
Operator Protection- Is point of operation protected from operator during machine operation?	0	+	+	
Pedestrian Protection- Is point of operation protected from pedestrian traffic during machine operation?	0	+	+	
How does design make power connection to LED or light source for lighting LED packages or light engines for domes?	0	+	S	
Does the system monitor the parameters required to measure a part accurately and are they controlled?	0	-	-	
Can the parts be located incorrectly in the holding trays or fixtures?	0	S	S	
Does operator wait on machine to cycle? Can operator be separated from machine to do other tasks?	0	S	S	
Does the system collect and log process parameters from history logs that can be analyzed to develop corrective actions from failures?	0	-	-	
LEDs: Are there options for putting LEDs into sleeves on current design?	1	+	S	
Are their by-products from the process? (Fumes) Are they contained and removed safely from system?	1	+	+	
Options for additional Hardware or software?	1	S	S	
Are their adjustments that the operator must make. Can the adjustments effect quality?	1	S	S	
Foot print constraints meet functional specification.	1	+	+	
Glass dome picked up in location of non-light emitted area.	1	+	-	
LED picked up on non-light emitting area (PCB).	1	+	S	
Is machine mobile? Can the cell be reconfigured quickly?	1	+	S	
Stability- Is the machine frame stable and robust? Will machine maintain calibration and orientation?	1	S	S	
FOB shipping costs to Nela Park?	1	-	+	
Dome presented to machine, igloo dome up preferred?	1	S	S	
New tray aquisition for dome/LED cost accounted for in integrators system.	1	+	+	
System has options for egg-crating or tubing domes?	1	+	S	
Design software used. SolidWorks/AutoCad.	1	-	+	
If sphere is used inverted (poles reversed) W.P. preference is opening down.	1	S	S	
Capital Requirements, what does equipment cost?	5	+	S	
Ease of Maintenance/Trouble Shooting, robust equipment proved in production, References?	5	S	+	
Components Defined, does system identify the components needed for the process?	5	+	S	
Tact time, does the equipment meet and exceed (machine cycle time + manual load time+ manual unload time)?	5	+	S	
System production and delivery schedule, can they meet expected time lines?	5	S	S	
After sales support - do they supply training and support & at what cost?	5	+	+	
Measurement area has light containment area to shield test area from stray light?	5	+	+	
Ease of adding machine system tact time features at a later date?	5	-	+	
System has queued station or system that keeps parts available to machine?	5	S	S	
Are the controls and system well documented to facilitate root cause analysis? Manuals, etc...	5	+	S	
System supplier Capability, has supplier been successful in delivering to GE LS in the past?	5	-	+	
Detection of misload, will the process detect a loading error & prevent the process from starting so parts are not damaged?	5	+	S	
Do they maintain an inventory of parts? (OEM parts vs. std. Parts) Are the components standard and easily purchased?	5	+	S	
Control of cross contamination possibilities?	5	+	S	
Robot pick and place design or SERVO positioning system or Gantry system?	5	S	S	
Percentage of design, fabrication, software development and programming done in house?	5	+	+	
Component access- are components easy to replace?	5	S	S	
How many DUT does end effector pick up after testing. + score for more than 2.	5	+	S	
2p placement is accounted for in current design and not an add on option with extra cost?	5	+	+	
Confidence of implementation, software, hardware, etc...?	10	+	+	
Photometry Requirements, system delivers the photometry requirements according to W.P. equipment?	10	-	S	
Can sphere or part move to accomodate true 2p position?	10	+	+	
Reliability of System?	10	+	+	
Does the system have the capability to stop the process if parameters are not maintained?	10	-	-	
Can integrator service what they sel? Do they supply training and support for troubleshooting by phone, internet, pc anywhere, ect..	10	+	+	
Experience - process known (know how) at vendor?	10	+	S	
Flexibility of Operation?	10	S	S	
Proposal cost split - Design Engineering vs. capital equipment cost?	10	S	S	
Sum of Positives		30	20	
Sum of Negatives		8	4	
Sum of Sames		19	33	
Weighted Sum of Positives		118	80	
Weighted Sum of Negatives		-32	-11	
Overall Weighted Score		86	69	

Figure-15 Pugh Matrix highlighting the criteria used in selection of the final MI company.

Based on the outcome of these Pugh matrices based review process, final selections for the MI company and SSBS supplier were completed. The SSBS system was purchased from the supplier and provided to the MI company. The MI company proceeded to integrate the equipment as per the design specification. The MI company also added additional binned LEDs packaging capabilities to the machine.

The purchased SSBS system was qualified in June 2011. The qualification trials were carried out on remote phosphor domes. Successful results for intermediate milestone (# 3) were reported in June prior to delivery of the SSBS system to the MI company. The MI company worked on machine integration of the SSBS system into the mechanical platform. They were able to successfully complete the integration in Nov. 2011. Results supporting this integration were reported at milestone-4. The MI company had designed the machine to also include binned LEDs packaging capability. They were able to complete this additional part of the project and deliver a fully operational machine by end of March 2012.

Figure-16 is a compilation of images depicting the final assembled machine. A separate video has been provided to DOE in the report for Feb. 2012 that shows the machine in operation.

Figure-16 The final assembled LED characterization machine per task-4.

Milestones-3 (6/30/2011) and milestone-4 (11/30/2011) tie with the goals of Task-4.

Milestones-3 and 4 (as highlighted in the PMP) have been accomplished. The results that support the accomplishment of these milestones have been discussed below.

Milestone-3

Title: Develop in-line characterization method for phosphor domes

Planned Date: 6/30/2011

Description & Verification Method: Task 4 in the proposal intends to develop high-speed characterization techniques for phosphor domes and assembled light engines. This milestone deals with the development of in-line characterization methods for phosphor domes. Activity leading to this milestone will involve screening various combinations of light sources – photometry measurement equipments (in far field measurements) and software interfaces. The end goal will be an automated, repeatable system that can provide an almost instantaneous photometric feedback on remote phosphor domes to enable real time process modifications for color etc. correction on domes.

Quantitative verification methods will involve –

1. Photometry -

- *A quantitative transfer function between the photometry parameters measured on the domes using this system and the photometry parameters that may be obtained from that dome, when assembled into a complete light engine.*
- *Success criteria will be transfer functions developed for domes for the various CCT / CRI combinations for products in the VioTM catalog.*

The equipment plans to characterize remote phosphor domes and LED packages. The characterization equipment set up would be such that individual test domes would be placed on standard LED light engines and measured for photometry performance. The photometry results obtained would be a function of –

1. The color characteristics of the remote phosphor domes.
2. The LED light engine used.
3. The separation of the Dome + LED from the integrating sphere during measurements.

This project has developed the molded remote phosphor domes technology. As demonstrated earlier the color characteristics of molded domes are extremely reproducible (within less than 2 step MacAdam ellipse). Given this extremely high reproducibility, we know the transfer function for item # 1 above would be a simple linear function (i.e. as the phosphor blend formulation is changed to achieve different CCT, the color point for all subsequent remote phosphor production domes would change – but the population distribution would be extremely narrow).

The LED light engine would be a standard light engine (emitting at either 405nm or 450nm) and it would not change in emission wavelength. Therefore the transfer function would be a simple linear function.

Item # 3 however will significantly dictate the photometry performance / results obtained. Transfer functions need to be developed to characterize separation and pick the appropriate

separation that works for a particular set of LED + Domes combination. This transfer function development is described below -

A test set up has been established at GE to evaluate the performance of the LED packages in 2π partial flux vs. true 2π measurements. This set up is shown in figure-17.

LED device placed on a platform that can be raised or lowered.

- separation between LED and sphere
= 0 mm = true 2π

- separation between LED and sphere
> 0 mm = 2π partial flux

Figure-17 Set up to evaluate 2π partial flux vs. true 2π measurements

Results have been gathered with test separation (between LED package and integrating sphere) of 6.5mm, 10mm and 15mm. Important photometry variables (such as CCX, CCY, CCT, Lumens, CRI) have been measured. For reference true 2π measurements have also been conducted.

The results gathered and the transfer function for these photometry variables are captured in the following charts.

For reference on x-axis:

0-True 2π

6.5-separation of 6.5mm

10-separation of 10mm

15-separation of 15mm

Figure-18 Transfer functions developed for various photometry parameters for different 2π partial flux measurement distances

2. Manufacturing cost savings –

- Demonstrated reduction in yield defects (domes rejected due to unacceptable photometry parameters).
- Success criteria will be the achievement of cost reduction targets highlighted in the proposal (a maximum of 10 currency units reduction in cost due to elimination of phosphor dome photometry defects). These reductions will be demonstrated on the lab scale equipment (milestone # 3) and later confirmed in pilot scale up during work on milestone # 4. Manufacturing costs data will be reported in a format similar to that used in the proposal document.

The results for this part of the milestone are discussed below –

- As discussed in the project continuation report (and reproduced here), the phosphor molding process allows for a much higher repeatability in the remote phosphor dome color point as compared to the spray coating process. The results obtained in test run using the spray coating and phosphor molding process have been reproduced here. Also as discussed previously, we now

have the capability to alter the color point and center it within a specified bin or near the Planckian locus.

Results : Reduced ccx, ccy variation during manufacturing

Figure-19 A significant reduction in the spread in ccx, ccy possible using the molded remote phosphor domes. Can tailor phosphor blend to get color point reproducibly near the Planckian locus and within a specified bin. This allows for reduction in manufacturing rejects due to color point being out of the specification

b). The remote phosphor molded dome allows for a reduction in manufacturing defects. Examples of defects that can be avoided in the molded domes are included below.

Figure-20 Sample #1 – phosphor molded dome attached to a glass cap - no defects observed. Frequent defects observed in spray coated samples - coating delamination (sample # 2), spray coating inclusions (sample # 3).

Defects such as phosphor coating delamination, spray coating inclusions are no longer an issue in a remote phosphor molded dome (attached to a glass cap). These defects (samples # 2, 3) contribute significantly to yield losses in the production process.

Results discussed in this section (a, b) demonstrate the accomplishment of manufacturing savings possible due to injection molding process.

The manufacturing costs savings that reflect the items discussed in a, b, in this section have been listed below

Summary			Start of project	at 6/30/2011	Reduction to date		Target in proposal (for milestone # 3)
			(arbitrary currency units)				(Reduction)
Phosphor			16	2	14		0
Yield			15	5	10		5
Labor			22	19.8	2.2		0
Chip	(Remain unchanged)		27	27	0		0
Other	(Remain unchanged)		20	20	0		0
Total			100	73.8	26.2		5

Table-12 Manufacturing savings at the accomplishment of Milestone-3. These have been listed for representative 1W Vio™ package

Milestone-4

Title: Develop in-line characterization method for assembled Vio™ LED packages and pilot scale up of characterization methods for domes and assembled LED packages.

Planned Date: 11/30/2011

Description & Verification Method: Work completed in milestone # 3 will feed into achieving this milestone. The lab scale system built to characterize domes will be expanded to include measurement capability for assembled LED packages. A pilot scale up of this expanded system will be demonstrated.

Quantitative verification methods will involve –

1. Photometry and binning –

- Demonstrated ability to complete automated photometry measurements and Color, CCT, Lumens, Vf binning of assembled LED packages.
- Success criteria will be greater than 99% accuracy in completing binning operations using automated system as compared to the current manual system.

The following results demonstrate the accomplishment of photometry and binning criteria. Figures-21 through 23 are color point plots of LED devices being measured using the automated system (Test) and the manual system (Ctrl). As can be seen from these results the color points measured by these two distinct systems vary within less than 1 step MacAdam ellipse. For all the measured Test points they lie within the same color bin as the Ctrl measurements.

Figure-21 ccx, ccy color point plot for 1.2W device. The color point measured with the manual system (green marker) and that measured with the automated system (purple marker) for the same device. We see a less than 1 step MacAdam ellipse shift between both of these measurements for the same device.

Figure-22 ccx, ccy color point plot for 3.6W device. The color point measured with the manual system (green marker) and that measured with the automated system (purple marker) for the same device. We see a less than 1 step MacAdam ellipse shift between both of these measurements.

Figure- 23 ccx, ccy color point plot for 7.2W device. The color point measured with the manual system (green marker) and that measured with the automated system (purple marker) for the same device. We see a less than 1 step MacAdam ellipse shift between both of these measurements.

Lumens						
	Test		Ctrl		2-T test	Test and Ctrl mean statistically
	Mean	Std dev.	Mean	Std dev.	P value	same
1.2W	68.6	4.3	68.8	4.5	0.93	Yes
3.6W	187.8	2.2	187.7	2.4	0.96	Yes
7.2W	344.4	8.4	341.2	9.3	0.43	Yes
CCT						
	Test		Ctrl		2-T test	Test and Ctrl mean statistically
	Mean	Std dev.	Mean	Std dev.	P value	same
1.2W	3463.5	32.4	3480	36.8	0.3	Yes
3.6W	2916.5	19.4	2927.6	20.5	0.14	Yes
7.2W	2892.2	17.5	2909.1	19.9	0.06	Yes
Vf						
	Test		Ctrl		2-T test	Test and Ctrl mean statistically
	Mean	Std dev.	Mean	Std dev.	P value	same
1.2W	3.444	0.0151	3.44	0.0127	0.56	Yes
3.6W	9.998	0.0107	10.008	0.0163	0.08	Yes
7.2W	19.582	0.2	19.554	0.197	0.75	Yes

Table-13 2-sample T-test results for Lumens, CCT and V_f – Test is statistically comparable to Ctrl.

Summary				Start of project	at 11/30/2011	Reduction to date		Target in proposal (for milestone # 4)
				(arbitrary currency units)				(Reduction)
Phosphor				16	2	14		0
Yield				15	5	10		0
Labor				22	7.8	14.2		12
Chip	(Remain unchanged)			27	27	0		0
Other	(Remain unchanged)			20	20	0		0
Total				100	61.8	38.2		12

Table-15 Manufacturing savings at the accomplishment of Milestone-4. These have been listed for representative 1W VioTM package.

As can be seen from table-15, the overall manufacturing costs reduction due to the cumulative effect of tasks 1, 2, 3 and 4 is 38.2 currency units.

Task-5 Design and simulation testing of automated, large-scale manufacturing line

Task-5 has involved the development of a manufacturing design / plan to scale up the volume from the current 40,000 LEDs per month to 1,000,000 per month. This activity involved –

1. The detailed review of the equipment capacity currently available on the pilot line and ways to maximize the utilization of this equipment capacity.
2. Possible reconfiguration of the existing pilot line to improve utilization.
3. Market survey to identify new equipment / capabilities that could be used to replace / support the existing equipment. The goal of this exercise was to maximize the capacity available on the line while avoiding replicating the existing equipment capabilities and reducing capital equipment costs.
4. Development of detailed manufacturing models that show a ramp up to a volume of 1,000,000 LEDs per month. These models included manufacturing rate calculations as well as capital equipment costs needed for the scale up.

The proposal document discussed possible prototyping work that may have been necessary in case there were any significant hurdles in scaling up the existing Vio™ design. The only significant design modification that was evaluated involved the use of phosphor molded inserts as the remote phosphor element. The prototyping work for this activity was successfully completed in tasks-2, 3. No additional prototyping work was required in this task.

The scope for this part of the project was discussed in detail with 2 outside consulting companies. These partners were skilled in the manufacturing scale up of semiconductors and had significant experience in manufacturing scale up of pilot production. Proposals were received from both of these partners. After a detailed review a partner was selected to complete the manufacturing plan.

The partner split the task into 2 phases.

In phase 1, the partner evaluated the pilot manufacturing line. They understood the existing equipment capabilities in significant detail. They also completed a ‘gap analysis’ that highlighted short-comings in the existing equipment capability and the needs for a scaled up volume of 1,000,000 per month. As a part of phase 1 they also created a potential list of equipment / capabilities available in the market that could support the scale up.

In phase 2, the partner started creating manufacturing models that looked at different scale up scenarios. In addition, they also started putting more details around the equipment / capability needs highlighted in phase 1. They were able to narrow the list down to specific equipment / process recommendations. In conjunction with the scale up models, they were able to refine the equipment list to maximize the manufacturing rate while minimizing the overall capital equipment costs needed for the scale up.

At the end of this activity the partner was able to provide a detailed manufacturing plan (provided to the DOE as a deliverable). This plan document along with the associated models enabled the design for a pilot line scale up to 1,000,000 LEDs per month. This activity also provided guidance for capital equipment costs savings of over \$2 Million by potentially purchasing more efficient equipment highlighted in this study rather than replicating the existing equipment for volume scale up.

Task-5 reached a conclusion with the achievement of milestone-5 (3/30/2012). A manufacturing plan document was provided to the DOE as a deliverable supporting the completion of task-5.

11. Summary -

LED manufacturing costs savings summary

Summary		Start of project	at 3/31/2012	Reduction to date
		(arbitrary currency units)		
Phosphor		16	2	14
Yield		15	5	10
Labor		22	5	17
Chip		27	15	12
Other		20	15	5
Total		100	42	58

Table-16 Summary of manufacturing costs after completion of all tasks.

The manufacturing costs reductions due to various tasks have been highlighted earlier in the report. In this section 3 additional cost reductions are highlighted.

1. Additional costs reduction in labor due to activities in task-5 (additional ~ 2.8 currency units).
2. LED die costs reduction (~12 currency units). This could be possible due to the use of high efficiency Blue (450nm) LEDs in the same footprint as the VioTM LEDs. Given the high market penetration of Blue LEDs and multiple competing manufacturers, we expect this cost reduction to be as high as 44% as compared to the near UV LED (405nm) die costs. We have also demonstrated good reliability and performance using Blue LEDs in a remote phosphor configuration (figures-9, 10). We anticipate launching the high CRI, high lumen packages based on Blue LEDs in the near future.
3. Manufacturing depreciation costs reduction (~5 units). This could be possible as highlighted by work in task-5. We now have a design available that could be used for volume scale up without the associated linear increase in the equipment needed for scale up. The smaller manufacturing equipment footprint at this scaled up level would allow for lower manufacturing depreciation costs.

The total manufacturing costs reduction accomplished in this project meet the objective set forth in the proposal document.

LED performance and reliability summary

Tasks-2 and 3 have enabled the development of LED products that meet the performance, tight manufacturing distributions and reliability objectives set forth in the original proposal. This includes the accomplishment of LEDs approaching 95LPW in warm white CCT (table-8), LED products with manufacturing color distribution within 4 step MacAdam ellipses (Figure-6), reliability that demonstrates L70 of greater than 50,000hrs (Figure-7) and expected color shift of less than 2 step MacAdam ellipse after 50,000hrs (Figure-8).

The project work has been completed and all objectives highlighted in the original proposal have been met.