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“Arc Tube Coating System for Color Consistency”
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Executive Summary

DOE has enabled the use of coating materials using low cost application methods on light sources to positively affect the output of those sources. The coatings and light source combinations have shown increased lumen output of LED fixtures (1.5%-2.0%), LED arrays (1.4%) and LED powered remote phosphor systems – Philips L-Prize lamp (0.9%). We have also demonstrated lifetime enhancements (3000 hrs vs 8000 hrs) and shifting to higher CRI (51 to 65) in metal halide high intensity discharge lamps with metal oxide coatings.

The coatings on LEDs and LED products are significant as the market is moving increasingly more towards LED technology. Enhancements in LED performance are demonstrated in this work through the use of available materials and low cost application processes.

EFOI used low refractive index fluoropolymers and low cost dipping processes for application of the material to surfaces related to light transmission of LEDs and LED products. Materials included Teflon AF, an amorphous fluorinated polymer and fluorinated acrylic monomers.

The DOE SSL Roadmap sets goals for LED performance moving into the future. EFOI's coating technology is a means to shift the performance curve for LEDs. This is not limited to one type of LED, but is relevant across LED technologies.

The metal halide work included the use of sol-gel solutions resulting in silicon dioxide and titanium dioxide coatings on the quartz substrates of the metal halide arc tubes. The coatings were applied using low cost dipping processes.

Project Successes

DOE has enabled the use of coating materials using low cost application methods on light sources to positively affect the output of those sources. The coatings and light source combinations have shown increased lumen output of LED fixtures (1.5%-2.0%), LED arrays (1.4%) and LED powered remote phosphor systems (0.9%). We have also demonstrated lifetime enhancements and color shifting in metal halide high intensity discharge lamps.

The DOE SSL Roadmap sets goals for LED performance moving into the future. EFOI's coating technology is a means to shift the performance curve for LEDs. This is not limited to one type of LED, but is relevant across LED technologies.

The figure below shows the DOE SSL efficiency goals for Warm White LED Luminaire Efficacy along with the gains achieved by applying this technology from EFOI.

Figure 1. EFOI's coating could provide 6 months of the increases projected on the DOE roadmap.

The technology developed at EFOI works with LEDs and LED fixtures. The DOE outlines year over year efficiency goals for LED products. Most of the increased efficiency comes from the LED and its improvements in materials and architecture.

Some improvement can come from other items such as more effectively moving light out of the LED and fixture. This is the technology EFOI is affecting. These advances lessen the burden on basic LED technology improvements to meet the DOE goals.

LED Fixtures

EFOI selected one of its commercially available and sold LED based products for evaluation. This product includes a linear array of LEDs housed in a transparent plastic element. The plastic element provides a level of protection and support. Placed between the transparent element and the LED array is a layer of diffusing film.

The gains of 1.5% to 2% increased light output from the fixture were demonstrated at EFOI by applying an anti-reflective coating to the protective lens material of one of our LED fixture products. The coating is applied using a low cost dipping method. Several of the protective lens portions of the LED luminaire are shown here.

Figure 2. Protective plastic lens/cover for EFOI's LED luminaire

Coatings were applied to the transparent protective element. To clearly show the effect of the coating, portions of the protective element were coated with the material. An LED housed inside of the protective element was moved sequentially along while measures were taken. Figure 3 shown here illustrates the gains made due to the coating.

Figure 3. Demonstration of increased light output from EFOI's protective plastic cover with treatment of low RI coating. Increased output of light is 1.5-2.0%.

Our success in extracting more light from the LED fixture was demonstrated using an amorphous fluoropolymer manufactured by DuPont. The polymer is dissolved in an appropriate solvent making it easily handled and applied to the desired surfaces. The material is especially amenable to application processes such as dipping.

LED Coatings

Coating material was also applied to large array Cree LEDs. The choice of coating material was lower refractive index fluoropolymer. Shown here are the LEDs coated for this experiment.

Figure 4. Cree LED arrays used in coating experiment – Demonstrated a 1.4% increase in lumen output from the array with EFOI's coating.

The LEDs are manufactured by Cree and labeled as CXA2011 White XLAMP CXA LED Wt. After coatings were applied, measures were taken. The results are shown in the figure here.

Figure 5. Performance of LEDs coated with fluoropolymers

Six of the LEDs were coated with a fluoroacrylic solution. A second set of six were coated using Teflon AF amorphous fluoropolymer and the third set of six were left as uncoated controls.

The luminous output of Teflon AF coated LED arrays increased by 1.4% as compared to the uncoated LED arrays. The LEDs coated with an acrylic fluoropolymer showed degraded performance as compared to the uncoated control set.

Coatings for Remote Phosphors - Philips L-Prize Lamp

Philips remote phosphor lamp provided a good test bed for EFOI's coating technology. The light transmitting portions were coated with the same material used on EFOI's LED lamp. The lamp treated is shown here.

Figure 6. Philips L Prize lamp used in our testing

The LED lamp is shown on the coating equipment in the figure below.

Figure 7. Philips L Prize lamp with EFOI's coating equipment

A summary of the testing results are shown here.

Figure 8. Performance of uncoated and coated Philips L Prize lamp

The lamp was illuminated for 60 minutes, allowing the lumen output to stabilize. The initial measure for the lamp without an EFOI coating was approximately 984 lumens. The plastic portions of the lamp were then coated using amorphous fluoropolymer Teflon AF. After coating, the lamp was measured again under the same conditions as the initial measure. The output increased to approximately 994 lumens, giving an increase in lumen output of approximately 0.9%.

Coatings for Metal Halide HID Lamps

We have demonstrated a positive effect on the lifetime of metal halide arc tubes with metal oxide coatings. The figure below summarizes the results of the life testing. Several of the coatings in two different material systems have beneficial effects on lamp life.

Coatings Life Summary	Tested to:		Coating Runs				Median Life	
	Starts	Hours					Starts	Hours
Successful	12000	10000	TaO ₂	Ta ₂ O ₅ /SiO ₂ #1	Ta ₂ O ₅ /SiO ₂ #2	Sn	6000	8000
Borderline	12000	10000	Si	ZrO ₂	Control_Pre-clean	TiN	3500	5000
Failure	8000	6000	Si ₃ N ₄	SiO ₂	SiO ₂ /Si ₃ N ₄	Ta	2000	3000
			ZrO ₂ /SiO ₂ #1	Al	AlN	Al ₂ O ₃		
			Ta ₂ O ₅ /SiO ₂ #3	Ta ₂ O ₅ /SiO ₂ #4	ZrO ₂ /SiO ₂ #2	Zr		
			Ti	TiO ₂	Control_Baseline			

Figure 9. Condensed summary of life effects for the coating matrix tested by EFOI. The 8000 hour life is not representative of the results of the proposed effort.

Three coatings have little or no effect while fourteen have a detrimental effect. We successfully demonstrated the color manipulation of metal halide high intensity discharge lamps through the use of selected metal oxide coatings produced using sol-gel solution and dipping technology.

We have also demonstrated manipulation of CCT and CRI with metal oxide coatings on 400W metal halide arc tubes.

	CCT	CRI
average coated	4615	64.9
average uncoated	5406	51.6

Figure 10. Data comparison from coated and uncoated 400W arc tubes

It is seen that the set of arc tubes that were coated have a higher CRI and have lower CCT values compared to the uncoated arc tubes.

Suggestions for Additional Work

During the proposal preparation stage and at the onset of this project, EFOI was producing technology based on metal halide HID light sources. It was recognized at that time that LED technology was rapidly moving forward with efficiencies increases dramatically. LED efficiencies have increased from an estimated 60 lumen per watt (lpw) to 120 lpw and more.

The technology EFOI was exploring was particularly relevant to HID sources with high temperature surfaces close to the arc that were amenable to metal oxide coatings, especially coatings with some effect on the spectral output of the lamp. Lifetime of these lamps has also been extended by the application of metal oxide coatings to the arc tubes.

The technology we have developed, particularly the application of metal oxide films to silica surfaces has relevance to screw base halogen IR sources. AR layers applied to these sources can enhance the light output of the device, making it more efficient. Additional work can be beneficial to create processes and match materials to enhance these lighting devices.

It is recognized now that LEDs hold a prominent place in the world of lighting and will continue to expand in importance as we move into the future. In contrast, HID lighting has experienced more modest growth.

The lighting market has made a marked shift towards LEDs. In response, we expanded the scope of development to include LED sources and have thus opened up additional technologies that can be applied to enhance the output of light from the LED light source. Enhancement of LED sources is where the most benefit per dollar is found, not so much with the enhancement of metal halide sources.

We have demonstrated an increase in light output from LED fixture components by applying AR coatings to the light transmitting surfaces. In EFOIs case, we applied

coatings to the surfaces of a hollow plastic protective element. This is one of many possible shapes associated with LED light transmitting surfaces.

The lenses and other packaging of LED products come in various shapes and sizes. It would be of benefit to reconfigure the tooling and processes to make use of this technology for applying coatings to the different components of LED fixtures.

We have demonstrated a small segment of application for this technology. There are many LED based devices, seemingly nearly all of which could benefit from the use of EFOI's technology. In each case, some optimization would likely be required for applying coatings on the required pieces in the proper manner. The optimization would require the identification of the proper equipment for applying the coating and the appropriate coating materials to elicit the greatest benefit.

As LED performance continues to improve, it is likely that companies will expand their production and offerings of LED based lighting products. Inclusion of EFOI's technology on production lines may be desirable. Equipment can also be developed for placement on LED fixture factory floors for coating of components as they come directly off the production line. Adoption of this technology would require the manufacture of specific equipment pieces to conform to the produced components.

Additional effort needs to be directed to optimizing coatings for various shapes and forms associated with the light transmission portions of LED based devices.

Key points on additional work.

1. Expand investigation of materials – EFOI has evaluated a limited palette of materials, metal oxides and fluoropolymers. Other materials within these two groups may find wider spread or more specific enhanced benefits. EFOI has defined a solution for high temperature applications like MH and low temperature applications like LED fixtures. There are more material solutions that should be investigated.
2. Evaluate other coating application processes – EFOI made use of low cost dipping type coating approaches. Further investigation and evaluation of other low cost coating methods should be carried out.
4. Optimize coatings to surfaces – Coating flat and smooth surfaces is less problematic than curved surfaces or surfaces with abrupt changes. Investigations should be made into coating non-curved and featured surfaces.
5. Equipment development – For large scale application of coatings on production pieces, coating equipment will need to be designed and developed. The equipment would be designed for applying coatings to a specific part that would be fabricated into a lighting fixture.

6. Optimizing coatings with LEDs – EFOI demonstrated that applying coatings to LEDs can be beneficial. We provided a single solution to this application. Further work should be done to identify additional materials and coating methods to enhance LED performance.

Details for LED Applications

LED Fixtures

One of EFOI products sold into the US military is a linear LED arrangement housed in a clear plastic protective element. Coatings applied to the clear plastic element have increased light throughput by 2%. The clear plastic elements are shown here with diffusing films inserted.

Figure 11. Clear plastic elements for protective covers of EFOI's LED lamps

This component is shown as an example of LED related fixture devices that could benefit the technology developed in this project.

A low refractive index coating was applied to both the inner and outer surfaces of the hollow plastic element. In the case of the measurement only a portion of the protective element was coated.

To evaluate the effectiveness of the coating, a single LED was used as the light source inside of the plastic element. The single LED was moved in increments of 5mm from the open end further into the element. This was done over approximately 15cm. The coating extended from the end of the element to approximately 10cm from the end. The

apparatus was placed in an integrating sphere and light output measures were taken at each increment.

This process was repeated for twelve protective elements. Of those twelve protective elements, six had received coatings while six were uncoated. Of the protective elements receiving coatings, there was also a portion of the protective element that remained uncoated and was also measured.

The data is shown here.

Figure 12. Lumen output through EFOI's protective plastic element – coated and uncoated portions

The orientation of the protective element is shown here.

Figure 13. EFOI's protective plastic element with coating applied to left hand portion

The red line at the bottom of the chart shows the lumen output measures of the uncoated protective element. The lumen output measures at an average of about 18.45 for the six protective elements measured.

The upper blue line shows the lumen output measures of the protective elements with coatings. As is seen the output is higher over the coated portion of the protective

element. When the light source reaches about 130mm, the average of the six protective elements with coatings is within the region of the measures of the protective elements with no coating. Beyond approximately 130mm where the protective elements have no applied coating, the measured values overlay each other.

Averages and standard deviations were calculated at each measurement point for the protective elements with and without coatings. At each measurement point, a t-value was calculated. The green line shows the calculated t-value at each measurement point. The dashed black line near the bottom shows the Critical t-value at a 95% confidence level. When the calculated t-value is higher in value than the critical t-value, the means can be considered statistically different. When the calculated t-value falls below the critical t-value, then the means can not be considered statistically different at the 95% confidence level.

It is seen that over the region coated, the difference between the coated portion and the uncoated portion is statistically significant. The difference amounts to approximately 1.5% up to a 2% increase in light output in areas with the applied coating.

The increase light output at the different measurement points is shown in the figure here.

Figure 14. Increase of light output from EFOI's protective plastic cover with treatment of low RI coating. Increased output of light is 1.5-2.0%.

The fall off in the region between 110 and 130mm is due to the difference in coating coverage at the “deeper” portion of the protective element.

Additional coated protective elements are shown here.

Figure 15. EFOI's protective plastic element with coating applied. The colored areas show the applied coating.

The multicolored areas on the protective element are where the coating has been applied. The multicolor effect comes from the interference pattern of light as a portion is reflected back through the coating.

Coatings of metal oxide were also applied to the hollow plastic protective elements. Four of these protective elements are shown here.

Figure 16. EFOI's protective plastic element with TiO₂ (upper pair) and SiO₂ (lower pair) coatings applied.

The two upper examples were coated with titanium dioxide. The lower two examples received a coating of silicon dioxide.

Figure 17. Lumen output for before and after coating of plastic protective elements using TiO2 (l), SiO2 (r)

Applying metal oxide coatings to the plastic protective elements did not enhance light output of the device. The TiO2 coated protective elements experienced less reduction in light output than the SiO2 coated protective elements.

LED Coating

Coating material was also applied to large array Cree LEDs. The choice of coating material was lower refractive index fluoropolymer. Shown here are the LEDs coated for this experiment.

Figure 18. Cree LED arrays used in coating evaluation

The LEDs are manufactured by Cree and labeled as CXA2011 White XLAMP CXA LED Wt. A description from Mouser is shown here.

Figure 19. Data summary for the Cree LED arrays used in evaluation

After coatings were applied, measures were taken. The results are shown in the figure here.

Figure 20. Cree LED array performance with coating type

Six of the LEDs were coated with a fluoroacrylic solution. A second set of six were coated using amorphous fluoropolymer and the third set of six were left as uncoated controls.

The luminous output of Teflon AF coated LED arrays increased by 1.4% as compared to the uncoated LED arrays. The set of LEDs coated with fluoroacrylic polymer showed a lower mean lumen output. It is possible that the ethyl acetate solvent used in this solution adversely affected the LED.

Coatings for Remote Phosphors - Philips L-Prize Lamp

Philips remote phosphor lamp provided a good test bed for EFOI's coating technology. The light transmitting portions were coated with the same material used on EFOI's LED lamp. The lamp treated is shown here.

Figure 21. Philips L Prize lamp used in our testing

The LED lamp is shown on the coating equipment in the figure below.

Figure 22. Philips L Prize lamp with EFOI's coating equipment

A summary of the testing results are shown here.

Figure 23. Performance of uncoated and coated Philips L Prize lamp

The lamp was illuminated for 60 minutes, allowing the lumen output to stabilize. The initial measure for the lamp without an EFOI coating was approximately 984 lumens. The plastic portions of the lamp were then coated using amorphous fluoropolymer Teflon AF. After coating, the lamp was measured again under the same conditions as the initial measure. The output increased to approximately 994 lumens, giving an increase in lumen output of approximately 0.9%.

Material Choices for Coating

Different classes of chemicals can be used for application of coatings on substrates. Even with the limitations of optical clarity and durability, there are several options available. We have explored both inorganic and organic options.

The inorganic materials were silicon dioxide and titanium dioxide. These two materials are amenable for making sol-gel precursors and applying the sol-gel to the substrate and then curing the material. Each of the materials has unique properties making them useful in different ways for optical coatings.

The sol-gel process uses metal alkoxides and volatile alcohol as a solvent. As the solvent is removed, the metal alkoxides condense to form extended networks of metal oxides. Heat is used to drive off any remaining solvent and to finish the conversion of alkoxide to oxide, thus compacting the film.

A reaction scheme for the condensation of the alkoxide to a titania network is shown here. This reaction scheme can be generalized to include the formation of silicon dioxide (silica) coatings as well.

The first step is the hydrolysis of the alkoxide. This diagram shows each of the alcohol groups being removed, but this is not required to occur before condensation and network creation can occur.

Figure 25. Condensation reaction, eliminating water

The coating solution is applied to the substrate by dipping the substrate into the solution, then removing the substrate from the solution at a measured rate. The liquid coated substrate is held out of the solution and allowed to dry. As the solvent evaporates, the materials in solution concentrate, forcing the titanium hydroxide molecules together, breaking the stable colloid. The metal hydroxide molecules then combine as shown here.

In the specific case shown, as the condensation reaction proceeds, titanium hydroxides condense with themselves forming extended chains. As the chains extend, the multiple reactive sites on the titanium center create many branched chains, resulting in a highly cross-linked network. The network continues in all directions and becomes the thin

layer film on the substrate surface.

Silicon dioxide has a refractive index (1.46) in the range of typical optical plastics like acrylic and polycarbonate. Titanium dioxide has a higher refractive index (2.49-2.61) than typical optical plastics depending on the phase composition of the material.

Low RI coating materials

Organic materials of interest are fluorinated components. Due to the incorporation of fluorine, these materials often have lower refractive indices (1.33-1.40) as compared to the typical plastics used in optical components.

We selected several fluorinated acrylic monomers for evaluation along with an amorphous Teflon polymer in a fluorinated solvent.

Teflon AF is shown here. This is a low refractive index fluorinated polymer produced by DuPont.

Figure 27. Teflon AF material supplied by DuPont

The material possesses several useful properties. The polymer is soluble in suitable solvents, making it useful for application to surfaces in thin layers. The figure below illustrates additional advantageous aspects of the material.

Figure 28. Properties of Teflon AF: %Transmission (l), Refractive Index (c) and Coefficient of Thermal Expansion (r)

http://www2.dupont.com/Teflon_Industrial/en_US/products/product_by_name/teflon_af/properties.html

Teflon AF has a % transmission over 90% for the entire range of visible wavelengths of light. The transparency extends well into the near infrared. Transmission drops at shorter wavelengths, particularly in the region less than 200nm.

The material has a low refractive index, around 1.315 at 100C. The coefficient of thermal expansion is steady at about 300ppm/C.

Various fluorinated acrylic based monomers were selected for evaluation. These materials can undergo free radical polymerization to create higher molecular weight fluorinated polymers. The polymers can be made in solution, providing a means for easy application of the polymer in solution so substrate surfaces.

Figure 29. Fluorinated acrylate and methacrylate monomers

Several variations of fluorinated monomers were obtained. An example of a properties sheet for one of the selected monomers is shown here.

2,2,3,3,4,4,4-Heptafluorobutyl methacrylate
97%

◆ [DOWNLOAD MSDS \(PDF\)](#)
Synonym: HFBMA

CAS Number 13695-31-3 | Linear Formula $\text{H}_2\text{C}=\text{C}(\text{CH}_3)\text{CO}_2\text{CH}_2\text{CF}_2\text{CF}_2\text{CF}_3$ | Molecular Weight 268.13
EC Number 237-217-7 | MDL number MFCD00039251 | PubChem Substance ID 24868094

POPULAR DOCUMENTS: [FTIR \(PDF\)](#)

Properties

Related Categories	Acrylic Monomers, Fluorinated Acrylics, Fluorine-Containing Monomers for 157 nm UV Lithography Resist Polymers, Lithography Monomers, Low Refractive Index Monomers, More...
assay	97%
refractive index	$n_{20\text{D}}$ 1.341 (lit.)
bp	134-136 °C (lit.)
density	1.345 g/mL at 25 °C (lit.)

Figure 30. Date summary of a fluorinated acrylic monomer

The key property shown on this page is the refractive index of the material given at 1.34.

Advantages to Coating Approach

The dip coating process has several advantages particularly for LED based applications. The coating is conformal. This has the advantage of not interfering with the design benefits of LED lighting. The coating can be confined to lenses and other light transmitting portions of the fixture. Coatings are thin and should not add significant thermal barriers if the coated portion is included in the thermal heatsink path.

The coatings evaluated here are nonconductive. Unlike ITO coatings, these coatings will not interfere with radio transmissions. This is of concern since lighting fixtures are expected to contain more functionality and communication capability with future developments.

The dipcoating technology is a lower cost path for applying coatings. This approach may be particularly beneficial for companies that produce lower margin products and would benefit from the enhanced light output.

Coating Equipment Details

A coating station was manufactured to apply coatings to pieces using a dipping process. The machine allows the user to perform several functions from applying the coating to heating it in place to provide a post application cure.

The equipment fits on a bench top and allows for some variation in shape to be coated. The figure here shows the coating equipment on a benchtop. The equipment requires 230V single phase electricity and compressed air to operate.

Figure 31. Bench top coating equipment

The coating bench has three primary sections of operation – the dipping stage, manipulator arm and curing stage.

The actual coating station in the equipment consists of a well for holding the coating material and a manipulator for holding, lowering and raising the object to be coated.

The liquid coating material is placed in the well. The well is a stainless steel vessel that is approximately 1 liter in size. Material selection for the well construction is of importance since some of the coating materials conceived in this project can be reactive over extended periods of contact.

Figure 32. Coating solution well of the coating station

The well possesses a cover to place over the opening when not in use. This allows for short term storage of coating materials in the well particularly between coating applications. Some of the coating materials may have more volatile components that could escape the vessel if it is not covered.

The well has an internal diameter of approximately 2.75 inches and is approximately 9 inches deep which is very useful for metal halide arc tubes and LED arrays. Other well designs can be used to accommodate coating of parts of other size and scale.

The component to be coated is held in place using a clamping device. This is shown in the figure here.

Figure 33. Clamping device to hold parts in place for coating

The clamping device holds the component to be coated in place while the coating operation is performed. The “jaws” of the clamping device are detachable and can be changed to accommodate different sizes and shapes of components.

The “jaws” are opened and closed using an air actuation system. The valve set for controlling the opening and closing action is seen in the upper left portion of the fiber directly above the label “OPEN/CLOSE”. Moving the lever up opens the clamp while moving the lever down closes the clamp.

The clamping device is also configured to move upwards and downwards providing the dipping and withdrawal action. The air actuator for this motion is shown in the figure above the “open/close” actuator.

Figure 34. Controls for opening and closing clamps and for raising and lowering parts for coating

The up and down travel is powered by compressed air in a piston type assembly. The assembly is shown here. The long, slender piston is located on the top of the clamping mechanism.

Figure 35. Piston assembly for vertical motion

The length of the piston provides a limit to the vertical travel of the dipping mechanism. If cases are encountered where a further dipping extent may be required, a different piston could be installed. The piston is spring loaded such that when no air is applied to the cylinder, the mechanism defaults to the “up” position.

One of the critical features for applying coatings using a dipping approach is the uniform withdrawal rate of the component from the coating solution. Compressed air provides a good solution for controlling withdrawal rates and for giving a smooth withdrawal of the component from the solution. The withdrawal rate is controlled by manipulating the air pressure. High air pressure gives a faster withdrawal rate than lower pressures. The pressure can be finely controlled using the air pressure regulator mounted on device.

The air input to the coating device is shown here. This portion contains a master on/off for the gas input, the pressure regulator and oil bubblers.

Figure 36. Reverse side of coating station showing air input location for powering vertical and clamping motions.

The air regulator is mounted on the back side of the equipment. We are currently making use of “house” air as an input. The equipment could be operated more remotely using compressed gas cylinders.

The equipment also has a heating station for post curing of the coating materials. The heating station may be used to drive off volatile components or provide heat to promote polymerization or polymer chain cross-linking reactions.

The heating control station and the heating chamber are shown here.

Figure 37. Coating station heating arrangement for curing.

The heating control is done through the use of a Watlow controller. This controller provides a user friendly interface for selecting adjusting temperature setpoints and monitoring the temperature in the heating chamber.

The heating elements are shown here.

Figure 38. Heating elements within the heating station

The heating chamber is composed of four ceramic based heating elements. The elements are arranged to provide radiant energy from four sides of the object being treated. The arrangement is a compromise, since the heat application may not be strictly uniform in this configuration but is good for the elements used.

The heating station has a wide temperature range, from 100F to 600F. This range allows us to operate with a broader palate of coating materials from organics to inorganic materials.

Figure 39. Heating station controller

Shown here is the heating element operating at 586F. The heating elements have a relatively fast response time, requiring approximately three minutes to reach 500F.

Market Introduction and Technology Transfer

As CTO for EFOI, Roger Buelow is active with seeking out and contacting companies that have similar, compatible or synergistic technologies both as possible partners and customers. He is active with DOE areas, attending the DOE SSL R&D Workshop and the Strategies in Light in 2013.

Specifically for this project, he has made contact with lamp manufacturers, including GE, Cree, Osram and Philips. He also talked with a few start up companies, including Next and Lucidity. These all could be perspective users of the technology. He reviewed how the technology could fit into the DOE roadmap and the types of fixtures in the NGLIA portfolio. He believes there are good fits for this technology as it could allow these manufacturers the ability to improve output by 2-4%.

Film Thickness

The ideal and minimum film thickness for an AR film is a $\frac{1}{4}$ wavelength of light at the desired wavelength. Since we are concerned with the visible spectrum, we can center the best performance at about 600nm. With that constraint, the ideal film thickness would be 150nm. For a square meter of surface, this would equate to 1.5×10^{-7} m³ of material or 0.15 ml per square meter of surface.

The protective plastic element shown for EFOI's LED lighting product has an outer surface area of approximately 125 in². The inner surface area is approximately the same. Combining both surfaces, the total surface area is approximately 250 in² or 0.16 m². This surface area would require $0.16 \text{ m}^2 \times 0.15 \text{ ml/m}^2$ or 0.024ml of material for an optimal coating.

The coating area for the L Prize lamp is only about 6 square inches, assuming a coating is applied to both the inner and outer surfaces of the light transmitting phosphor loaded plastic components. Six square inches is approximately 0.004m². Coating the light transmitting portions of the L Prize lamp requires approximately 5.8×10^{-4} ml of polymer for an optimal coating.

Metal Halide Arc tubes

The initial steps in this project are the installation of specific pieces of equipment for the measuring of metal halide arc tubes and the application of a coating to the tube.

For the initial work, arc tubes were obtained from Venture Lighting Inc (VLI). These are 400W metal halide PulseStart light sources. This style of arctube forms a large market

segment for VLI. These lamps find widespread application in light fixtures used in the illumination of large indoor industrial and warehouse spaces. These lamps also find application in outdoor street and space lighting. The arc tube configuration selected for this work is not flame coated with diffusing material.

VLI uses this arc tube in several lamp configurations. The differences in lamp design are in the base and shape of the glass envelop. Shown here is the data sheet from a 400W lamp design commercially offered by VLI. This is their popular PulseStart arc tube that is used in several different lamp package offerings.

VENTURE
LIGHTING
UNIFORM
PULSE START METAL HALIDE LIGHTING SYSTEMS

400 Watt

Pulse Start Lamp

73531

DATA SHEET

Vertical ±15°

ED37

Dia. = 4.6" (120mm)
MOL = 11.5" (292mm)
LCL = 7.0" (178mm)
Base = Mogul (E39)

MS 400W/V/PS/740

GENERAL Characteristics

Lamp Type	MH Pulse Start Single Ended
ANSI Code	M135, M155/E
Bulb Shape	ED37
Base Type	Mogul (E39)
Bulb Finish	Clear
Rated Life	30000 hours
Operating Position	Vertical ±15°
Dimming	50% Rated Power

PHOTOMETRIC

Initial Lumens	44000
Scotopic Lumens (S/P 1.7)	75000
Lumens Per Watt	110
Lamp Lumen Depreciation (LLD)	.86 (86%) @ 8000 hours
Correlated Color Temperature	4000K
Chromaticity Coordinates (CIE-x,y)	.385 .390
Color Rendering Index (CRI)	68

PHYSICAL

Bulb Diameter	4.6" (120mm)
Max. Overall Length (MOL)	11.5" (292mm)
Light Center Length (LCL)	7.0" (178mm)
Effective Arc Length	43.9 mm
Max. Base Temperature (°C)	210
Max. Bulb Temperature (°C)	400
Socket Pulse Rating (KV)	4
Luminaire Type	Enclosed Rated

ELECTRICAL

Lamp Watts	400
Lamp Oper. Voltage (Nom.)	135

SUSTAINABILITY

Recycling Program	Smartpac® 800-451-2606
Picograms Hg per Mean Lumen Hour	35
MR-Credit 4: Reduced Mercury in Lamps	1 LEED point
EISA 2007 Compliant	Yes

NOTES

Lamp performance ratings published in this data sheet are based on operation with approved electronic ballasts. Performance of position-rated lamps outside of their tolerances will result in poor performance. Minimum Starting Temperature: -40°C/-40°F. To calculate nighttime Scotopic lumens, multiply the lumen rating by the S/P ratio. **LEED V3, MR CREDIT 4: Sustainable Purchasing - Reduced Mercury in Lamps is awarded 1 point for projects which at least 90% of all mercury-containing lamps purchased during the performance period comply and meet the target for mercury content of 90 picograms per lumen-hour or less.

Spectral Distribution

Lumen Maintenance

(800) 451-2606
or (440) 248-3510
 Fax: (800) 451-2605
 10295 Philipp Parkway
 Streetsboro, Ohio 44241 USA
 E-mail: venture@adlt.com
VentureLighting.com

THIS LAMP CONFORMS TO FEDERAL STANDARD 21 CFR 1040.30

Warning: This lamp can cause skin burns and eye inflammation from shortwave ultraviolet radiation if outer envelope of the lamp is broken or punctured. Do not use where people will remain for more than a few minutes unless adequate shielding or other safety precautions are used. Lamps that will automatically extinguish when outer envelope is broken or punctured are commercially available.

This Product is Recyclable Through Smartpac

VLI-0992551-0710

Figure 40. Product data sheet for Venture Lighting 400W Pulse Start Lamp

The color distribution of Metal Halide lights is known to be relative broad in comparison to other lighting technologies such as Ceramic Metal Halide (CMH), Halogen and LED systems. The reduced lamp to lamp color consistency of metal halide lights can limit their use in applications that require a more uniform color between lamps.

Figure 41. Graphic description of color variation with different lamp types and anticipated outcome of this project.

The objective is to improve Metal Halide color variation into a single MacAdam ellipse with automated spectrophotometry and application of cost effective coatings with plant self correction mechanisms. The general process is shown below.

Figure 42. Outline of lamp measurement and coating steps

Commercial Considerations

It was important to identify a suitable vehicle to demonstrate and commercialize this concept. We felt the best fit was with the higher voltage metal halide high intensity discharge (HID) lamps. This would include lamps in the general range of 320-400W. Other higher wattage lamps may be considered and cases could be made for lower wattage lamps as well, depending on their market volumes.

Creating color corrected/matching HID lamps will facilitate wider installation of the more energy efficient HID systems. The higher wattage lamps have a wide commercial installation base with a significant untapped market. The goal is the displacement of fluorescent tubes in commercial spaces where energy performance is the primary selection criteria. This can expand the HID manufacturer's market base.

Adding the color correcting coating to a lamp will increase the price of the lamp to the end user. The coating will constitute a fraction of the lamp cost and will add the same cost to a 150W bulb as it would to a 400W bulb. At the higher base price, the added coating cost is a lower fraction of the finished bulb cost.

We have identified a suitable HID commercialization partner in Venture Lighting (VLI) in Solon, OH. They have agreed to work with us on this project to the extent possible without being a subcontractor on the effort.

VLI has agreed to assist us on several fronts. They have agreed to identify and have identified a good candidate product of theirs for this work. This product, the 400W Pulse Start arc tube, will be discussed in more detail later. VLI agreed to supply us with 700 arc tubes for evaluation and will finish about 50% of those into completed lamps. They will also take 0hr, 100hr and 1000hr photometry on those finished lamps. VLI will lifetest 30 lamps to 1000 hrs, 20 lamps to 10,000 and 10 lamps beyond 10k hours to end of lifetime. They will also assist in writing specifications for an equipment station for photometry and coating that would be compatible with the current Venture equipment group. We also have a single point of contact within VLI who is in charge of VLI efforts on this program.

Individual arc tubes are shown below with a ruler for a reference scale. The “active” portion of the arc tubes is about two inches long and the over all tube is about six inches long, including the wire leads. The body of the arc tube is about an inch in diameter. The individual tubes shown here have not been “burned” so are still clear and appear very clean. The metal halide salts are still in pellet form and have not vaporized and recondensed on the interior of the arc tube.

Figure 43. Arc tubes from Venture Lighting – 400W Pulse Start arc tubes.

A pan containing additional arc tubes is shown below. These are all 400W arc tubes similar to those shown above. These arc tubes have been “burned” and the metal halide salts have vaporized and condensed on the interior of the arc tube bodies giving them a cloudy, hazy appearance.

Figure 44. Several 400W Pulse Start arc tubes from Venture Lighting for use in measurement and coating development.

We have received 30 400W PulseStart arc tubes from VLI for the development of fixturing for the measurement station and the coating station. We have ordered and additional arc tubes to run initial samples through the measuring and coating stations. We worked with both tipped (made in Solon) and non-tipped (made in India) arc tubes for evaluation of process and product.

Measurement

The measurement station consists of a large, 2 meter diameter, integrating sphere. The integrating sphere is large, due to the physical size and power output of the 400W metal halide arc tube. The output of a 400W arc tube operating at 400W has an initial lumen output of 30,000 lumens. The large sized sphere is needed to measure an integrated value of light output and to avoid overloading the sensor array in the detection equipment. The measurement sphere is shown here.

Figure 45. Integrating sphere for use in this project.

This sphere uses a CCD detector and allows the examination of energy per wavelength of light in spectral range between 350 and 1050nm. The data collection for the sphere is controlled using a desktop computer loaded with Labsphere SLMS software.

Additional fixturing is required for measuring 400W arc tubes in the sphere. The portion of the fixturing that holds the arc tube resides within the measuring sphere. Wire leads connect the arc tube holder with the ballast and power controller that resides outside the sphere. Test fixturing was fabricated to hold the arc tubes in place while testing the light output when the tube is powered. The fixturing requires support structure and power to the tube.

Figure 46. Arc tube fixture, made up of high voltage high temperature wires and ceramic standoffs

The fixture consists of heavy duty clips to hold the arc tube leads, a mounting means with ceramic standoffs to insulate the power leads from the mounting structure. This structure is mounted to a plate located near the center of the measurement sphere.

Figure 47. Closeup of arc tube in fixture mounted in the sphere

The lamp is mounted in the sphere using the fixturing shown above. The power leads are seen moving down, out of the picture. The clips allow for easy insertion and removal of the lamp after measurement.

Figure 48. Mounting assembly and arc tube in the sphere

The arc tube is mounted near the center of the integrating sphere. A glass cover is used to cover the arc tube during operation within the sphere. This protects the inner sphere surfaces and the operator in the event of a non-passive tube failure.

Figure 49. Arc tube with glass cover inside the measurement sphere

Once mounted in place, the sphere is closed, the arc tube is powered on and the measurement is taken. This procedure approach adds an additional layer of safety for the operator in the event of tube failure and exposure to excessive high energy (<400nm light).

Due to the high light output of the 400W arc tube, measurement parameters have been tuned to accommodate. The integration sphere uses an iris to at the detector location to reduce the amount of light reaching the detector without affecting the wavelength power distribution. The iris size and corresponding exposure time have been tuned to provide suitable measures. The measurement system can also take multiple measurement scans of the same lamp and average those scans to a single data output. This averages out noise associated with the measurement.

The arc tubes require additional electronics to power them. Electronic components are shown here.

Figure 50. Venture Lighting 400 Watt Pulse Start ballast

The 400W arc tube uses Venture Lighting's 400 Watt Pulse Start Ballast to provide properly conditioned power to the unit. Power is delivered to the ballast using a power meter and Variac. This allows for a standard setting of power input to the ballast/arc tube system.

Figure 51. Power meter and Variac setup for power controlling

The above figures illustrate the electrical components wired together but not organized in a final long term arrangement.

Metal Halide HID Concerns

Due to the construction and function of metal halide lamps, the output color (and CCT) varies over time as the lamp is powered up. This is due to the heating and evaporation of the metal salts and, in the longer term, chemical reactions of the salts.

Measures would best be taken on a “warmed up” lamp, one that had been powered for a significant amount of time. An ideal warm up time is about 100 hours. At this time, the short term effects have stabilized and the lamp is quite consistent. However, this amount of warm up time is not practical for this effort due to the time required and the physical effects on the arc tube, such as electrode oxidation.

Show on the graph below is an example of lumen and CCT variation of a 400W arc tube as is powered up and held over a short amount of time.

Figure 52. CCT and lumen variation over time for an HID metal halide lamp

The graph shows data from 0 to 50 minutes. The lumen scale is on the left for the dark blue line and the CCT scale is on the right for the purple/brown line. The change is dramatic over the first two minutes for both measures, then levels for lumen output and climbs for the following approximately 18 minutes for the CCT measure. At 20 minutes, both measures are relatively stable. The ideal evaluation measurement occurs in the first 5 minutes of operation.

Spectral Database

The software utilized for measurement of the spectral distributions from the arc tubes is LabSphere SLMS software. The software displays the power output per wavelength from 350nm to 1050nm. The data is exported from the SLMS software in a format that can be further manipulated in Microsoft Excel. This arrangement is convenient since the measurement software and data manipulation software can reside on the same computer. With the appropriate software, the analysis and feedback processes can be automated, significantly reducing the need for operator interaction.

A computer has been identified for dedicated use on this system. The number of files stored on the computer is limited by the disk capacity. It is also possible to use the computer for spectrum scanning and data manipulation while storing the data files on a non-local server.

Shown here is a scan from an uncoated 400W arc tube generated using our measurement system.

Figure 53. Scans of a new 400W arc tube taken in the measurement sphere

The scans were taken on a new arc tube at three different times. Each scan closely overlays the others.

MH Arc Tube Coating

Our primary path is to utilize the application of sol-gel solutions on the glass arc tube substrate to deposit metal oxide films onto the surface. Different processing options exist for application of sol-gel to a substrate. The four widely used sol-gel application methods include 1) dip-withdrawal, 2) spin-coating, 3) meniscus coating, and 4) spray/flow application. The most sensible approach for this work is the dip-withdrawal method. The other approaches mentioned are more amenable for applying coatings to flat surfaces. Spin coating for example, can efficiently produce multilayer coatings without material cross-contamination. Meniscus coating is also cost efficient and would work well for flat and rectangular parts, and is amenable to multilayer coatings. Spray or flow application is a well known coating method when sensitivity to thickness errors is low. All are scalable to high volumes and high throughputs. However, only the dip-withdrawal method is suitable for non-flat surfaces and sufficient layer thickness control. Shown here are depictions of two coating approaches, dip-withdrawal and meniscus.

Figure 54. Two sol-gel coating approaches, a) dip-withdrawal and b) meniscus

Depending on the deposition process, sol-gel coating thickness is a function of the velocity with which the substrate moves past the deposition zone. The relationship shown here is the Landau-Levich equation and describes the film thickness as a function of several variables. The coating thickness is proportional to the 2/3 power of the

$h = \frac{0.94 * (\eta * v)^{(2/3)}}{\gamma^{(1/6)} \rho^{(1/2)} g^{(1/2)}}$	<p>h: film thickness η: gel viscosity v: withdrawal speed</p>	<p>γ_{lv}: surface tension ρ: sol-gel density g: acceleration of gravity</p>
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Figure 55. Landau-Levich equation describing applied film thickness.

velocity but must be empirically determined for each production setup and solvent batch by a calibration procedure since the thickness is also dependent on viscosity, solution density and the surface tension of the material. The full formula is illustrated.

The coating station consists of a container holding the sol-gel solution, a linear actuator that is remotely controlled using a computer interface and fixturing to hold the pieces being coated. The linear actuator component is shown here. This device is controlled by a computer that allows inputs for several different parameters. The key factors involve the distance the arms travel up and down the height of the device and the speed at which that occurs.

Figure 56. Linear actuator component dipping and withdrawal equipment

The linear actuator is shown with the arms lifted to the highest point. The upper stopping point and lower stopping points are programmed into the device using the computer interface. This provides for sufficient movement to immerse the arc tubes to a sufficient level in the coating solution to cover the relevant areas of the tubes with the coating.

The arc tubes are held in fixtures as depicted below.

Figure 57. Fixture design for coating multiple arc tubes

The arc tubes are held in a series for coating in the sol-gel solution. This configuration can be extended to expand the number of arc tubes coated at one time. The fixturing can also be reduced to allow for coating of individual arc tubes.

Figure 58. Fixture for single arc tube coating

The image shows the nature of the fixture and how each arc tube being coated has a specific location on the fixturing. This provides suitable positioning of the arctubes for each to receive an uninterrupted coating of material. The fixturing is specific for the size of the 400W metal halide arctube. Other sizes of arctubes can be used, but would require size specific tooling.

With the tooling configuration, it is possible to coat multiple arc tubes using several of the tooling fixtures. This is shown below.

Figure 59. Fixtures for an array of arc tubes receiving the same coating.

The arms of the linear actuator device have positions available for multiple fixtures holding arc tubes. This would allow for the coating of multiple arc tubes when needed.

Figure 60. Linear actuator with fixtures holding arc tubes for coating

In this figure, one set of tooling is holding six arc tubes on the linear actuator dipping mechanism. The arms have positions for five additional fixtures providing additional space for multiple arc tubes being dipped in the same solution.

Sol-gel Chemistry

Sol-gel chemistry has been practiced for many years. The process uses metal alkoxides and volatile alcohol as a solvent. As the solvent is removed, the metal alkoxides condense to form extended networks of metal oxides. Heat is used to drive off any remaining solvent and to finish the conversion of alkoxide to oxide, thus compacting the film.

Figure 61. Hydrolysis reaction

Raw Materials and Reactions

Our sol-gel solution is prepared using a metal alkoxide and alcohol as the solution solvent. A small amount of water is added along with a strong acid or a weak base to act

as a catalyst. The reaction steps producing the final product of titanium oxide are described in Figure 24 and show hydrochloric acid as the catalyst. The reaction scheme is the same as other metal/non-metal oxides including silicon, zirconium and tantalum.

Figure 62. Condensation reaction, eliminating water

Substrate Coating

The coating solution is applied to the substrate by dipping the substrate into the solution, then removing the substrate from the solution at a measured rate. The liquid coated substrate is held out of the solution and allowed to dry. As the solvent evaporates, the materials in solution concentrate, forcing the titanium hydroxide molecules together, breaking the stable colloid. The metal hydroxide molecules then combine as shown below.

Figure 63. Extended network

In the specific case shown, as the condensation reaction proceeds, titanium hydroxides condense with themselves forming extended chains. As the chains extend, the multiple reactive sites on the titanium center create many branched chains, resulting in a highly cross-linked network. The network continues in all directions and becomes the thin layer film on the substrate surface.

Cure

Once the sol-gel solution is applied to the substrate surface, an initial lower temperature, 100C for 30 minutes, curing step is used to drive off residual alcohol and water. A longer higher temperature, 450C for 2 hours, curing step is used to drive the equilibrium even further and densify the film. Shown below is an SEM examination of the cross section of a coated Si wafer after the final curing step.

Figure 64. SEM of non heat treated coating layer (left) and heat treated/annealed coating (right).

The film, after an initial low temperature cure shows a thickness of about 770 Angstroms. The same sample, after the longer cure at higher temperature shows a reduced film thickness of 560 Angstroms. This level of curing occurs on the surface of the arc tube during the initial use of the tube since the arc tube surface reaches 400C degrees during typical use. Any additional curing occurs to completion on the first time the arc tube is powered for longer than 2 hours.

Materials

We have obtained several materials useful as coating precursors, solvents and catalysts for making the sol-gel solution for the coating process. A selection of these materials is shown in the figure below.

Figure 65. Material for making sol-gel solutions

Precursors we have obtained include titanium isopropoxide, tin t-butoxide, tetraethyl orthosilicate, zirconium ethoxide, and tantalum ethoxide. We also have the alcoholic solvents, ethyl, isopropyl and t-butyl required for the solution make up and the reaction catalysts, nitric acid, hydrochloric acid, acetic acid and ammonia.

Spectra Collection and Manipulation

Significant work was done to centralize and automate the retrieval and manipulation of the spectra as they are measured in the integrating sphere. An outline of the steps are shown below that are required to move data from the integrating sphere measurement location to a Microsoft Excel format for further manipulation. These steps are required to allow the algorithm to generate color correction spectral filters for the arc tubes.

Figure 66. Required steps for spectral data transfers to use in color filter generation

The data captured by the LabSphere software of measures done in our integrating sphere are saved as .scn files. These files are converted to .dt0 files in the LabSphere software. The files in this format can be exported to Microsoft Excel and then converted to .xls files for use in further data manipulation.

Once in Microsoft Excel, the data is loaded into the Color Correction Filter Generation module. The following two figures show screen shots of this module.

Figure 67. Screen shot of the Color Correction Filter Generation module

The above screen shot shows several data “read outs” of the arc tube measured in the integrating sphere. The upper right portions shows the power distribution per wavelength of the measured source. The left hand column of data shows various condensed measures, including CCT, CRI and other more specific R values. The lower right hand portion shows the ccx and ccy coordinates, the sources location in that space and the black body curve. The green cells at the bottom of the screen shot are locations where desired target data for the resulting filtered source can be entered. These include and u and v values and the distances from desired ccx and ccy values.

Figure 68. Screen shot of the Color Correction Filter Generation module

This portion of the Color Correction Filter Generation module shows the transmission of the desired filter in the upper right hand portion of the figure. In the lower right hand portion of the figure is the location of the output of the source in color space with the filter in place. This point is shown as a black square among the colored lines. The columns of data near the center are various measures of the filter as it is being generated. These measures ensure that the filter does not contain too steep of cutoffs and that the change from adjacent points is not too abrupt making a actual filter inaccessible.

The Color Correction Filter Generation module was applied in a step wise fashion using a metal halide tube spectrum to document the performance. The first example is shown below.

Figure 69. Illustration of the tradeoff of lumens for higher CRI in the filtered system

Several CRI targets were selected and the module was allowed to develop an optimal filter for each target. The initial metal halide source spectrum had a 45 CRI. The lumen output for each target was recorded and plotted. As is seen, the higher the CRI required, the lower was the lumen output. This occurs since the filter removes the lower wavelength energy in favor of the higher wavelength energy. As a higher CRI is targeted, additional higher energy light is filtered out of the spectrum.

The Color Correction Filter Generation module operates in a step wise, iterative fashion. Each step moves the source/filter combination closer to the desired target. The steps of the filter generation are captured in the figure below.

Figure 70. Iterative steps in the Color Correction Filter Generation module to reach a target CRI value

The source spectrum used was the same as previously examined, a 400W metal halide source and is shown at the bottom of the figure for reference. The initial CRI was 45 and the target CRI was set at 80. The figure shows how the filter develops over the iterative steps of the algorithm. The filter transmission is shown in the colored lines with the legend showing the color of the line that corresponds with each iterative step in the filter development process. The initial step creates the filter that deviates somewhat from the 100% transmission line with small sedge taken from the wavelength range of about 425-450nm and a much larger wedge taken from the range of about 535-610nm. Each subsequent step in the development process deepens the wedges in those identified areas of the spectrum. The result, at the end of 14 iterations is very deep cuts into the wavelength ranges identified that will yield a CRI for the source of 80.

Different CCT targets were also examined. The same initial spectrum was used in this work as was used above, a 400W metal halide source with a CRI of 45. The results of that evaluation are shown in the figure below.

Figure 71. Filters for various CCT targets produced in the Color Correction Filter Generation module

The amount of filtering required also depends on the target CCT set. As is seen in the figure, higher CCTs targets require a less absorbing filter. Targeting a lower CCT requires a stronger, more absorbing filter to reach the desired result.

The Color Correction Filter Generation module was applied to several light sources other than 400W metal halides. The target for all of the sources was a CRI 80 or greater and a CCT of 3000K. The results of this work are shown below.

The first case was examining an incandescent halogen source.

Figure 72. Filter generation for an incandescent source

The source used in this determination was a GE MR-16 lamp. The spectrum of the source is seen at the bottom of the figure and the filter required to meet the target parameters is shown across the top. In this case, no filter is needed as the filter shows a 100% transmission across the entire visible range. This was expected since incandescent sources provide high CRI and low color temperature on the black body curve.

The next example shown is using a ceramic metal halide source.

Figure 73. Filter generation for a ceramic metal halide source

The source used in this determination was a Phillips CMH Par lamp. The spectrum of the source is seen at the bottom of the figure and shows the spikes of a metal halide source. The filter required to meet the target parameters is shown across the top. In this case, minimal modification is needed via the filter to meet the desired CRI and CCT values.

Another CMH lamp was examined that required more modification with a filter to meet the desired target parameters. This evaluation is shown below.

Figure 74. Filter generation for a ceramic metal halide source

The source used in this determination was a second Phillips CMH Par lamp. The spectrum of the source is seen at the bottom of the figure and shows the spikes of a metal halide source. The filter required to meet the target parameters is shown across the top. In this case, additional modification is needed via the filter to meet the desired CRI and CCT values.

Several metal halide lamps were also examined. These lamps require significant modification with a filter to meet the desired target parameters. Each of these evaluations is shown below.

Figure 75. Filter generation for a metal halide source

The source used in this determination was a GE MRV 100W metal halide lamp. The spectrum of the source is seen at the bottom of the figure and shows the spikes of a metal halide source. The filter required to meet the target parameters is shown across the top. In this case, significant modification is needed via the filter to meet the desired CRI and CCT values.

Evaluation of another metal halide source, RAB LMH 100 lamp is shown below.

Figure 76. Filter generation for a metal halide source

The source used in this determination was a RAB LMH 100 metal halide lamp. The spectrum of the source is seen at the bottom of the figure and shows the spikes of a metal halide source. The filter required to meet the target parameters is shown across the top. In this case, significant modification is needed via the filter to meet the desired CRI and CCT values.

The evaluations presented here demonstrate the capabilities and performance of the Color Correction Filter Generation module. These show the iterative nature of the process and the tradeoffs that occur when setting CCT and CRI targets. The system is also validated in the examination of the various lamp types, particularly the recognition that incandescent sources require minimal adjustment and sources that have spectra characteristics between smooth incandescent and spiky metal halides require intermediate modification to meet the desired targets.

Coated MH Arc Tube Evaluation

We have coated several 400W arc tubes using a titanium metal based sol-gel solution and dipping process. Two sets of six arc tubes were taken from the initial supply of arc tubes received from VLI. In each set, one half of the tubes were selected to be coated while the

tubes in the other half were not coated. All twelve arc tubes were measured. Shown below is a comparison of data taken comparing coated and uncoated tubes.

Figure 77. Data from coated and uncoated 400W arc tubes

The data from the coated tubes was averaged and the data from the uncoated tubes was averaged resulting in single lines on the graph for the coated and uncoated data. The averaged spectra of the coated arc tubes are shown in yellow and the average spectra of the uncoated arc tubes are shown in blue. An effect is seen in this figure where on average, the peaks are higher at the longer wavelengths for the coated arc tubes. This is a demonstration of the output distribution of the arc tubes being shifted to longer wavelengths with the applied coating.

A second representation of the coated and uncoated arc tube data is shown below in a different comparative format.

Figure 78. Data comparison from coated and uncoated 400W arc tubes

The figure uses the same spectral data as was used in the previous figure. In this case, the spectral data from the non-coated lamps was divided by the spectral data from the coated lamps. This gives a better illustration of the uncoated lamps delivering a higher amount of light at the lower wavelengths and relatively less at the higher wavelengths when compared to the coated lamps. If the two sets of lamps were delivering the same amount of light across the spectrum, the result in this analysis would be a flat line at 1.0.

CCT and CRI Comparison

The CCT and CRI of the coated and uncoated arc tubes were collected. These values are shown in the figure below.

	CCT	CRI
average coated	4615	64.9
average uncoated	5406	51.6

Figure 79. Data comparison from coated and uncoated 400W arc tubes

It is seen that the set of arc tubes that were coated have a higher CRI and have lower CCT values compared to the uncoated arc tubes. The data used for this comparison is the same presented in the averaged spectral data in Figure 77 and Figure 78.

Process Automation

We have begun investigating options for enhancing the automated nature of the processing. Key components that would reduce human interaction would be automated integrating sphere operation and the movement of arc tubes from the assembly line to the measurement station and the coating station. It is conceivable that the spectral measurement could be accomplished while the arc tube is on the production line, however, application of the coating would likely be problematic without actually removing the arc tube from the production equipment. We have reviewed a few options available for automated integrating spheres and robotic arms that would be capable of picking up and moving arc tubes from one location to another.

Lighting Sciences offers an automated integrating sphere setup called the RoboSphere. This is an automated sphere system for lamp production testing.

RoboSphere

Figure 80. Automated integration sphere measurement system

It is a combination of a carousel onto which multiple test lamps are placed and an automated open-and-shut sphere. The systems allow for batch testing of a group of lamps in a totally automated sequence under computer control.

We also investigated the availability of robotic arms for manipulating and moving arc tubes. We found several different vendors and models available. Some of these are shown below.

Figure 81. Robotic arms

We found several vendors offering robotic arms with movement in 1 to 6 axes. The arms themselves are relatively inexpensive, with costs from \$5k to \$20k. By far the most expensive aspect of the robotic arms is the required programming to set the movements of the devices. These costs begin at \$20k. Further investigation is needed for this aspect of the project.

Interim Summary

We have had several discussions with Venture Lighting to sell them on the technology and develop them as a commercial partner. The responses from VLI have been favorable and VLI has agreed to assist us with the effort on several levels. They supplied us with 400W Pulse Start arc tubes for our development work.

We have performed several measurements of 400W arc tubes in our integrating sphere set up and have verified out sol-gel coating technology. We have also measured coated and uncoated arc tubes and have demonstrated a measurable effect of the coating process.

We have developed the means to move the captured spectral data from the LabSphere software to Microsoft Excel. In Microsoft Excel we have developed a Color Correction Filter Generation module that produces numerically the desired filter for the light source that makes the light source meet a desired CCT and/or CRI target. We have demonstrated this module for several different types of lamps and have evaluated the filter generation for various CCT and CRI targets. We have also evaluated the tradeoffs

for setting high CRI target and using low CRI initial sources. We have also shown filter adjustments based on chosen CCT targets.

Further Evaluation of Coated MH Arc Tubes

We ordered and received 400, 400W metal halide high intensity discharge lamps from Venture Lighting (VLI). The purpose for securing these lamps was to coat them with metal oxide and understand the scalability of the coating with these higher output lamps. With consultation with Venture Lighting, it was determined the best arc tube types would be arc tubes featuring VLI's cool white dosage and their warm white dosage.

Samplings of the received 400W arc tubes are shown in the figures below. The first two figures show arc tubes manufactured in Solon, OH and the third figure shows arc tubes manufactured in India.

Pieces from both manufacturing sites were coated in the experimental work described below.

Figure 82. Warm white arc tubes manufactured in Solon, OH

Figure 83. Cool white arc tubes manufactured in Solon, OH

Figure 84. Cool white arc tubes manufactured in India.

We created a Design of Experiments as a 2 Level 5 Factorial design with 3 repetitions at each condition. This design layout requires 96 test samples for completion. We executed the full design, choosing not to reduce the number of experiments by performing a fractional factorial and confound any interactions between variables. In addition to the 96 test samples in the DOE, we included 10 control lamps in the testing set.

Design of Experiments Variables

The variables introduced to the DOE included lamp type, coating type and three variables that influenced the coating thickness – tube withdraw rate, solution concentration and an additional layer of coating added to the tube.

Two different types of arc tubes were included – a “warm” white and a “cool” white. Both types of arc tubes are manufactured by Venture Lighting. The “cool” white arc tubes are manufactured in India and do not possess a side tip. The “warm” white arc tubes are manufactured at VLI’s Ohio manufacturing site and possess side tips.

The two coating materials for the arc tubes were selected based on work previously performed on lower wattage arc tubes. We selected a titanium dioxide coating and a silicon dioxide coating. These materials are both available as alkoxides, titanium (IV)

isopropoxide and tetra-ethyl orthosilicate. The materials can be formulated into alcohol solutions. The chemistry of these materials has been discussed in prior reports.

Two different concentrations of the coating materials were made. The low concentration was formulated at 10% for each of the chemistries. A high concentration of 30% was also produced for each of the coating chemistries. The high concentration may have been too high for the titanium material since some white residue was observed on arc tubes coated with solution at this concentration.

A variable was set to add either a single layer of each coating to the arc tube, or a double layer. This was designed to increase the thickness of the coating in a large stepwise manner.

The final variable for the experiment was the withdrawal rate of the arc tube from the coating solution. This variable has an impact on the coating thickness. The variable was set at a low withdrawal rate of 30 seconds and a higher withdrawal rate of 10 seconds. The slower withdrawal rate produces a thinner coating.

Experimental Procedure

All arc tubes were measured in a large 2 meter diameter integrating sphere. The CCT, lumen output and CRI were determined for each arc tube. The power input was monitored and manually controlled for each measurement. All arc tubes were weighed prior to photometric measurement. These measurements were done in a single day.

After the initial measurements, each of the arc tubes was photographed.

Figure 85. Arc tubes after initial striking and measurement

A sampling of the arc tube photos are shown here. These pictures were selected to illustrate the variation in the metal halide pool that occurs in metal halide, high intensity discharge lamps and can be used to correlate any arc tubes that have abnormal output performance.

The sol-gel solutions were made from chemical stock supplied by Sigma-Aldrich. The solutions were made the day prior to application of the solution to the arc tubes.

Figure 86. Four containers of sol-gel solution used for arc tube coating

The four solutions were made in sufficient volume to fill a 1 liter sized bottle. The size of the bottle was needed to allow for full coverage of the arc tube as it was submerged in the solution. The four solutions from left to right were titanium (IV) isopropoxide in isopropanol with a 10% concentration, titanium (IV) isopropoxide in isopropanol with a 30% concentration, tetraethylorthosilicate in ethanol at a 10% concentration and tetraethylorthosilicate in ethanol at a 30% concentration

The arc tubes were coated in a random run order. This required the alternating of coating solutions for the arc tubes as they were coated. After coating, the arc tubes were heated in an oven at 80C for two hours. This step is used to remove any remaining alcohol from the coating and promotes the condensation of the metal oxide components in the coating. All arc tubes were coated with the solutions and heat treated in a single day.

The arc tubes were then photometrically measured a second time in the 2 meter integrating sphere. The same procedure was used with this measurement as was done with the initial measurement.

The responses measured for the arc tubes were luminous flux, corrected color temperature (CCT) and color rendering index (CRI). The mass of each arc tube was recorded before and after coating.

Purpose of this experiment

We want to generate data on the performance of the coating in a 400W arc tube system that was earlier used with the 80W arc tube system previously examined. It is important to understand the performance as the product is scaled to a larger size and output level.

The design of experiments gives guidance to determining an optimal set of conditions to push the arc tube performance to a desired region. We wish to lower the CRI with a minimal impact on luminous flux.

We want to produce many samples from which we can have VLI make finished lamps. The finished lamps include a glass shroud covering the arc tube. The added shroud modifies the output of the arc tube, producing typically a lower CCT light with a higher CRI that ultimately leaves the shroud.

The three of the variables directly affect the amount of coating applied to the arc tubes. Examination of the coated arc tubes data with this in mind assists in understanding the affects of the coating thickness with arc tube performance.

The design of experiments is show in the figure below. The figure shows the lamp number, the coating material used, the solution concentration, the withdrawal rate, the number of layers applied and the arc tube type.

Lamp	Coating Type	Solution Conc	Withdrawal Rate	Layers	Lamp Type
1	silicon dioxide	30%	10 sec	1	warm
2	silicon dioxide	30%	10 sec	2	cool
3	titanium dioxide	10%	10 sec	1	cool
4	titanium dioxide	30%	30 sec	2	warm
5	silicon dioxide	30%	30 sec	2	warm
6	titanium dioxide	30%	10 sec	1	cool
7	titanium dioxide	10%	10 sec	2	cool
8	silicon dioxide	30%	30 sec	2	cool
9	silicon dioxide	30%	30 sec	1	warm
10	silicon dioxide	10%	10 sec	2	cool
11	titanium dioxide	30%	30 sec	1	cool
12	silicon dioxide	30%	30 sec	2	cool
13	titanium dioxide	30%	30 sec	1	cool
14	titanium dioxide	30%	30 sec	1	cool
15	titanium dioxide	10%	10 sec	1	warm
16	silicon dioxide	30%	30 sec	2	cool
17	silicon dioxide	10%	30 sec	1	cool
18	titanium dioxide	30%	10 sec	2	cool
19	silicon dioxide	10%	30 sec	2	cool
20	titanium dioxide	10%	30 sec	1	warm
21	titanium dioxide	30%	10 sec	1	warm
22	silicon dioxide	10%	10 sec	1	cool
23	silicon dioxide	10%	30 sec	2	warm
24	titanium dioxide	10%	10 sec	2	cool
25	silicon dioxide	10%	30 sec	2	warm
26	titanium dioxide	30%	10 sec	2	warm
27	silicon dioxide	30%	30 sec	2	warm
28	titanium dioxide	30%	30 sec	2	cool
29	titanium dioxide	30%	10 sec	1	warm
30	titanium dioxide	10%	10 sec	1	warm
31	titanium dioxide	10%	10 sec	2	warm
32	titanium dioxide	10%	30 sec	2	warm
33	titanium dioxide	30%	10 sec	2	cool
34	silicon dioxide	30%	10 sec	1	cool
35	silicon dioxide	10%	30 sec	2	cool
36	silicon dioxide	10%	30 sec	1	warm
37	titanium dioxide	10%	10 sec	2	cool
38	titanium dioxide	10%	30 sec	1	cool
39	silicon dioxide	10%	30 sec	1	warm
40	titanium dioxide	10%	30 sec	1	warm
41	titanium dioxide	10%	30 sec	2	warm
42	silicon dioxide	30%	30 sec	2	warm
43	silicon dioxide	30%	30 sec	1	cool
44	silicon dioxide	10%	10 sec	1	cool
45	titanium dioxide	10%	10 sec	1	cool
46	titanium dioxide	10%	10 sec	2	warm
47	titanium dioxide	30%	30 sec	2	warm

Figure 87. Details for design of experiments

48	titanium dioxide	30%	30 sec	1	warm
49	titanium dioxide	10%	10 sec	2	warm
50	silicon dioxide	30%	10 sec	1	cool
51	titanium dioxide	10%	30 sec	2	cool
52	titanium dioxide	30%	30 sec	2	warm
53	silicon dioxide	10%	10 sec	1	warm
54	silicon dioxide	30%	30 sec	1	cool
55	titanium dioxide	30%	10 sec	1	cool
56	silicon dioxide	30%	10 sec	2	cool
57	silicon dioxide	10%	30 sec	1	cool
58	silicon dioxide	10%	30 sec	1	warm
59	titanium dioxide	10%	30 sec	2	warm
60	titanium dioxide	30%	10 sec	2	warm
61	silicon dioxide	10%	10 sec	2	warm
62	titanium dioxide	10%	10 sec	1	warm
63	titanium dioxide	30%	10 sec	2	cool
64	silicon dioxide	30%	30 sec	1	warm
65	titanium dioxide	30%	30 sec	1	warm
66	silicon dioxide	10%	10 sec	1	cool
67	titanium dioxide	10%	30 sec	1	cool
68	silicon dioxide	30%	10 sec	2	warm
69	silicon dioxide	30%	10 sec	2	cool
70	silicon dioxide	10%	10 sec	2	warm
71	titanium dioxide	10%	30 sec	2	cool
72	silicon dioxide	10%	10 sec	1	warm
73	titanium dioxide	10%	10 sec	1	cool
74	silicon dioxide	30%	10 sec	1	cool
75	silicon dioxide	30%	10 sec	1	warm
76	titanium dioxide	30%	30 sec	1	warm
77	titanium dioxide	10%	30 sec	1	warm
78	titanium dioxide	30%	30 sec	2	cool
79	silicon dioxide	10%	10 sec	2	cool
80	titanium dioxide	30%	10 sec	1	warm
81	titanium dioxide	30%	10 sec	1	cool
82	silicon dioxide	10%	10 sec	1	warm
83	silicon dioxide	30%	30 sec	1	cool
84	silicon dioxide	30%	30 sec	1	warm
85	silicon dioxide	10%	30 sec	1	cool
86	silicon dioxide	30%	10 sec	2	warm
87	titanium dioxide	30%	30 sec	2	cool
88	titanium dioxide	30%	10 sec	2	warm
89	silicon dioxide	10%	30 sec	2	warm
90	silicon dioxide	10%	30 sec	2	cool
91	silicon dioxide	10%	10 sec	2	warm
92	silicon dioxide	30%	10 sec	1	warm
93	titanium dioxide	10%	30 sec	2	cool
94	silicon dioxide	10%	10 sec	2	cool
95	titanium dioxide	10%	30 sec	1	cool
96	silicon dioxide	30%	10 sec	2	warm

Figure 88. Details for design of experiments

A design of experiments of this type makes the statistical analysis of the results more amenable.

Initial Measurements

All lamps were measured prior to the application of the coatings. This was done to develop a baseline for noise in the measurements and to give a clearer assessment of the effects of the coating on the individual lamp performance.

The initial measures are shown here in the figure below. The measured values are luminous flux, CCT, CRI and mass.

Lamp	Coating Type	Solution Conc	Withdrawal Rate	Layers	Lamp Type	Luminous Flux	CCT	CRI	Mass
54	silicon dioxide	30%	30 sec	1	cool	38758.66	3994	66.2	9.985
48	titanium dioxide	30%	30 sec	1	warm	31728.94	4021	51.9	10.059
2	silicon dioxide	30%	10 sec	2	cool	39199.04	4050	66.3	10.240
63	titanium dioxide	30%	10 sec	2	cool	38347.02	4141	64.4	10.066
39	silicon dioxide	10%	30 sec	1	warm	28002.39	4166	46.4	9.812
44	silicon dioxide	10%	10 sec	1	cool	38639.68	4176	63.9	10.091
56	silicon dioxide	30%	10 sec	2	cool	39271.41	4176	65	10.079
86	silicon dioxide	30%	10 sec	2	warm	33506.34	4181	54.7	9.877
79	silicon dioxide	10%	10 sec	2	cool	39362.41	4187	64.7	10.077
8	silicon dioxide	30%	30 sec	2	cool	36544.53	4189	63.1	10.103
6	titanium dioxide	30%	10 sec	1	cool	42818.69	4198	65.7	10.157
1	silicon dioxide	30%	10 sec	1	warm	27397.79	4199	45.7	9.936
37	titanium dioxide	10%	10 sec	2	cool	39627.64	4209	64.4	9.946
90	silicon dioxide	10%	30 sec	2	cool	37927.65	4230	63.5	10.142
25	silicon dioxide	10%	30 sec	2	warm	30528.76	4237	49.6	10.003
73	titanium dioxide	10%	10 sec	1	cool	38655.26	4238	63.8	9.940
93	titanium dioxide	10%	30 sec	2	cool	40080.87	4265	64.7	10.024
50	silicon dioxide	30%	10 sec	1	cool	39965.98	4269	64.4	10.230
57	silicon dioxide	10%	30 sec	1	cool	41330.44	4271	64.9	10.107
83	silicon dioxide	30%	30 sec	1	cool	36264.29	4281	61	9.955
30	titanium dioxide	10%	10 sec	1	warm	28661.88	4287	47.9	9.957
61	silicon dioxide	10%	10 sec	2	warm	28543.59	4288	48.3	10.068
58	silicon dioxide	10%	30 sec	1	warm	28634.63	4293	48.8	9.992
68	silicon dioxide	30%	10 sec	2	warm	23979.21	4296	39.6	10.040
13	titanium dioxide	30%	30 sec	1	cool	39095.18	4308	63.3	10.253
60	titanium dioxide	30%	10 sec	2	warm	27210.31	4335	45.4	9.972
89	silicon dioxide	10%	30 sec	2	warm	25985.76	4340	43.9	9.917
46	titanium dioxide	10%	10 sec	2	warm	28355.91	4343	48	9.960
31	titanium dioxide	10%	10 sec	2	warm	23933.53	4364	40.5	9.892
70	silicon dioxide	10%	10 sec	2	warm	25926.86	4364	43.6	9.826
71	titanium dioxide	10%	30 sec	2	cool	38795.98	4389	64.1	10.110
92	silicon dioxide	30%	10 sec	1	warm	27305.27	4391	47.1	10.067
16	silicon dioxide	30%	30 sec	2	cool	39505.69	4411	64	10.052
76	titanium dioxide	30%	30 sec	1	warm	25384.43	4439	43.3	10.025
85	silicon dioxide	10%	30 sec	1	cool	41051.7	4459	65.6	10.008
75	silicon dioxide	30%	10 sec	1	warm	23862.65	4469	40.5	9.895
78	titanium dioxide	30%	30 sec	2	cool	37288.22	4471	61.4	10.129
67	titanium dioxide	10%	30 sec	1	cool	38620.83	4481	63.3	9.970
9	silicon dioxide	30%	30 sec	1	warm	26044.77	4494	45.2	10.043
40	titanium dioxide	10%	30 sec	1	warm	25685.26	4532	43.8	9.788
84	silicon dioxide	30%	30 sec	1	warm	27214.99	4532	47.3	9.852
82	silicon dioxide	10%	10 sec	1	warm	25025.76	4539	42.4	9.868
20	titanium dioxide	10%	30 sec	1	warm	24709.65	4583	42	10.118
38	titanium dioxide	10%	30 sec	1	cool	39478.35	4591	65	10.089
42	silicon dioxide	30%	30 sec	2	warm	26989.59	4595	46.5	9.949
23	silicon dioxide	10%	30 sec	2	warm	26678.97	4606	44.1	10.018
62	titanium dioxide	10%	10 sec	1	warm	23076.89	4632	39.2	9.866
88	titanium dioxide	30%	10 sec	2	warm	25594.25	4632	46.6	9.892
91	silicon dioxide	10%	10 sec	2	warm	26630.8	4636	44.9	10.136
10	silicon dioxide	10%	10 sec	2	cool	28636.78	4647	52	10.082
27	silicon dioxide	30%	30 sec	2	warm	25629.83	4651	43.7	9.851
65	titanium dioxide	30%	30 sec	1	warm	22179.04	4682	37.9	9.908
69	silicon dioxide	30%	10 sec	2	cool	26535.78	4719	48.2	9.985
5	silicon dioxide	30%	30 sec	2	warm	25633.61	4721	43.6	10.124
55	titanium dioxide	30%	10 sec	1	cool	35434.42	4722	59.5	10.108
41	titanium dioxide	10%	30 sec	2	warm	24186.89	4735	42.4	9.804
21	titanium dioxide	30%	10 sec	1	warm	32112.61	4748	55.3	10.009
32	titanium dioxide	10%	30 sec	2	warm	25152.75	4764	42.7	9.808
77	titanium dioxide	10%	30 sec	1	warm	23319.39	4769	40.4	9.807
29	titanium dioxide	30%	10 sec	1	warm	23327.17	4771	38.5	10.216
4	titanium dioxide	30%	30 sec	2	warm	25365	4773	43.7	9.918
80	titanium dioxide	30%	10 sec	1	warm	26750.1	4774	47.2	9.927
64	silicon dioxide	30%	30 sec	1	warm	27303.49	4784	47.4	10.142
81	titanium dioxide	30%	10 sec	1	cool	26151.08	4785	47.6	10.073
59	titanium dioxide	10%	30 sec	2	warm	28023.82	4786	48.4	9.933
96	silicon dioxide	30%	10 sec	2	warm	19241.73	4804	33.9	9.952
17	silicon dioxide	10%	30 sec	1	cool	29755.62	4805	52.6	10.012
53	silicon dioxide	10%	10 sec	1	warm	28943.51	4817	50.5	9.742
52	titanium dioxide	30%	30 sec	2	warm	26738.68	4832	46.3	9.890
47	titanium dioxide	30%	30 sec	2	warm	20774.63	4845	35.6	9.796
49	titanium dioxide	10%	10 sec	2	warm	27080.65	4856	46.9	10.035
3	titanium dioxide	10%	10 sec	1	cool	32595.09	4862	58.7	10.008
66	silicon dioxide	10%	10 sec	1	cool	30253.94	4897	52.6	10.073
72	silicon dioxide	10%	10 sec	1	warm	22872.83	4907	39.1	9.855
95	titanium dioxide	10%	30 sec	1	cool	27762.37	4920	51.2	10.206
26	titanium dioxide	30%	10 sec	2	warm	23063.5	4981	39.5	9.903
33	titanium dioxide	30%	10 sec	2	cool	43575.82	5012	67.2	10.069
15	titanium dioxide	10%	10 sec	1	warm	27230.58	5019	46.8	10.129
94	silicon dioxide	10%	10 sec	2	cool	31644.96	5043	54.7	10.026
45	titanium dioxide	10%	10 sec	1	cool	33300.11	5057	58.6	10.147
51	titanium dioxide	10%	30 sec	2	cool	29583.96	5076	54.2	10.128
36	silicon dioxide	10%	30 sec	1	warm	24590.17	5078	42.6	9.925
7	titanium dioxide	10%	10 sec	2	cool	27703.27	5083	49.8	10.038
24	titanium dioxide	10%	10 sec	2	cool	33468.43	5123	57.4	10.141
35	silicon dioxide	10%	30 sec	2	cool	35992.54	5139	63.2	9.963
28	titanium dioxide	30%	30 sec	2	cool	34050.98	5142	59	10.119
14	titanium dioxide	30%	30 sec	1	cool	28574.99	5197	52.2	10.025
19	silicon dioxide	10%	30 sec	2	cool	35738.58	5240	61.5	10.119
34	silicon dioxide	30%	10 sec	1	cool	31176.65	5263	54	10.073
18	titanium dioxide	30%	10 sec	2	cool	31959.74	5278	54.9	10.186
74	silicon dioxide	30%	10 sec	1	cool	31017.43	5317	54.4	10.091
87	titanium dioxide	30%	30 sec	2	cool	35966.34	5340	60.6	10.054
12	silicon dioxide	30%	30 sec	2	cool	35486.43	5489	61.2	10.003
43	silicon dioxide	30%	30 sec	1	cool	34888.16	5497	60	10.191
11	titanium dioxide	30%	30 sec	1	cool	29030.52	5517	53.4	10.109
22	silicon dioxide	10%	10 sec	1	cool	36555.4	5535	60.1	10.224
C1	N/A	N/A	N/A	N/A	cool	37282	5350	59.5	10.190
C2	N/A	N/A	N/A	N/A	warm	27384.13	4279	45.7	10.007
C3	N/A	N/A	N/A	N/A	warm	30715.42	4317	52	9.875
C4	N/A	N/A	N/A	N/A	cool	39594.3	4389	65.2	10.096
C5	N/A	N/A	N/A	N/A	warm	27720.77	4380	46.4	10.007
C6	N/A	N/A	N/A	N/A	warm	26824.77	4776	46.3	9.663
C7	N/A	N/A	N/A	N/A	cool	38172.39	5288	64.1	10.104
C8	N/A	N/A	N/A	N/A	warm	26072.41	4855	43.8	10.046
C9	N/A	N/A	N/A	N/A	cool	39994.96	4329	64.2	10.082
C10	N/A	N/A	N/A	N/A	cool	32235.9	5368	56.9	10.103

Figure 89. Initial measures of uncoated arc tubes to be used in the experimental design

The measured data was separated into various categories for ease of comparison. The different comparisons are shown below. The data is represented in box plots to aid in the visual comparison of the data. A data table is given at the end of this section showing the numbers used to make the plots.

In each of the charts, four data sets are illustrated. The set on the far left shows a small subset of cool white arc tubes used as control samples. The next set from the left shows a small subset of warm white arc tubes also used as control samples. The next set to the right is the larger set of cool white arc tubes that were coated in the experiment. The set of data farthest to the right is data collected from the large set of warm white arc tubes that were coated.

Figure 90. Boxplot of initial arc tube luminous flux measurements

The set of cool white arc tubes have a higher measured luminous flux than the warm white arc tubes. The median of the cool white tubes was determined to be about 35,000 lumens with the warm white was about 26,000 lumens. The range of the cool white values appears wider than that of the warm white tubes.

Figure 91. Boxplots of initial arc tube CCT measurements

The median of the CCT of the cool white arc tubes appears slightly higher than that of the warm white arc tubes. The measured values for the median of the cool white arc tubes is approximately 4700K while that for the warm white tubes is about 4600K. The CCT of the cool white lamps spans a greater range than is seen with the warm white lamps but there is significant overlap of the ranges of the two arc tube types.

Figure 92. Boxplots of initial arc tube CRIs

The measured CRI of the two lamp types appear to show differences in median values and similar magnitudes of range. The median value of the cool white arc tubes is about 60 while that of the warm white arc tubes is about 45.

Figure 93. Boxplots of initial arc tube masses

The mass of each of the arc tubes was measured prior to coating. The median value for the cool white arc tubes is slightly higher than that measured for the warm white arc tubes. The median values for the cool white arc tubes is approximately 10.08 grams and that of the warm white arc tubes was measured at approximately 9.95 grams. The spread of data appears slightly greater for the warm white arc tubes. There appears to be a great deal of overlap in the measured values between the two arc tube types.

A summary of the measured values is given on the table below.

Variable	Lamp Typ	N	Mean	Median	StDev	Minimum	Maximum	Q1	Q3
Luminous	con cool	5	37456	38172	3115	32236	39995	34759	39795
	con warm	5	27744	27384	1775	26072	30715	26449	29218
	cool	48	35364	36128	4628	26151	43576	31294	39173
	warm	48	26169	26015	2745	19242	33506	24288	27375
CCT	con cool	5	4945	5288	536	4329	5368	4359	5359
	con warm	5	4521	4380	272	4279	4855	4298	4816
	cool	48	4722.7	4720.5	470	3994	5535	4266	5135
	warm	48	4581.1	4619	251.6	4021	5078	4348.3	4773.8
CRI	con cool	5	61.98	64.1	3.6	56.9	65.2	58.2	64.7
	con warm	5	46.84	46.3	3.07	43.8	52	44.75	49.2
	cool	48	59.823	61.3	5.479	47.6	67.2	54.475	64.4
	warm	48	44.575	44.5	4.429	33.9	55.3	42.1	47.275
Mass	con cool	5	10.115	10.103	0.043	10.082	10.19	10.089	10.147
	con warm	5	9.9196	10.007	0.1574	9.663	10.046	9.769	10.0265
	cool	48	10.083	10.081	0.08	9.94	10.253	10.024	10.129
	warm	48	9.948	9.93	0.1104	9.742	10.216	9.8665	10.0325

Figure 94. Summary of measures of arc tubes prior to coating

The measures of Luminous Flux, CCT, CRI and mass are shown. The table gives the Lamp Type, broken out into “con cool” and “con warm” for the sets of respective cool and warm control samples. The labels of “cool” and “warm” indicate the set of arc tubes that were coated in the experiment.

The column labeled as “N” gives the number of repetitions in each set. The Mean, Median and standard deviation (StDev) are shown for each set. The Minimum and Maximum values measured in each set are shown along with the Q1 and Q3 values.

The Q1 value indicates the lower boundary of the box in the plot while the Q3 value shows the upper boundary of the box. The first quartile (25th percentile) is the highest value for the lowest 25% of the observations. Median, second quartile (50th percentile) is the middle observation and the third quartile (75th percentile) is the lowest value for the highest 25% of the observations. Q1 and Q3 are often used to calculate the inter-quartile range (IQR), which is another statistic used to describe dispersion.

It is expected that the initial data should fall into two groups, that of the warm white tubes and that of the cool white tubes. The data for each tube reflects the baseline noise associated with each of the tube types.

Measured Values of Coated Lamps

The design of experiment is conducted with **five** variables at two levels.

	Low	High
Lamp Type	Cool	Warm
Coating type	Silicon dioxide	titanium dioxide
Solution concentration	10%	30%
Withdrawal rate	10 sec	30 sec
Layers	1	2

Figure 95. Four containers of sol-gel solution used for arc tube coating

The design has four responses: Luminous flux, CCT, CRI and mass. The purpose of the experiment is to investigate the effects of coating type, solution concentration, withdrawal rate and the number of layers on the responses. When performing an experiment, varying the levels of the factors simultaneously rather than one at a time is efficient in terms of time and cost, and also allows for the study of interactions between the factors.

The measured data from the experiment is shown here.

Lamp	Coating Type	Solution Conc	Withdrawal Rate	Layers	Lamp Type	Luminous Flux	CCT	CRI	Mass
1	silicon dioxide	30%	10 sec	1	warm	38349.74	3716	58.3	9.989
2	silicon dioxide	30%	10 sec	2	cool	38822.49	3954	64.4	10.288
3	titanium dioxide	10%	10 sec	1	cool	39622.11	4465	66.8	10.032
4	titanium dioxide	30%	30 sec	2	warm	31052.23	4987	54.7	9.098
5	silicon dioxide	30%	30 sec	2	warm	27818.56	4831	48.2	10.134
6	titanium dioxide	30%	10 sec	1	cool	42847.4	4071	67.1	10.162
7	titanium dioxide	10%	10 sec	2	cool	41710.81	4768	67.6	10.048
8	silicon dioxide	30%	30 sec	2	cool	37365.39	4028	65.4	10.081
9	silicon dioxide	30%	30 sec	1	warm	32365.42	4694	55.8	10.050
10	silicon dioxide	10%	10 sec	2	cool	35814.41	3964	60.8	10.107
11	titanium dioxide	30%	30 sec	1	cool	39034.14	4920	65.1	10.096
12	silicon dioxide	30%	30 sec	2	cool	39043.92	4065	65	9.992
13	titanium dioxide	30%	30 sec	1	cool	39536.44	4060	65.3	10.249
14	titanium dioxide	30%	30 sec	1	cool	38854.77	4896	64.5	10.026
15	titanium dioxide	10%	10 sec	1	warm	30161.68	4858	54	10.128
16	silicon dioxide	30%	30 sec	2	cool	38907.03	4220	64.4	10.034
17	silicon dioxide	10%	30 sec	1	cool	36340.91	4677	61.5	9.992
18	titanium dioxide	30%	10 sec	2	cool	41416.21	4497	64.2	10.205
19	silicon dioxide	10%	30 sec	2	cool	38608.01	4208	66	10.139
20	titanium dioxide	10%	30 sec	1	warm	27019.89	4779	47.1	10.133
21	titanium dioxide	30%	10 sec	1	warm	32875.72	4784	57.6	10.010
22	silicon dioxide	10%	10 sec	1	cool	38753.34	4192	64.8	10.245
23	silicon dioxide	10%	30 sec	2	warm	29210.17	4892	52	10.008
24	titanium dioxide	10%	10 sec	2	cool	37702.11	3875	66.3	10.115
25	silicon dioxide	10%	30 sec	2	warm	27266.33	4626	48.6	9.982
26	titanium dioxide	30%	10 sec	2	warm	30697.66	4803	54.4	9.918
27	silicon dioxide	30%	30 sec	2	warm	30050.96	4822	52.8	9.876
28	titanium dioxide	30%	30 sec	2	cool	37865.03	4349	65.4	10.136
29	titanium dioxide	30%	10 sec	1	warm	27582.15	4862	48.3	10.241
30	titanium dioxide	10%	10 sec	1	warm	31859.71	4455	55.1	10.043
31	titanium dioxide	10%	10 sec	2	warm	30843.63	4636	56.7	9.922
32	titanium dioxide	10%	30 sec	2	warm	32638.1	4795	56.4	9.883
33	titanium dioxide	30%	10 sec	2	cool	37511.99	3779	63.4	10.065
34	silicon dioxide	30%	10 sec	1	cool	33144.17	5439	57.1	9.726
35	silicon dioxide	10%	30 sec	2	cool	37939.13	4231	66.9	9.590
36	silicon dioxide	10%	30 sec	1	warm	30972.23	4834	54.2	9.445
37	titanium dioxide	10%	10 sec	2	cool	39945.94	4109	66.8	9.415
38	titanium dioxide	10%	30 sec	1	cool	38110.02	3952	66	10.071
39	silicon dioxide	10%	30 sec	1	warm	36509.29	3920	59	9.811
40	titanium dioxide	10%	30 sec	1	warm	29023.82	4850	51	9.774
41	titanium dioxide	10%	30 sec	2	warm	33804.96	4670	57.9	9.755
42	silicon dioxide	30%	30 sec	2	warm	32018.93	4884	55.5	9.951
43	silicon dioxide	30%	30 sec	1	cool	40416.04	4476	67.6	10.144
44	silicon dioxide	10%	10 sec	1	cool	37814.73	3689	63.3	10.066
45	titanium dioxide	10%	10 sec	1	cool	40343.63	4882	67.8	9.987
46	titanium dioxide	10%	10 sec	2	warm	34861.04	4630	59.7	9.946
47	titanium dioxide	30%	30 sec	2	warm	28309.15	4847	52	9.810
48	titanium dioxide	30%	30 sec	1	warm	35488.53	4124	56.6	10.044
49	titanium dioxide	10%	10 sec	2	warm	30451.23	4820	53.2	9.998
50	silicon dioxide	30%	10 sec	1	cool	40608.15	4086	65.3	10.236
51	titanium dioxide	10%	30 sec	2	cool	40360.52	5030	65.9	10.088
52	titanium dioxide	30%	30 sec	2	warm	27174.48	4905	48	9.865
53	silicon dioxide	10%	10 sec	1	warm	30735.35	4791	54.2	9.718
54	silicon dioxide	30%	30 sec	1	cool	38403.16	3910	64.7	10.001
55	titanium dioxide	30%	10 sec	1	cool	38340.79	4373	63.4	10.127
56	silicon dioxide	30%	10 sec	2	cool	38780.86	3938	63.4	10.057
57	silicon dioxide	10%	30 sec	1	cool	38781.04	4032	63.9	10.071
58	silicon dioxide	10%	30 sec	1	warm	30806.16	4665	52.8	9.952
59	titanium dioxide	10%	30 sec	2	warm	29391.91	4726	52	9.871
60	titanium dioxide	30%	10 sec	2	warm	26568.51	4774	46.2	9.995
61	silicon dioxide	10%	10 sec	2	warm	30182.15	4341	53.2	10.065
62	titanium dioxide	10%	10 sec	1	warm	31331.89	4678	55.6	9.885
63	titanium dioxide	30%	10 sec	2	cool	37794.32	3882	63.6	10.080
64	silicon dioxide	30%	30 sec	1	warm	26137.83	4957	46.1	10.134
65	titanium dioxide	30%	30 sec	1	warm	32152.59	4613	54.5	9.922
66	silicon dioxide	10%	10 sec	1	cool	34635.83	4965	58.5	10.099
67	titanium dioxide	10%	30 sec	1	cool	38677.18	3965	64.9	9.949
68	silicon dioxide	30%	10 sec	2	warm	30881.3	4888	53.6	9.978
69	silicon dioxide	30%	10 sec	2	cool	34424.63	4929	60.2	9.945
70	silicon dioxide	10%	10 sec	2	warm	27361.36	4730	48.6	9.846
71	titanium dioxide	10%	30 sec	2	cool	38874.64	4055	65.7	10.182
72	silicon dioxide	10%	10 sec	1	warm	27361.42	5033	48	9.838
73	titanium dioxide	10%	10 sec	1	cool	38109.89	4027	66.7	9.955
74	silicon dioxide	30%	10 sec	1	cool	41272.49	4666	65.6	10.099
75	silicon dioxide	30%	10 sec	1	warm	27255.13	4862	48.5	9.919
76	titanium dioxide	30%	30 sec	1	warm	32021.63	4485	54.3	10.058
77	titanium dioxide	10%	30 sec	1	warm	28469.16	4900	50	9.840
78	titanium dioxide	30%	30 sec	2	cool	39085.43	4138	64.4	10.166
79	silicon dioxide	10%	10 sec	2	cool	38828.97	3980	64.4	10.102
80	titanium dioxide	30%	10 sec	1	warm	33305.6	4651	58.9	9.938
81	titanium dioxide	30%	10 sec	1	cool	36991	4432	62.7	10.076
82	silicon dioxide	10%	10 sec	1	warm	30711.98	4595	52.9	9.865
83	silicon dioxide	30%	30 sec	1	cool	37569.25	4403	63.2	9.954
84	silicon dioxide	30%	30 sec	1	warm	30987.3	4784	54	9.872
85	silicon dioxide	10%	30 sec	1	cool	40912.63	4230	66.7	10.012
86	silicon dioxide	30%	10 sec	2	warm	32029.09	4479	53.8	9.856
87	titanium dioxide	30%	30 sec	2	cool	38663.03	4190	65	10.080
88	titanium dioxide	30%	10 sec	2	warm	36426.05	3774	61.2	9.924
89	silicon dioxide	10%	30 sec	2	warm	30243.31	4652	52.7	9.926
90	silicon dioxide	10%	30 sec	2	cool	39014.31	4215	64.4	10.133
91	silicon dioxide	10%	10 sec	2	warm	28842.52	4455	49.8	10.131
92	silicon dioxide	30%	10 sec	1	warm	28300.72	4888	50.2	10.064
93	titanium dioxide	10%	30 sec	2	cool	39258.29	3912	65.3	10.036
94	silicon dioxide	10%	10 sec	2	cool	40200.76	4226	65.6	9.997
95	titanium dioxide	10%	30 sec	1	cool	39774.72	4443	66.9	10.192
96	silicon dioxide	30%	10 sec	2	warm	22835.57	4932	43.1	9.967
C1	N/A	N/A	N/A	N/A	cool	41009.54	4111	64.7	10.171
C2	N/A	N/A	N/A	N/A	warm	28344.08	4676	49.3	10.052
C3	N/A	N/A	N/A	N/A	warm	36130.36	4503	59.5	9.860
C4	N/A	N/A	N/A	N/A	cool	38621.31	3750	63.5	10.045
C5	N/A	N/A	N/A	N/A	warm	29550.65	4792	51.1	9.981
C6	N/A	N/A	N/A	N/A	warm	29601.45	4568	51.4	9.693
C7	N/A	N/A	N/A	N/A	cool	38593.58	3842	63.9	10.127
C8	N/A	N/A	N/A	N/A	warm	30030.89	3927	48.5	10.141
C9	N/A	N/A	N/A	N/A	cool	40699.54	4286	65.4	10.121
C10	N/A	N/A	N/A	N/A	cool	40430.02	4503	65.6	10.163

Figure 96. Four containers of sol-gel solution used for arc tube coating

The measured data was entered into statistical software, Minitab 13, and analyzed using ANOVA (Analysis of Variance).

The software produces several comparisons within the data set and identifies the primary effects of the variables on the responses and also identifies interactions between the variables.

The data from this analysis is presented below in several tables. The tables consist of tabulated numbers under several column headings.

The “Effect” term is used to determine the relative strength of the effects. The absolute value of the effect determines its relative strength. The higher the value is, the greater the effect on the response. A positive signed effect indicates that the high factor setting results in a higher response than the low setting. A negative signed effect indicates that a lower factor setting results in a higher response than the high setting.

The “coefficients” can be used to formulate an equation representing the relationship between the response and the factors.

“P-values” in the table are used to determine which of the effects are statistically significant. We first look at the interaction effects in the model because a significant interaction influences how you interpret the main effects. The alpha level chosen for this experiment is 0.05

If the p-value is less than or equal to alpha level, we conclude that the effect is significant. If the p-value is greater than alpha level, we conclude that the effect is not significant.

Various comparisons are described in the tables below.

LUMINUOUS FLUX:

COOL WHITE – Luminous Flux

Term	Effect	Coef	P
Constant		38684	0
Coating	1001.2	500.6	0.098
Solution	-143.1	-71.6	0.809
Withdraw	248.2	124.1	0.676
Layers	-39.8	-19.9	0.946
Coating*Solution	-236	-118	0.691
Coating*Withdraw	-601.7	-300.9	0.313
Coating*Layers	35.3	17.7	0.952
Solution*Withdraw	-15.8	-7.9	0.979
Solution*Layers	-571.7	-285.8	0.338
Withdraw*Layers	-79	-39.5	0.894

Coating*Solution*Withdraw	58.8	29.4	0.921
Coating*Solution*Layers	31.4	15.7	0.958
Coating*Withdraw*Layers	103.4	51.7	0.861
Solution*Withdraw*Layers	209.8	104.9	0.723
Coating*Solution*Withdraw*Layers	-293.4	-146.7	0.621

Figure 97. Anova analysis results for cool white arc tubes

For cool white arc tubes, the interaction effects and main effects are not significant at a 0.05 level. Among main effects, coating type has the biggest effect on luminous flux.

WARM WHITE – Luminous Flux

Term	Effect	Coef	P
Constant		30473.8	0
Coating	1011.6	505.8	0.264
Solution	109.4	54.7	0.903
Withdraw	-36.6	-18.3	0.967
Layers	-867.7	-433.9	0.336
Coating*Solution	207	103.5	0.817
Coating*Withdraw	-831.6	-415.8	0.357
Coating*Layers	944.9	472.5	0.296
Solution*Withdraw	-90.9	-45.4	0.919
Solution*Layers	-878.9	-439.5	0.33
Withdraw*Layers	-213.5	-106.7	0.812
Coating*Solution*Withdraw	749.6	374.8	0.406
Coating*Solution*Layers	-1398	-699	0.126
Coating*Withdraw*Layers	-164.5	-82.3	0.854
Solution*Withdraw*Layers	-161.4	-80.7	0.857
Coating*Solution*Withdraw*Layers	-1636.6	-818.3	0.075

Figure 98. Anova analysis results for warm white arc tubes

For warm white arc tubes, the interaction effects and main effects are not significant at a 0.05 level. Among main effects, coating type has the biggest effect on luminous flux. The three way interaction Coating*Solution*Layers has the biggest effect among interactions.

CCT:

COOL WHITE - CCT

Term	Effect	Coef	P
Constant		4287.35	0
Coating	14.46	7.23	0.904
Solution	67.04	33.52	0.577
Withdraw	-24.29	-12.15	0.84
Layers	-196.21	-98.1	0.109
Coating*Solution	-58.37	-29.19	0.627
Coating*Withdraw	86.79	43.4	0.471

Coating*Layers	37.71	18.85	0.753
Solution*Withdraw	-8.29	-4.15	0.945
Solution*Layers	-117.37	-58.69	0.331
Withdraw*Layers	85.96	42.98	0.475
Coating*Solution*Withdraw	198.96	99.48	0.104
Coating*Solution*Layers	-43.63	-21.81	0.716
Coating*Withdraw*Layers	-21.12	-10.56	0.86
Solution*Withdraw*Layers	-51.54	-25.77	0.668
Coating*Solution*Withdraw*Layers	-93.46	-46.73	0.438

Figure 99. Four containers of sol-gel solution used for arc tube coating

For cool lamps, the interaction effects and main effects are not significant at a 0.05 level. Among main effects, number of layers has the biggest effect on CCT. Coating*Solution*Withdraw – a three way interaction – has the biggest effect among interactions

WARM WHITE - CCT

Term	Effect	Coef	P
Constant		4680.77	0
Coating	5.63	2.81	0.947
Solution	0.62	0.31	0.994
Withdraw	75.29	37.65	0.378
Layers	46.71	23.35	0.583
Coating*Solution	-99.62	-49.81	0.245
Coating*Withdraw	4.38	2.19	0.959
Coating*Layers	-19.38	-9.69	0.819
Solution*Withdraw	51.37	25.69	0.546
Solution*Layers	78.79	39.4	0.356
Withdraw*Layers	122.62	61.31	0.155
Coating*Solution*Withdraw	-78.88	-39.44	0.356
Coating*Solution*Layers	-10.96	-5.48	0.897
Coating*Withdraw*Layers	46.54	23.27	0.584
Solution*Withdraw*Layers	21.71	10.85	0.798
Coating*Solution*Withdraw*Layers	219.63	109.81	0.014

Figure 100. ANOVA analysis results for warm white arc tubes

For warm white arc tubes, 4-way interaction, Coating*Solution*Withdraw*Layers, is significant at 0.05 alpha level. The main effects are not significant at a 0.05 level. Among main effects, withdrawal rate has the biggest effect on CCT.

CRI:

COOL WHITE - CRI

Term	Effect	Coef	P
Constant		64.6646	0

Coating Type	1.5708	0.7854	0.012
Solution	-0.9625	-0.4812	0.113
Withdraw	1.0125	0.5063	0.096
Layers	0.2125	0.1063	0.721
Coating*Solution	-0.9208	-0.4604	0.129
Coating*Withdraw	-1.1792	-0.5896	0.054
Coating*Layers	-0.5125	-0.2563	0.392
Solution*Withdraw	0.6208	0.3104	0.301
Solution*Layers	-0.4458	-0.2229	0.455
Withdraw*Layers	0.0792	0.0396	0.894
Coating*Solution*Withdraw	0.4292	0.2146	0.472
Coating*Solution*Layers	0.3958	0.1979	0.507
Coating*Withdraw*Layers	0.0542	0.0271	0.927
Solution*Withdraw*Layers	0.0208	0.0104	0.972
Coating*Solution*Withdraw*Layers	0.1625	0.0813	0.785

Figure 101. ANOVA analysis for cool white arc tubes

The two way - Coating*Withdraw interaction - is borderline significant and has the biggest effect among interactions. For cool lamps, the main effect – Coating type – is significant at a 0.05 alpha level. None of the interactions are significant. After coating type, withdrawal rate has the second biggest effect on CRI among main effects.

WARM WHITE – CRI

Term	Effect	Coef	P
Constant		52.9438	0
Coating Type	2.0625	1.0313	0.088
Solution	-0.3375	-0.1688	0.776
Withdraw	-0.3708	-0.1854	0.754
Layers	-0.5292	-0.2646	0.655
Coating*Solution	0.1708	0.0854	0.885
Coating*Withdraw	-1.8292	-0.9146	0.129
Coating*Layers	1.3125	0.6562	0.272
Solution*Withdraw	0.2375	0.1188	0.841
Solution*Layers	-1.1042	-0.5521	0.354
Withdraw*Layers	0.1458	0.0729	0.902
Coating*Solution*Withdraw	0.8792	0.4396	0.459
Coating*Solution*Layers	-1.9625	-0.9812	0.104
Coating*Withdraw*Layers	0.3208	0.1604	0.786
Solution*Withdraw*Layers	-0.1958	-0.0979	0.869
Coating*Solution*Withdraw*Layers	-1.5542	-0.7771	0.195

Figure 102. ANOVA analysis results for warm white arc tubes

For warm white arc tubes, no main or interaction effects are significant at a 0.05 level. Among the main effects, the coating type has the biggest effect on CRI. Coating*Solution*Layers interaction effect has the biggest effect among interactions.

MASS:

COOL WHITE - Mass

Term	Effect	Coef	P
Constant		10.0552	0
Coating	0.0178	0.0089	0.705
Solution	0.0584	0.0292	0.221
Withdraw	0.0075	0.0037	0.874
Layers	-0.0203	-0.0101	0.668
Coating*Solution	0.0581	0.029	0.223
Coating*Withdraw	0.0762	0.0381	0.113
Coating*Layers	-0.0053	-0.0026	0.911
Solution*Withdraw	-0.0164	-0.0082	0.728
Solution*Layers	0.0397	0.0198	0.402
Withdraw*Layers	0.0119	0.006	0.8
Coating*Solution*Withdraw	-0.0609	-0.0305	0.202
Coating*Solution*Layers	-0.0148	-0.0074	0.753
Coating*Withdraw*Layers	0.0311	0.0155	0.511
Solution*Withdraw*Layers	-0.0282	-0.0141	0.551
Coating*Solution*Withdraw*Layers	-0.0105	-0.0053	0.824

Figure 103. ANOVA analysis results for cool white arc tubes

No main effects or interaction effects are significant at a 0.05 alpha level. Among the main effects, solution concentration has the biggest effect on mass.

WARM WHITE - Mass

Term	Effect	Coef	P
Constant		9.92454	0
Coating	-0.01567	-0.00783	0.739
Solution	0.03533	0.01767	0.454
Withdraw	-0.08292	-0.04146	0.085
Layers	-0.04033	-0.02017	0.394
Coating*Solution	-0.06492	-0.03246	0.174
Coating*Withdraw	-0.075	-0.0375	0.118
Coating*Layers	-0.12892	-0.06446	0.009
Solution*Withdraw	0.00083	0.00042	0.986
Solution*Layers	-0.11542	-0.05771	0.019
Withdraw*Layers	-0.03267	-0.01633	0.489
Coating*Solution*Withdraw	-0.04775	-0.02387	0.314
Coating*Solution*Layers	0.0175	0.00875	0.71
Coating*Withdraw*Layers	-0.04625	-0.02312	0.329
Solution*Withdraw*Layers	-0.03592	-0.01796	0.447
Coating*Solution*Withdraw*Layers	-0.035	-0.0175	0.459

Figure 104. ANOVA analysis results for warm white arc tubes

For warm white arc tubes, the two way interactions Solution*Layers and Coating*Layers are significant at 0.05 alpha level. No main effects are significant. Among the main effects, withdrawal rate has the biggest effect on mass.

Summary of results

Shown here is a summary table of the data shown above. The table illustrates the main effects on the responses measured in this experiment.

	Coating Type	Solution Concentration	Withdrawal Time	Layers
Cool White Luminous Flux	Strong			
Cool White CCT				
Cool White CRI	Statistically Significant			
Cool White Mass				
Warm White Luminous Flux				
Warm White CCT				
Warm White CRI	Strong			
Warm White Mass			Strong	

Figure 105. Summary of results showing effects of main variables without interactions.

The primary variables solution concentration and the number of layers did not have any statistical significance. A statistically significant response is one that shows a P value of less than 0.05.

CRI showed a dependency on the type of coating for both cool white and warm white arc tubes.

The type of coating produced a strong correlation to the luminous flux for the cool white arc tubes.

The withdrawal time of the arc tube from the coating bath produced the strongest effect on the mass of warm white arc tubes.

The interactions of the variables were also examined. The summary table below shows the effects of the variable interactions on the measured responses.

	2-way interactions	4 way interactions
Cool White Luminous Flux		
Cool White CCT		
Cool White CRI		
Cool White Mass		

Warm White Luminous Flux		Strong – Interaction of coating type, solution concentration, withdrawal time and number of layers
Warm White CCT		Statistically Significant - Interaction of coating type, solution concentration, withdrawal time and number of layers
Warm White CRI		
Warm White Mass	Statistically Significant: Solution*Layers and Coating type*Layers	

Figure 106. Summary of relevant effect interactions of variables

Two two-way interactions, solution*layers and coating type*layers are statistically significant in warm white mass response.

In one case, a 4-way interaction of the variables showed a statistically significant effect. In the case of the luminous flux of warm white arc tubes, the interaction of coating type, solution concentration, withdrawal time and the number of layers produced the strongest effect. The combination of variables produced a statistically significant effect on the luminous flux of warm white arc tubes.

The interaction of these four variables is notable since combinations of variables will lead to the thickest or thinnest coating of material on the arc tube. It is conceivable that the additive effects of the variable could lead to this result and it requires the interaction of all variables to reach a level of significance.

We have demonstrated effects on the performance of responses due to the changes in the variables of this experiment.

VLI MH Arc Tube Measurement

Venture Lighting assembled a number of the coated and uncoated arc tubes into HID lamps.

Figure 107. Summary of relevant effect interactions of variables

The arc tubes were mounted in quartz outer jackets as shown here.

Figure 108. Summary of relevant effect interactions of variables

The arc tube is sealed within the outer jacket. Once the lamp is fabricated, it is “burned in” for approximately 100 hours then photometric measures are taken

Figure 109. Summary of relevant effect interactions of variables

The large sphere shown here is part of Venture Lighting's photometric department.

Show here are lamps on the "burn-in" and "life-test" racks.

Figure 110. Coated 400W arc tubes in lamps on lifetest rack at VLI

Photometry of the finished lamps was taken and is shown here.

Lamp Type: MS 400W/V/PS/740										
Orientation: BU										
Lp Num	Lp Power	Lp Volts	Lp Curr	P.F.	Lumens	CCx	CCy	CCT	CRI	Lp Hrs
01-W	400.1	121.6	3.554	0.926	30920	0.342	0.37	5177	53.3	125
04-C	399.9	131.2	3.251	0.937	42577	0.382	0.408	4176	66.9	125
06-C	400.4	139.1	3.081	0.935	43269	0.388	0.406	4014	66.7	125
21-W	400.6	125	3.48	0.921	33431	0.344	0.371	5101	58.3	125
34-C	398.9	132	3.226	0.937	43822	0.385	0.409	4088	67.3	125

Figure 111. Photometry of HID lamps at 125 hours

Lp Num	Lp Power	Lp Volts	Lp Curr	P.F.	Lumens	CCx	CCy	CCT	CRI	Lp Hrs
01-W	400.5	126.2	3.451	0.919	33518	0.344	0.371	5115	57.2	681
04-C	400.9	134	3.21	0.932	42506	0.386	0.408	4065	67.4	681
06-C	401.9	144.8	2.995	0.927	42236	0.39	0.408	3975	68	681
21-W	401.7	130.1	3.355	0.921	35545	0.344	0.375	5126	60.4	681
34-C	402	134.8	3.217	0.927	42000	0.383	0.404	4126	66.8	681

Figure 112. Photometry of HID lamps at 681 hours

A key to the lamp types tested is given here.

Lamp ID (Lp Num)	Coating Type	Dose Type
01-W	SiO ₂	Warm
04-C Uncoated	No Coat	Cool
06-C	TiO ₂	Cool
21-W	TiO ₂	Warm
34-C	SiO ₂	Cool

Figure 113. Key to lamp type in photometry data

The arc tubes contained either of two dose types – “warm” or “cool”. The arc tubes were coated with either SiO₂ or TiO₂. One uncoated arc tube was included as a control.

Graphical presentation of comparisons of lumen output, CCT and CRI are shown here.

Figure 114. Comparison of lumen output from lamps tested

The lumen output remained nearly constant for the uncoated lamp at the 681 hour mark. Lumen output increased by about 2000 lumens for each of the warm dose lamps, seemingly independent of the coating type. Lumen output from cool dose lamps decreased over the time period by about 1000 and 2000 lumens for each lamp.

Figure 115. Comparison of CCT from lamps tested

No discernible shifts in CCT are seen in the data over the testing period between the lamp coating types.

Figure 116. Comparison of CRI from lamps tested

The CRI remained nearly constant for the uncoated lamp at the between the 125 and 681 hour marks. The CRI increased in each of the warm dose lamps with the SiO₂ coated arc tube increase being more than that seen with the TiO₂ coated arc tube. The CRI showed less change in the cool dosed lamps with the TiO₂ coated arc tube increasing over time while the SiO₂ coated arc tube remained steady.

Arc Source Multi-Layer Coatings to Double Lighting System Lifetimes without Affecting Performance.

Figure 117. Accelerated life testing shows that coated lamps can undergo 4 times more starts before failure.

This effort focused on increasing the lifetime of conventional MH lamps by investigating the beneficial effects of coatings. We succeeded in quadrupling the life of 70W DC MH arc lamps by inhibiting certain failure modes related to quartz devitrification. The above figure summarizes the results for lamps coated with a 4-layer Tantalum-Silicon oxide coating using LPCVD. The magnetron sputtering and sol-gel methods also produce coatings which show lamp life improvements. The lamps were coated using a variety of optical coatings in both oxides and nitrides in order to evaluate spectral, conductive, interactive and barrier effects.

A listing of coated arc tubes is given here.

			ID										
Run				1119	from proposal (not tested and confirmed yet)								
					Spectral	Barrier	Conductive	Reference	UV or IR	AR	Nitride	Oxide	Metal
Machine	Quote	Coating Description	Qty										
41375	Run 1a	Single layer of Si-160A	16										
41374	Run 1b	Single layer of Si-120A	16			*							*
41373	Run 1c	Single layer of Si-80A	16										
41379	Run 2	Single layer of Si3N4 1000A	48			*					*		
41371	Run 3	Single layer of SiO2 1000A	48			*		*				*	
41381	Run 4	AR of SiO2/Si3N4	48		*					*			
41385	Run 5a	Single layer of Ta-160A	16										
41384	Run 5b	Single layer of Ta-120A	16			*	*						*
41383	Run 5c	Single layer of Ta-80A	16										
41386	Run 6	Single layer of TaO2 1000A	45			*		*				*	
41389	Run 7	AR of Ta2O5/SiO2	42		*			*		*			
41390	Run 8	Rod coating Ta2O5/SiO3	49		*				*				
41391	Run 9	IR Reflector Ta2O5/SiO2	49		*				*				
41388	Run 10	"Tint" coating Ta2O5/SiO2	48		*				*				
41395	Run 11a	Single layer of Zr-160A	16										
41394	Run 11b	Single layer of Zr-120A	16			*							*
41393	Run 11c	Single layer of Zr-80A	16										
41397	Run 12	Single layer of ZrO2 1000A	45			*						*	
41399	Run 13	UV reflector ZrO2/SiO2	48		*				*				
41398	Run 14	IR Reflector ZrO2/SiO2	48		*				*				
41402	Run 15a	Single layer of Al-160A	16										
41401	Run 15b	Single layer of Al-120A	16			*							*
41400	Run 15c	Single layer of Al-80A	16										
41403	Run 16	Single layer of AlN 1000A	48			*					*		
41404	Run 17	Single layer of Al2O3 1000A	48			*						*	
41407	Run 18a	Single layer of Ti-160A	13										
41406	Run 18b	Single layer of Ti-120A	13			*							*
41405	Run 18c	Single layer of Ti-80A	13										
41408	Run 19	Single layer of TiO2 1000A	48			*						*	
41409	Run 20	Single layer of TiN 1000A	48			*	*				*		
41412	Run 21a	Single layer of Sn-160A	15										
41411	Run 21b	Single layer of Sn-120A	15				*						*
41410	Run 21c	Single layer of Sn-80A	15										
41413	Run 22	Control_Pre-clean_no coat	50					*					
	NC	Uncoated	83					*

Figure 118. Experimental matrix of lamp coatings, primary mechanisms and materials (left), all-metal Sn (tin) coated lamps (right). The lamps with pure metal coatings all undergo thermal oxidization to become clear barrier coatings within seconds of starting the lamp.

After the initial success of improving lamp life using the 4-layer LPCVD coatings, a complete battery of thin film materials and structures were evaluated. The above figure shows the experimental matrix of coatings classified by type and material. The spectral, conductive, and barrier categories have been used to classify 23 coatings including single and multilayer stacks of nitrides, oxides, and base metal in spectrally neutral, tinted, UV and/or IR filtering coatings of the elements Si, Ta, Ti, Zr, Al, and Sn. The second set of coatings was completed from a subset of the most promising screening coatings: an anti-reflective multilayer stack of the oxide of Ta, single layer of the Ta oxide, and single layer of the base metal Sn. There is a different spectral effect for each type of coating independent of coating method.

The figure here summarizes the results of the life testing. Several of the coatings in two different material systems have beneficial effects on lamp life.

Coatings Life Summary	Tested to:		Coating Runs				Median Life	
	Starts	Hours					Starts	Hours
Successful	12000	10000	TaO2	Ta2O5/SiO2 #1	Ta2O5/SiO2 #2	Sn	6000	8000
Borderline	12000	10000	Si	ZrO2	Control_Pre-clean	TiN	3500	5000
Failure	8000	6000	Si3N4	SiO2	SiO2/Si3N4	Ta	2000	3000
			ZrO2/SiO2 #1	Al	AlN	Al2O3		
			Ta2O5/SiO2 #3	Ta2O5/SiO2 #4	ZrO2/SiO2 #2	Zr		
			Ti	TiO2	Control_Baseline			

Figure 119. Condensed summary of life effects for the coating matrix tested by EFOI. The 8000 hour life is not representative of the results of the proposed effort.

Three coatings have little or no effect while fourteen have a detrimental effect. In addition to the effect on lamp life, extensive photometric data was collected on the entire suite of coated lamps as shown here. Some coatings have dramatic and beneficial effects on CRI and CCT while others are marginal or detrimental.

ID				Photometric results																
Run			1119	199	Input				Lamp											
Machine	Quote	Coating Description	Qty	100 hr	V	I	W	LPW	V	I	W	LPW	Lum	CCT	CRI	ccx	ccy	R9	CCT σ	
41375	Run 1a	Single layer of Si-160A	16	9	120.0	0.770	75.6	77.1	101.8	0.667	67.8	85.9	5825	3986	67.8	0.379	0.365	-85	351	
41379	Run 2	Single layer of Si3N4 1000A	48	9	120.7	0.793	76.1	74.9	94.8	0.718	67.8	84.0	5698	3730	70.6	0.389	0.369	-76	312	
41371	Run 3	Single layer of SiO2 1000A	48	8	120.3	0.829	77.4	77.8	94.6	0.729	68.9	87.3	6016	4035	67.6	0.378	0.369	-87	247	
41381	Run 4	AR of SiO2/Si3N4	48	9	119.3	0.837	76.9	79.7	96.7	0.714	68.6	89.2	6124	3757	69.5	0.389	0.372	-65	372	
41385	Run 5a	Single layer of Ta-160A	16	9	120.7	0.735	76.9	75.3	94.5	0.730	68.8	84.1	5811	3734	71.6	0.392	0.373	-70	247	
41386	Run 6	Single layer of TaO2 1000A	45	9	120.1	0.810	76.4	76.9	97.4	0.701	68.2	86.1	5870	3830	73.0	0.384	0.368	-65	215	
41389	Run 7	AR of Ta2O5/SiO2	42	8	119.6	0.738	76.5	80.3	97.7	0.704	68.6	89.5	6145	3812	70.1	0.385	0.368	-78	267	
41390	Run 8	Rod coating Ta2O5/SiO3	49	7	120.4	0.806	76.2	78.0	95.9	0.711	68.0	87.3	5939	3355	76.3	0.409	0.383	-51	152	
41391	Run 9	IR Reflector Ta2O5/SiO2	49	9	118.9	0.831	76.4	67.8	96.6	0.707	68.3	75.8	5177	3356	81.2	0.408	0.381	-25	178	
41388	Run 10	"Tint" coating Ta2O5/SiO2	48	9	120.8	0.773	76.4	78.3	100.2	0.684	68.4	87.4	5979	3347	70.7	0.410	0.383	-72	150	
41395	Run 11a	Single layer of Zr-160A	16	9	120.7	0.730	76.3	77.0	97.4	0.707	68.6	85.7	5876	3645	71.4	0.393	0.373	-72	285	
41397	Run 12	Single layer of ZrO2 1000A	45	9	122.1	0.749	76.2	75.7	96.2	0.712	68.4	84.3	5770	3650	73.9	0.393	0.372	-60	286	
41399	Run 13	UV reflector ZrO2/SiO2	48	9	120.5	0.803	76.2	81.6	100.0	0.686	68.1	91.2	6212	3675	73.5	0.392	0.372	-64	206	
41398	Run 14	IR Reflector ZrO2/SiO2	48	9	121.9	0.741	76.2	70.9	94.7	0.722	68.4	79.0	5399	3016	77.8	0.432	0.396	-38	111	
41402	Run 15a	Single layer of Al-160A	16	8	122.6	0.723	76.2	75.8	97.4	0.703	68.4	84.4	5776	3988	67.5	0.378	0.363	-87	379	
41403	Run 16	Single layer of AlN 1000A	48	9	123.0	0.722	76.4	76.5	93.0	0.735	68.4	85.4	5841	3931	68.6	0.381	0.369	-83	293	
41404	Run 17	Single layer of Al2O3 1000A	48	9	122.7	0.718	76.8	74.3	91.8	0.749	68.7	83.0	5704	3769	68.5	0.384	0.367	-84	338	
41407	Run 18a	Single layer of Ti-160A	13	9	122.6	0.717	76.6	77.9	94.1	0.732	68.8	83.8	5973	3574	72.8	0.399	0.380	-66	207	
41408	Run 19	Single layer of TiO2 1000A	48	9	118.3	0.846	76.5	75.3	95.8	0.713	68.2	84.4	5757	3518	75.7	0.404	0.391	-53	204	
41409	Run 20	Single layer of TiN 1000A	48	9	122.8	0.713	76.3	76.4	91.7	0.744	68.2	85.4	5825	3903	68.4	0.382	0.370	-84	206	
41412	Run 21a	Single layer of Sn-160A	15	6	119.9	0.738	76.6	78.4	90.7	0.757	68.6	87.5	6005	3764	69.6	0.388	0.372	-81	209	
41413	Run 22	Control_Pre-clean_no coat	50	9	123.5	0.707	76.1	77.0	91.3	0.746	68.0	86.2	5863	3913	68.3	0.382	0.368	-85	345	
	NC	Uncoated	83	9	120.2	0.792	76.7	75.3	88.7	0.775	68.2	84.7	5776	4039	66.6	0.376	0.363	-91	169	
		Phase II- Super Control	181	26	121.3	0.776	76.7	76.7	91.5	0.750	68.4	86.1	5885	3995	67.5	0.378	0.367	-88	253

Figure 120. Photometric results of lamp coating material matrix. Some single layer coatings are surprisingly effective at achieving a beneficial color correction.

Summary

DOE has enabled the use of coating materials using low cost application methods on light sources to positively affect the output of those sources. The coatings and light source combinations have shown increased lumen output of LED fixtures (1.5%-2.0%), LED arrays (1.4%) and LED powered remote phosphor systems – Philips L-Prize lamp (0.9%). We have also demonstrated lifetime enhancements (3000 hrs vs 8000 hrs) and shifting to higher CRI (51 to 65) in metal halide high intensity discharge lamps with metal oxide coatings.

The coatings on LEDs and LED products are significant as the market is moving increasingly more towards LED technology. Enhancements in LED performance are demonstrated in this work through the use of available materials and low cost application processes.

EFOI used low refractive index fluoropolymers and low cost dipping processes for application of the material to surfaces related to light transmission of LEDs and LED products. Materials included Teflon AF, an amorphous fluorinated polymer and fluorinated acrylic monomers.

The DOE SSL Roadmap sets goals for LED performance moving into the future. EFOI's coating technology is a means to shift the performance curve for LEDs. This is not limited to one type of LED, but is relevant across LED technologies.

The metal halide work included the use of sol-gel solutions resulting in silicon dioxide and titanium dioxide coatings on the quartz substrates of the metal halide arc tubes. The coatings were applied using low cost dipping processes.

Key points for additional work.

1. Expand investigation of materials – EFOI has evaluated a limited palette of materials, metal oxides and fluoropolymers. Other materials within these two groups may find wider spread or more specific enhanced benefits. EFOI has defined a solution for high temperature applications like MH and low temperature applications like LED fixtures. There are more material solutions that should be investigated.
2. Evaluate other coating application processes – EFOI made use of low cost dipping type coating approaches. Further investigation and evaluation of other low cost coating methods should be carried out.
4. Optimize coatings to surfaces – Coating flat and smooth surfaces is less problematic than curved surfaces or surfaces with abrupt changes. Investigations should be made into coating non-curved and featured surfaces.

5. Equipment development – For large scale application of coatings on production pieces, coating equipment will need to be designed and developed. The equipment would be designed for applying coatings to a specific part that would be fabricated into a lighting fixture.

6. Optimizing coatings with LEDs – EFOI demonstrated that applying coatings to LEDs can be beneficial. We provided a single solution to this application. Further work should be done to identify additional materials and coating methods to enhance LED performance.