High Intensity Discharge Lighting Technology

Workshop Report
November 15, 2005
Washington, DC

Prepared for:

Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy

Building Technologies
Conventional Lighting R&D

Prepared by:

ICF Consulting

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COMMENTS

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EXECUTIVE SUMMARY

On November 15, 2005, the U.S. Department of Energy (DOE) held a High Intensity Discharge (HID) Lighting Technology Workshop to examine the current state of HID technologies and identify research and development (R&D) opportunities to enhance the performance, efficiency, and use of HID technologies in commercial lighting applications. Thirty-four HID technology experts gathered in Arlington, Virginia to present papers and participate in open dialogue to help identify the potential of HID technology.

The goal of the Workshop was to identify the current state of HID technology, including the current technical challenges, past R&D efforts, and opportunities to improve HID lighting capabilities for wide-spread adoption in commercial buildings. Specific objectives to help achieve the goal were: 1) gather input from experts in attendance, 2) identify cutting edge R&D efforts and challenges, and 3) identify existing metal halide (MH) performance and improvements that can be achieved within five to ten years, which would yield significant energy savings and increased market penetration. To achieve these objectives and the overarching goal, the attendees were asked to focus on science and engineering advances while considering new interior and exterior applications for HID technologies.

The workshop format was highly interactive. The morning sessions consisted of paper presentations from leading HID experts in industry and academia. The afternoon session was an open roundtable discussion led by a professional facilitator. The combination of prepared papers, prepared discussions, and open discussions supported the workshop objectives and provided valuable information that demonstrates the energy savings opportunity for HID, and specifically MH.

According to DOE's *U.S Lighting Market Characterization Report*, HID lighting holds significant opportunities to contribute to national energy savings. The paper presenters and attendees feel that MH holds the most opportunity to realize these energy savings. The prepared papers gave significant information on the current state of technologies and research. The discussions provided additional detailed information on what research is needed to overcome technical barriers and achieve increased performance and adoption of MH technology.

In addition, new research tools and methods were presented and discussed. These new tools and methods have recently become available in the past few years and offer an opportunity to provide analysis of the arc tube plasma and chemical fill that has not previously been possible. These new analytical tools allow the scientists to gain a deeper understanding of the performance inside the arc tube and analyze different chemical fills.

Table ES-1 below lists the potential for MH lamp performance based on the attendees' expert opinions. These potential performance improvements are significant compared to the current state of technology, but are only achievable by overcoming the existing technical barriers such as restrike issues, color shift, improving color rendering and reducing source size. The attendees feel these improvements, resulting in marketable products and energy savings, are achievable within the next five to ten years. However, the degree of the improvements will vary depending on the wattage size and technical approach used to improve the system.

Table ES-1: 5-10 Year Outlook of Potential Advancements through Additional R&D

Wattage Range	Low Wattage (≤70)		Medium Wattage (100-250)		High Wattage (300-400)	
MH Lamp Type	**Quartz**	**Ceramic**	**Quartz**	**Ceramic**	**Quartz**	**Ceramic**
Ballast Type	Electronic	Electronic (Integrated 70 w)	Electronic	Multi-lamp Electronic	Electronic	Multi-lamp Electronic
Ballast Efficiency	95%	95%	95%	95%	97%	97%
	Potential improvement over current MH technologies: 5 – 30%					
Lamp Efficacy (LPW)	100	125	110	130	120	135
	Potential improvement over current MH technologies: 10 – 50%					
System Efficacy (LPW)	95	115	100	125	110	130
	Potential improvement over current MH technologies: 12 – 50% or more					
Initial Lumens	7,000	8,750	27,500	32,500	48,000	54,000
	Potential increase over current MH technologies of same wattage: 15% or more					
Lumen Maintenance	90%	95%	90%	95%	90%	95%
	Potential improvement over current MH technologies: 12% or more					
CCT Shift in Degrees Kelvin	300	75	300	75	300	75
	Potential improvement over current MH: Reduce by 300K or to indistinguishable level					
Lamp Life in Hours	20,000	25,000	25,000	30,000	25,000	30,000
	Potential improvement over current MH: slight increase to two times, depending on approach					
Warm Up (to full light)	30 sec	30 sec	1 min	1 min	1 min	1 min
	Potential improvement over current MH: Reduced by 50% or more					
Restrike (to strike the arc)	<1 min	< 1 min	<2 min	<2 min	<2 min	<2 min
	Potential improvement over current MH: Reduced by 50% or more					
Other Potential Improvements	Coatings*	Continuous dimming	Coatings*	Continuous dimming	Coatings*	Continuous dimming

Source: High Intensity Discharge Lighting Technology Workshop, November 15, 2005 presentations and discussions from industry experts.
*Coatings: improved coatings could increase LPW (lumens per watt)

Table ES-2 lists the eight R&D topics the attendees believe can yield significant energy savings and/or overcome major technical barriers that impede wider adoption of MH technology. These eight were identified as the primary topics that must be addressed to achieve the improvements outlined in Table ES-1.

Table ES-2: Eight Suggested Areas for R&D

R&D Topic	Potential Goals
System Approach for Restrike	• < 1 minute restrike for low watt lamps • < 2 minute restrike for 100 to 400 watt • Refinement and practical application on microcavity plasma devices
Smooth/Continuous Dimming	• Continuous dimming to 10%
Characterization of Optical Processes: Photoassociation, Infrared Emission, and Metal-Halide Spectra	• 10% efficacy improvement • Improved color rendering • Ability to better select salt ratios and doses
Ballast Systems	• Reduce source size • Reduce ballast losses to 3% • Reduce color shift to <100K • More cost-effective electronic ballasts
Coatings	• Develop coatings that easily adhere to the bulb wall • 10-20% efficacy improvement • Reduce color shift • Improved lumen maintenance
Chemical Fill Optimization	• 10% or more efficacy improvement • Improved lumen maintenance • Reduce arc tube and lamp size
Arc Tube Material (quartz, PCA, Sapphire, Yttrium Oxide)	• 10% or more efficacy improvement • Reduce arc tube and lamp size
System Optimization (lamp/ballast/luminaire)	• 5% or more efficacy improvement • Reduce arc tube and lamp size • Improved lumen maintenance

The topics of restrike, use of coatings, and reduction of infrared losses received the most discussion. The attendees stressed that achieving the improvements necessary for wide-spread market adoption, such as instant restrike, is not easy. However, further exploration in areas such as microcavity plasma devices for instant restrike offers very promising results. In addition, coatings to reduce infrared losses and increase visible light production are an improvement that can yield significant efficacy gains, not only in terms of increasing efficacy, but can also extend lamp life, enhance performance, and reduce lamp manufacturing costs.

Throughout the Workshop the attendees kept in mind the importance of practical applications that yield real energy savings. To that extent, many of the attendees appeared excited about the potential of advanced HID technologies to replace many incandescent and halogen lamps in retail and commercial applications. Because MH lamps are a point source and their light can be focused, low-wattage MH lamps can be used where compact fluorescent lamps are not practical, such as retail and downlights in ceilings above 15 feet. Incandescent and halogen applications offer the greatest savings, but there are also savings to be gained by replacing older fluorescent and HID technologies.

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ABBREVIATIONS AND ACRONYMS

AC	Alternating Current
ADLT	Advanced Lighting Technologies, Inc.
ALITE	Advanced Light Source Research Consortium
APL	APL Engineered Materials, Inc.
BN	Boron Nitride
CCT	Correlated Color Temperature
CDM	Ceramic Discharge Metal Halide
CFL	Compact Fluorescent Lamp
CMH	Ceramic Metal Halide
COTS	Commercial-Off-The-Shelf
CPC	Compound Parabolic Concentrator
CWA	Constant Wattage Autotransformer
CRI	Color Rendering Index
CVD	Chemical Vapor Deposition
DC	Direct Current
DOE	Department of Energy
DOE	Design of Experiments
EFO	Efficient Fiber Optics
EMI	Electromagnetic Interference
EPRI	Electric Power Research Institute
HED	High Efficiency Distributed
HID	High Intensity Discharge
HPM	High Pressure Mercury
HPS	High Pressure Sodium
IR	Infrared
LED	Light-Emitting Diode
LPW	Lumens Per Watt
MH	Metal Halide
MV	Mercury Vapor
NEMA	National Electrical Manufacturers Association
NIST	National Institute of Standards and Technology
OLED	Organic Light-Emitting Diodes
PAR	Parabolic Aluminized Reflector
PECVD	Plasma Enhanced Chemical Vapor Deposition
QMH	Quartz Metal Halide
R&D	Research and Development
SEM	Scanning Electron Microscopy
SO	Simplex Optimization
SPD	Spectral Power Distribution
UHP	Ultra High Performance (High Pressure)
UV	Ultraviolet
VLI	Venture Lighting International, Inc.

OTHER TERMS

Degrees Kelvin - Measurement of the absolute temperature scale used to describe the color temperature appearance of a light source.
Dose - Recipe of rare earth halides and other chemicals introduced into the lamp arc tube.
Color Shift - Change in correlated color temperature.

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1. Introduction

On November 15, 2005, the U.S. Department of Energy (DOE), Building Technologies Program, and the National Electrical Manufacturers Association (NEMA) hosted the High Intensity Discharge (HID) Lighting Technology Workshop. In attendance were 34 HID technology experts from industry, academia, research organizations, and other government agencies. The Workshop was held in Arlington, Virginia to examine the current state of HID technologies and identify R&D opportunities to enhance the performance, efficiency, and use of HID technologies in commercial lighting applications.

High Intensity Discharge lighting accounts for 26 percent of the lighting energy use in the United States. Based on this large usage, small efficacy improvements to existing technologies could yield significant national energy savings. Yet, there are specific technical barriers that have limited the performance of HID technologies, and thus their wider adoption in the commercial marketplace. Technology experts and lighting designers agree that overcoming these technical barriers, such as color shift and restrike, would open more markets to HID. New technologies could widely replace older systems, such as incandescent and possibly fluorescent, in large use areas including retail and commercial.

The Workshop consisted of several prepared papers and presentations, prepared discussions, and facilitated open discussion sessions. The papers provided background information on the current state of HID technologies and R&D efforts, R&D challenges, and potential opportunities for efficacy and performance gains achievable through further research. The prepared discussions expanded on the papers and opened up the roundtable discussion. The papers and discussions primarily focused on metal halide (MH) lamp, ballast, and luminaire technologies mainly because MH is more advanced in terms of color and other performance issues that are required for commercial applications. Sodium and mercury vapor technologies were briefly discussed, but the attendees feel MH offers the most opportunity.

Chapters 2 and 3 of this report provide information on the goals of the Workshop and DOE's interest in HID technologies. Chapter 4 provides background information on current state of HID technologies and past research efforts, while Chapter 5 provides summaries of the papers and presentations. The attendee's comments and discussion are captured in Chapters 6 and 7. In Chapter 6, Table 6-2 provides a summary of the potential advancements that could be achieved through additional R&D. Chapter 7 provides details on eight R&D topics that attendees believe can yield significant energy savings and/or overcome major technical barriers that impede wider adoption of MH technology.

2. Workshop Goals and Objectives

The Department's goal for the Workshop was to identify the current state of High Intensity Discharge (HID) technology, including the current technical challenges, past R&D efforts, and opportunities to improve HID lighting capabilities for wide-spread adoption in commercial buildings.

Specific objectives to help achieve the goal were accomplished by the following:

- Gather Input from Expertise in Attendance
- Identify Cutting Edge R&D
- Identify Cutting Edge R&D Challenges
- Identify where Technology is Now and in the Future (5, 10 years)
- Focus on Science and Engineering Advances
- Consider New Interior and Exterior Applications

In addition, attendees wrote three specific R&D challenges that impede further advancement of HID technologies. This information was used in discussion at the Workshop to create of an outline covering the eight key R&D topics to advance the present status of HID technology through performance and efficacy improvements for potential energy savings in interior and exterior commercial applications. The outcome includes eight key topics that are further discussed in Chapter 7 of this report.

3. DOE Interest in HID Technologies

3.1 Building Technologies Program Mission Statement

The Building Technologies Program is designed to create technologies and design approaches that enable net-zero energy buildings at low incremental cost by 2025. A net-zero energy building is a residential or commercial building with greatly reduced needs for energy through efficiency gains, with the balance of energy needs supplied by renewable technologies. These efficiency gains will have application to buildings constructed before 2025 resulting in a substantial reduction in energy use throughout the sector.

3.2 Lighting Research and Development Technical Objective

By 2025, the Department's technical objective is to develop and demonstrate energy-efficient, high-quality, long-lasting lighting technologies that have the technical capability of illuminating our buildings using 50 percent less electricity compared to technologies in 2005.

3.3 DOE's HID Technology Interest

The Department is working in close collaboration with research and industry partners to increase end-use efficiency in buildings by aggressively pursuing R&D challenges with evolving lighting technologies. The Department's HID technology interest is:

- Push Technology Envelope – Research and Development (R&D)
- Achieve Energy Savings
- Assess the Need for Advanced Technology and R&D Efforts
- Advance HID Applications for Existing Applications
- Advance HID to Expand into New Applications

3.4 Energy Use of Savings Potential of HID Technologies

As reported in the *U.S. Lighting Market Characterization Volume II: Energy Efficient Light Technology Options Final Report*, the total energy consumption in the United States in 2001 was 98.3 quadrillion BTU's (98.3 quads), of which 37 quads were used for electricity production. Table 3-1 below shows the national energy use for lighting by end-use sector. The commercial sector was the largest energy user, consuming more than half of the lighting energy.

Table 3-1: U.S. National Energy Use for Lighting, Disaggregated by Sector

Sector	Electricity Use per Building (kWhr/yr)	Number of Buildings	Site Energy (TWh/yr)	Primary Energy (quads)	Percent of Total
Residential	1,946	106,989,000	208	2.2	27
Commercial	83,933	4,657,000	391	4.2	51
Industrial	475,063	227,000	108	1.2	14
Outdoor Stationary	n/a	n/a	58	0.6	8
Totals			765	8.2	100

Source: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy Building Technologies Program. "U.S. Lighting Market Characterization. Volume II: Energy Efficient Lighting Technology Options Final Report". September 2005. P 2.

The energy savings potential by making improvements to HID sources is significant given that HID lamps are responsible for 26 percent of the light produced each year (*U.S. Lighting Market Characterization Volume I: National Lighting Inventory and Energy Consumption Estimate Final Report. September 2002. P. 39*). Table 3-2 below presents ten technology options relating to improving the performance of HID light sources and provides the technical potential energy savings of each.

Table 3-2: Summary Table for Light Sources: HID

Description	Technology Maturity Stage	Technical Potential Energy Savings
HID Restrike Issues	Advanced Development	0.6 quad
HID Integral Ballast	Advanced Development	0.7 quad
HID Low -Wattage	Engineering Development	0.7 quad
HID Novel Gas	Applied Research	0.7 quad
HID Ceramic Arc Tube Research	Commercialization & Sales	1.2 quads
HID Electrode Research	Applied Research → Exploratory Development	0.2 quad
HID Electrodeless Lamp	Engineering Development	0.6 quad
Metal Halide Electronic Ballast (HF)	Engineering Development → Commercialization & Sales	0.2 quad
HID Dimmable Ballast	Engineering Development → Commercialization & Sales	0.4 quad
Sulfur Lamp	Advanced Development	0.8 quad

Source: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy Building Technologies Program. "U.S. Lighting Market Characterization. Volume II: Energy Efficient Lighting Technology Options Final Report". September 2005. P vi.

4. Background Summary of Current HID Technologies and R&D

This chapter provides a brief summary of current High Intensity Discharge (HID) technologies, their applications, trends, and currently known R&D efforts. Section 4.1 provides a summary of an HID background paper presented to DOE management. Section 4.2 compliments Section 4.1 by providing additional information on the co-existence of quartz and ceramic metal halide lamps in the market. Section 4.3 provides the latest public information on the ALITE program.

4.1 Current Status of HID Lamp Technology

The following information is a brief summary from the Walitsky and Vrabel paper "*General Technology Overview of the Current Status of High Intensity Discharge Lamp Technology*." This paper was presented to DOE on October 27, 2005 by Walitsky and Vrabel of ICF Consulting. The full paper is available in Appendix B.

4.1.1 Technologies and Applications

The High Intensity Discharge lamp family is composed of three distinct lamp types: Mercury Vapor (MV), High Pressure Sodium (HPS), and Metal Halide (MH). Low Pressure Sodium (LPS), while technically a low pressure discharge lamp, is often considered by industry a part of the HID family. LPS serves in particular applications as if it were an HID lamp, but is outside the purpose of this paper and not further discussed. Table 4-1 below summarizes the different characteristics of each lamp type, including different types of MH lamps.

Table 4-1: HID Lamps and Performance

	Mercury Vapor	High Pressure Sodium	Probe Start Metal Halide	Pulse Start Metal Halide	Ceramic Metal Halide
Wattage Range	**40-1000**	**35-1000**	**50-2000**	**50-2000**	**20-400**
System Efficacy (LPW)*	**39**	**94**	**51**	**68**	**87++**
Lumen Maintenance (Mean life)	**50%**	**90%**	**65%-75%**	**70%-80%**	**85%-90%**
CRI***	**22-45**	**21-25**	**65-70**	**62-96**	**81-95**
CCT* (^{0}K)**	**3700-6800**	**1800-2700**	**3000-4200**	**2900-5200**	**2900-4200**
Color Shift (^{0}K)	**+/-100**	**+/-100**	**+/-500**	**+/- 500**	**+/-200**
Warm up time (minutes)	**5-7**	**3-4**	**5-7**	**2**	**2**
Life (hours) ***	**24,000+**	**24,000+30,000**	**10,000-20,000**	**6000-20,000**	**9,000-20,000**

* using 400 watt lamps
++ using electronic ballast
*** Lifetimes, CCT and CRI from Osram Sylvania, Philips Venture and GE online catalogs

Mercury Vapor – First introduced in the 1930's, MV is the oldest of the HID family. While a breakthrough at the time, MV has been superseded by more efficacious technology with improved lumen maintenance.

Although their practical use is limited, they are still used in security lighting, landscape lighting, sign lighting, street lighting, and highway sign lighting, but use is decreasing. MV can be found in do-it-yourself, hardware, and farm stores due to its low cost and long life.

High Pressure Sodium – The HPS lamp was developed in the early 1960's. The Polycrystalline Alumina arc tube allowed the lamp engineers to use corrosive sodium along with the mercury to produce a much more efficient source of light. Efficacy ranges from 80 to 125 lumens per watt, which is very good compared to MV and better than MH. However, the drawback of HPS is its color appearance and color rendering properties. HPS produces a "yellow light" and is rated at 22 color rendering index (CRI). "White" HPS lamps were developed in the 1980's in an effort to improve color rendering for interior commercial applications. However, the color temperature was very "warm" in the 2200 to 2700^{o}K range, which is too warm for the desired temperatures of 3000^{o} to 4000^{o} Kelvin for commercial applications. In addition, the "price" of better color rendering and white light is a loss of system efficacy.

High pressure sodium is widely used in highway, street, parking lot, and area lighting. HPS lamps consume 32 percent of the electricity used for HID lighting and constitute 34 percent of lamp shipments in 2002 according to the National Electrical Manufacturers Association (NEMA). HPS is also common for warehouse, building façade and some indoor manufacturing. However, the number of interior applications is reducing due to the poor color of HPS and the advances in MH. In addition, more municipalities are using MH instead of HPS for urban and suburban lighting. This is due to the desire for "whiter" higher color rendering illumination for public areas, especially shopping and commerce areas.

Metal Halide – The MH lamp can be categorized by the type of arc tube construction and the mode of starting. Arc tubes are either quartz or ceramic (aluminum oxide), and the starting mode is either pulse or probe start.

Quartz arc tubes, introduced in the early 1960's, are the most popular arc tube and lowest cost for MH lamps. However, quartz MH lamps are subject to large color shift over life due to salt losses, and have high lumen depreciation. In addition, due to natural bending of the arc, MH lamps are sensitive to burning position, which can significantly impact efficacy.

Ceramic arc tubes are manufactured as cylinders or ball-shaped. Because the ball shaped vessel more closely follows the natural contours of the arc there is some efficacy increase over quartz. Ceramic arc tubes operate at higher temperatures, have lower temperature gradients and have a different salt mixture that produces a different emission spectrum. Benefits are less color shift, higher color rendering, and improved lumen maintenance. In addition, ceramic arc tubes result in less color variance among lamps during manufacturing, and can be manufactured in much smaller sizes.

The other primary difference in metal halide lamps is the mode of starting -- pulse start versus probe start. Both types of starting mechanisms are available for quartz, but only pulse start is available for ceramic MH lamps. Probe start is the traditional and most common type of starting. Pulse start lamps eliminate the internal starting probe and add the ignitor to the ballast circuitry, which improve performance. Pulse start technology has lengthened lifetimes of metal halide lamps by up to 50 percent and yielded system efficacy gains of greater than 25 percent.

Metal halide leads in the number of HID lamps sold per year. MH can be found in many exterior applications including street, highway, area, facade, and sign lighting. MH is also the preferred lamp for sports venues from baseball fields to tennis courts. Common interior applications include many "high-bay" applications where the ceiling is usually over 15 feet. Recent miniaturization of MH lamps down to 20 watts, made possible with ceramic arc tubes, is opening up new applications such as a replacement of halogen spot lights used for accent lighting in retail applications. However, starting time, color rendition, color control, and dimmability are still drawbacks.

Ballasts – The HID ballast market is dominated by core-and-coil electromagnetic (aka magnetic) ballasts, however electronic ballasts are available. Five basic circuits (described in detail in Appendix B) for magnetic ballasts are available and used depending on the needs of the lighting system. Pulse start ballasts have the same configuration but add an igniter to start the lamp. This allows for separation of the starting and operating functions, which improves performance and efficacy.

Electronic HID ballasts, first introduced in the mid 1990's, offer the possibility of true continuous dimming, system control, and miniaturization -- all of which lead to energy savings. Performance benefits include lumen maintenance, longer lamp life, and color quality control. Electronic HID ballasts operate with higher efficiency than the magnetic counterparts – 95 percent versus 80 percent. Electronic ballasts can also accommodate control systems integrating daylight dimming, occupancy control, and variable task demands. Electronic ballasts are recommended for driving ceramic metal halide lamps to control wattage and maintain high CRI and efficacies of 90 or more lumens per watt (in the low wattage lamps). In the medium wattage ceramic metal halide, which is now becoming available, electronic ballast operation is needed to maintain color and lumen maintenance.

4.1.2 Recent Advances and Trends

Recent advances in HID technology are focused on miniaturization and wattage range expansion of MH lamps. Smaller wattage lamps, less than 50 watts, with better color control are being introduced to the market for commercial interior applications. In addition, there is a push to introduce ceramic technology into lamps above 400 watts, again for better color control. Although significant advances have improved the efficacy of MH systems, color stability, starting/warm-up, and dimmability continue to limit wide adoption of MH in most commercial applications.

Ceramic Metal Halide Lamps – At low wattages, a 20 watt mini MH and an integrated screw-in (lamp/ballast) 25 watt MH were recently introduced. These lamps can replace 75 and 90 watt halogen lamps in the retail sector. The primary benefit is energy savings and long life.

Longer life and improved color rendering continues to be a focus of development for all MH technology. A 39 watt ceramic MH with a 12,000 hour rated life was recently announced and said to be the industry's longest life 39 watt. In the same wattage range, color rendering is moving steadily upward with a 95 CRI at 3000^{o} Kelvin now available.

At the higher wattage range, 400 watt ceramic MH lamps have been introduced, leading the way for higher wattage lamps including 1,000 watt and above. The introduction of these high wattage ceramic MH lamps, with correlating improvements in color consistency, present practical opportunities in sports and arena lighting where color is critical for television.

Quartz Metal Halide Lamps – The most recent advance in quartz technology is the introduction of pulse start lamps in the 1990's. Pulse start lamps continue to be introduced in more wattages for more applications. The main advantages of pulse start are energy savings and improved lumen maintenance.

In quartz arc tube technology, understanding effects of varying inner arc tube gas pressure and electrode composition, and control gear may lead to improvements in this technology. Recent research indicates that there may be avenues to further increase efficiency and lumen maintenance of these lamps.

Ballasts – Electronic ballasts offer the possibility of true continuous dimming down to 33 percent and possibly even lower levels. This will lead to increased use of the technology in areas where daylight harvesting requires dimming, which is gaining momentum due to US Green Building Council LEED® for new and existing construction and energy codes.

Ballast and lamp companies are also conducting forums to educate the design community that electronic ballast and ceramic technology is the key to sustainable lighting design where HID systems are needed. While initial cost is higher, the flexibility, improved performance, and efficiency have a decided economic advantage. This is especially true in the retail environment where MH could replace incandescent.

4.1.3 Opportunities

Low-wattage ceramic MH lamps are opening the door for significant energy savings in retail applications, replacing halogen and incandescent. Further advancement in lamp size reduction, color consistency, hot restrike time, and dimming all need to be addressed to overcome user barriers in this market.

Development of ceramic discharge lamps for wattages above 400 watts will open up the sports, industrial and high mast (highway) markets as well. Sports lighting can be a future beneficiary of improved system efficiency.

These opportunities are based on current market trends and known applied research. However, according to HID experts, there are additional energy savings opportunities that could be achieved through advanced R&D efforts. Chapters 5, 6 and 7 present some of these opportunities.

4.2 Quartz and Ceramic Arc Tubes vie for Metal Halide Lamps

Both quartz and ceramic arc tubes still exist in the market and in MH lamps. The information below provides a general overview of the competition between the two technologies, along with information on the advantages and limitations of each.

Metal halide lamps were developed in the late 1960's as an evolution of mercury vapor lamps, which were in wide use at the time. These early MH lamps used similar quartz arc tubes to those used in MV lamps. Quartz arc tubes have been used since, but the ceramic arc tubes for metal halide lamps were introduced in mid 1990's.

Quartz arc tubes are inexpensive compared to other types of arc tubes, but pose a number of challenges. Reactions between the salts and the arc tube wall will adversely affect performance, namely lumen depreciation, color rendering, color temperature, and efficacy. Over the life of the lamp these changes in performance become more noticeable, especially the wide swings in color temperature and color rendition.

Ceramic arc tubes, first used in high pressure sodium lamps, are now used in MH lamps. They contain new salt mixtures, can be operated at higher temperatures, and are less susceptible to sodium loss over life of the lamp. These advanced features help improve color rendition, color stability, lumen maintenance, and efficacy. Coincident with the introduction of ceramic metal halide lamps, the market witnessed the development of electronic ballasts for these lamps. Although ceramic metal halide is designed to operate on standard low wattage MH magnetic ballasts, electronic ballasts do exist. The electronic ballasts allow for better control of the lamp over life, which improves color properties and efficacy.

Although there are some benefits to ceramic MH, industry still uses quartz lamps and some argue that quartz lamps may be the better alternative. Table 4-2 below outlines some of the pros and cons of each lamp type.

Table 4-2: Pros and Cons of Ceramic and Quartz Arc Tube Metal Halide Lamps

	Quartz	Ceramic
Pros	• Inexpensive (relative to ceramic) • Proven technology • Long ballast life (20years or more) • Formable material lends to shaping the arc tube for more efficient operation	• Higher operating temperature capability • Less salt losses • Arc tube impervious to salts attack • Better color stability

	• Clear arc tube material is more efficient for optical systems such as fiber optic applications.	• Higher color rendering • Higher efficacy • Less lumen depreciation • Ease and repeatability in manufacturer of form and volume
Cons	• Wall interactions and salt losses • High lumen depreciation • Color temperature shift • Efficacy losses	• Lamp initial cost • Electronic ballast initial cost

Although ceramic arc tube MH lamps have some clear performance benefits, the quartz arc tube lamps are often attractive due to lower cost. For projects where color stability and lumen depreciation is not a concern for the engineer or designer, the quartz arc tube lamps will usually be the first choice. However, this will lead to higher energy use than if ceramic arc tube lamps were used.

4.3 ALITE Program Summary

The Advanced Light Source Research Consortium (ALITE) was formed in 1997. Funded by lighting manufacturers and electric utilities, the ALITE-I program ran from 1997 to 2001 and their report (*ALITE-1 Advanced Light Source Research: Research in the Basic Science of Commercial Light Sources to Achieve Major Breakthroughs in Performance and Efficiency, Final Report,* December 2001) is available from the Electric Power Research Institute (EPRI). The ALITE-II program ran during the early 2000's, but that program's final report was not available at the time of DOE's HID Workshop. However, John Curry of the National Institute of Science and Technology (NIST) provided a brief presentation on ALITE, which is summarized in Chapter 5.

The objective of ALITE-I was to develop a consortium of industry, university, and national laboratory researchers to conduct research that would double the energy efficiency of low-pressure discharge lamps (i.e. fluorescent light sources). Participants included Los Alamos National Laboratory, NIST, University of Wisconsin, and Polytechnic University of New York (through competitive solicitation process); while Osram Sylvania coordinated the technical program.

The research conducted under the ALITE program was described by the consortium as "pre-competitive" research to investigate scientific phenomena not previously considered for light source applications in the quest to double the energy efficiency of discharge lamps. The ALITE consortium identified the following two areas for pre-competitive research:

1) non-equilibrium low pressure electric discharge light sources, and
2) multiphoton phosphors – quantum splitters.

ALITE-I focused on non-equilibrium low pressure electric discharge light sources. The major outcome of ALITE-I was that the consortium was able to model existing fluorescent lamps with much greater accuracy. The improved model made it possible to:

1) predict the performance of other atomic discharge species, including barium, and
2) optimize the performance of current fluorescent lamps, thus improving the efficiency by five to ten percent.

The work performed under the ALITE project is a valuable first step to advancing discharge lighting technologies. The "pre-competitive" research has opened up more doors to the industry's understanding of discharge lamps, and provided additional tools for future research and advancement of these lighting technologies.

5. Workshop Technical Presentations

Below are summaries of the Workshop paper presentations. Full papers are available in Appendix C. In addition, a summary of the ALITE presentation is provided, however no paper was requested from the ALITE representatives.

5.1 Energy Savings through Controllable, High Efficiency Ceramic HID Systems Jerzy Janczak, Philips Lighting

Focus of the Presentation

This paper presents recent developments in metal halide systems (lamp, ballast and luminaire), with an emphasis on the intrinsic advantages of ceramic lamps and electronic ballasts. The enhanced possibilities for energy savings when the lamp and ballast (and even the luminaire) is integrated as a system are described and illustrated -- such as dimming, efficacy optimization, power control, re-strike time, and spectral tailoring. The matching of integrated system to the application is also emphasized, and initial examples of such systems are presented.

Current Research Summary

Current research is dedicated to three key areas.

1. New electronic ballast for further size and cost reduction, efficiency improvement as well as additional increase in functionality. Implementation of microprocessors will improve dimming capabilities of new HID integrated systems.
2. New ceramic HID lamps. Current research focuses on new shapes, novel salt fills and integration with electronic ballasts. It is expected that these advancements will enable the achievement of better dimming and color characteristics.
3. Innovative lamp-ballast systems. The main benefits of this approach are maximum fixture design freedom, precise optical positioning, lowest cost of ownership, greater application flexibility and higher reliability.

Potential Technical Enhancements

New ceramic lamp – electronic ballast systems will permit:

- Higher efficacies, up to 120 lumens per system watt (not lamp watt).
- Better lumen maintenance, greater than 90 percent at forty percent of rated life.
- Dimming to 50 percent with well-maintained color properties.
- Much shorter re-strike times after the lamp is turned off.
- Much more compact systems, including the luminaire.

R&D and Technical Challenges

1. Dimming (with good color properties) to levels much lower than 50 percent power. During dimming, due to temperature variation of the plasma, currently used lamps feature noticeable color variation.
2. Achievement of "instant" start-up and restrike. "Instant" start-up of HID lamp requires voltages above 15kV. Existing lamps and lamp sockets are not designed to withstand such a high voltages.
3. The physical integration of lamps and ballasts, or the development of standards to promote interchangeability of lamps and ballasts. Promotion of this interchangeability would spur market penetration and energy savings.
4. Realization of the targeted benefits with higher wattage lamps, while the temperature constraints of the electronics becomes more severe. Higher wattage lamps generate more heat, which directly influences performance of the ballast.
5. Design issues associated with high temperatures in some outdoor applications. In hot environments higher ballast temperatures need to be managed.
6. Extending the superior color properties of 3000^{o} Kelvin lamps (especially color stability) to other color temperatures. As new salt mixtures are used, its chemistry must be managed.

5.2 Metal Halide Laser Spectroscopy and Microcavity Plasma Devices: Tools for Improving HID Lamp Performance

J. Gary Eden, PhD, University of Illinois

Focus of the Paper and Presentation

This paper presents information on newly-developed laser experimental methods that can now help analyze the arc tube plasma and chemical fill to study processes that are important to lamp efficacy but have not been previously accessible. The paper also provides an overview of how these methods recently helped develop a further understanding of optical processes within the plasma, including photoassociation (the absorption of a photon by a colliding pair of atoms) and the absorption and emission spectra of metal-halide molecular fragments. In addition, microcavity plasma devices that have the potential to reduce the lamp restrike time are presented.

Background

Despite advances in HID lamp technology, optical processes (of the arc tube plasma) critical to radiation transport and lamp efficiency are poorly understood. For example, little is known of the optical properties of the metal halide precursors (and their diatomic and triatomic fragments) with which lamps are routinely dosed. Another optical process, photoassociation (the absorption of a photon by a colliding pair of atoms), is also undoubtedly significant in the high pressure, broadband radiation environment provided by an HID lamp. This presentation focused on these processes and other gaps in current understanding of molecular absorption and emission of HID lamp plasmas. Newly-developed experimental techniques to address this need were presented, and the properties of microcavity plasma devices as a pathway to improving HID lamp restrike characteristics were also described.

Current Research Summary

The University of Illinois has developed laser spectroscopic techniques designed to isolate several optical processes that are suspected of having an important bearing on the efficiency of metal-halide lamps. For the first time, the photoassociation spectrum for colliding pairs of thermal Xe and I atomic pairs has been observed and extends over hundreds of nanometers. Similar measurements have been made for Kr-F atomic pairs. The combination of the large number densities ($>10^{18}$ cm^{-3}) of several atoms (Hg and I, in particular) and the intense, broadband radiation field present in HID lamps strongly suggest the importance of photoassociation to lamp efficiency, particularly in view of the high lamp operating temperature which will extend dramatically the photoassociation spectrum towards the red.

The University of Illinois has also demonstrated that the absorption and emission spectra of polyatomic metal-halide molecules, *and their fragments*, can be observed by a laser photodissociation process. This approach can readily be extended to DyI_3 and other important HID lamp salts.

A new class of plasma devices developed at the University of Illinois, known as microcavity plasma devices, can operate at gas pressures of one atmosphere and beyond. These devices are ideal sources of plasma which, when injected between lamp electrodes, can significantly reduce ignition and restrike voltages. The end result is reduced restrike time, which is one of the major barriers to the widespread adoption of high intensity lighting. However, further research is needed to refine and improve the process.

Potential Technical Enhancements and Suggested Future Work

1. The photoassociation spectra of Hg-I and Hg-Hg atomic pairs, involving the two most abundant atomic species in an HID lamp, should be measured. The spectra are likely to extend over much (if not all) of the visible spectrum. These data will be of considerable value for modeling of lamps and optimizing efficiency through the lamp dose and geometry.
2. The measurements described above should be made at several temperatures to reflect the decline of gas temperature with distance from the arc core. These data are important because, as light propagates outward from the arc core to the lamp envelope, it encounters progressively cooler regions. This rapid change in temperature changes the photoassociation spectrum dramatically, shifting it across the visible towards the blue.
3. The absorption and emission spectra of metal halides, such as DyI_3, and their diatomic and triatomic fragments (DyI, DyI_2) should be measured. Similar measurements for the iodides of Sc and several rare earths should also be made. These spectra are not known but are important to understanding the optical behavior of the lamp in the cooler regions near the lamp envelope. Diatomic fragments, in particular, are expected to be abundant and will filter the spectrum delivered by the lamp.
4. Incorporating microplasma devices for improved restrike characteristics should be further investigated and assess positive and negative impacts on lamp efficacy.

R & D and Technical Challenges

1. Combining data such as those described above with a comprehensive model of the lamp, including r-dependent radiation transport mechanisms.
2. Incorporating microplasma devices for improved restrike characteristics. Engineering these devices for the demanding chemical and thermal environment of the lamp and determining the maximum pressure at which the devices will operate are important goals.
3. Developing ballast and lamp excitation waveforms, based on spectral data proposed above, to optimize lamp efficiency.

5.3 Efficacy Limits of White Light Metal Halide Lamps

Walter P. Lapatovich, Osram Sylvania

Focus of the Presentation

This paper provides information on theoretical and practical efficacy (lumens per watt) limits for HID lighting. The paper demonstrates the opportunities for significant efficiency improvements and thus energy savings, and also briefly discusses practical pathways to achieve these savings.

Background

High-intensity, metal halide discharge lamp luminous flux and color content depend critically on the burner design. Factors influencing the design include: lamp size, geometry, arc tube composition, fill chemistry, electrode design and excitation modes. Modern ceramic metal halide lamps operate in the regime of 100-110 lumens per system watt, with a general color-rendering index of about 85-90. Efficacy improvements approaching a ceiling of about 230 lumens per system watt are possible while maintaining a "white light source" suitable for general illumination. Pathways to achieving efficacy increases are: novel chemical fills, radiation recapture, tailored excitation methods and thermal management.

Current Research

Current research is directed towards improving lamp efficacy in three approaches.

1. Novel chemical fills which optimize the plasma radiation within the Photopic eye response curve. These include combinations of rare-earth iodides and strong single line emitters. The use of broad-band emission from sulfur is intriguing, but only if suitable electrode materials can be devised.
2. Utilize custom excitation waveforms for enhancement of the lamp electric field, condensate distribution, particle distributions, temperature profile and power deposition. This is accomplished by introducing frequency components to the driving waveform, which beneficially excite selected acoustic resonances.
3. Carefully manage the energy balance within the lamp to recapture heat and unwanted near ultraviolet. Finite element modeling is used to optimize lamp shape for longest expected life and best performance. Novel radiation recapture schemes using vaporized fluorescing materials in multi-chambered lamps are under investigation.

Potential Technical Enhancements and Suggested Future Work

1. Higher system efficacy. Determine methods to improve the conversion efficiency of the plasma.
2. Lower wattage, smaller burners. Interior applications will require lower wattage, lower lumen packages for task lighting and easier distribution for background

lighting. Lamp size scales with wattage and smaller lamps are needed. However, the small lamps will still operate hot and certain temperature limits must not be exceeded.

3. Maintain or improve illumination levels with less electrical power. Smaller sources with higher efficacy permit better optical control and delivery of the light to the target area. Illumination levels may be maintained or increased at virtually no additional electrical cost.

R&D and Technical Challenges

1. Devising chemical fills with maximum visible spectral output. Modifying lamp fills by selection of atomic radiators is present art and limited by the periodic table. Addition of molecular species vastly increases the possibilities. However, molecular systems must be regenerative and efficient as well. To date only sulfur vapor has demonstrated promise, more systems ought to be possible but are yet undiscovered.
2. Conserving or recapturing heat and ultraviolet emission in HID lamps. Wasted power into UV or IR reduces the plasma conversion efficiency. Elimination of these radiation channels by subtle fill selection or recapture is needed to improve overall efficiency. So far, Stokes shifting of some UV to visible has been demonstrated, but recapture of the IR losses will yield greater efficacy gains.
3. Understanding and exploiting benefits of acoustic excitation in lamps. In general acoustic effects in lamps are deleterious, often causing arc instability and lamp failure. Operating in selected modes can change the temperature profile in the arc and permit excitation of molecular vapor clouds in the arc periphery, which can increase the overall efficacy.
4. Integrating lamp, ballast and optic to produce maximum system efficacy. The lamp driving waveform affects performance as in bullet three above. The lamp environment affects performance through efficient use of emitted radiation and unwanted retroreflections onto the lamp causing overheating. The optic must be designed to optimize visible throughput, while simultaneously minimizing the unwanted reflections.
5. Engineering electrode materials to withstand sulfur attack. To date all refractory metals currently used for electrodes have failed to withstand hot sulfur vapor for more than a few minutes of operation. Many alloys have not been tested and many conductive ceramics might also be considered.
6. Devising excitation waveforms to maximize visible output. Acoustic excitation could be fruitful, but other waveforms are also useful in maximizing visible light. Lamps based on non-local thermodynamic equilibrium have shown to be very efficient sources, but should be investigated and difficulties with EMI and acoustic noise must be overcome.
7. Fabricating, filling and sealing complicated ceramic arc tubes. As lamps become smaller, technology must be developed to dose, handle and seal lamps with manufacturing consistency. Very thin electrode shafts are brittle, capillaries are constricted making solid dosing difficult, and overall the lamp is small making sealing without inadvertently losing the chemical fill difficult. This is not so much a basic science issue as an enabling technology development.

5.4 Recent Lifetime Increases and Photometric Improvements to Quartz Metal Halide Lamps from Exterior Thin Film Coatings and Improved Ballast

Roger Buelow, Fiberstars Inc.

Focus of the Paper and Presentation

This presentation focused on the complete lighting system – lamp, ballast, and luminaire. The paper presents information on efficiencies of distributed lighting systems. In addition, thin film coating and improved ballast efficiencies of distributed lighting systems are discussed and test results presented.

Background

Distributed lighting systems offer a way to take advantage of high efficiency and high brightness quartz metal halide (QMH) lamps when a small lumen package is required, such as replacing halogen spot lights for retail applications. Distributed lighting systems produce tight, efficient beam distributions out of small fixtures. Because only one high intensity discharge lamp and one ballast produce up to eight "spotlights," the market is less sensitive to changes in costs of these components. Consequently, distributed lighting systems are an ideal place to test advancements in arc tubes and ballasts.

Current Research

Research over the last five years has focused on making energy efficient accent lighting systems. The result is a distributed lighting product called Efficient Fiber Optics (EFO). The system architecture spreads lamp and ballast costs over several points of light, making distributed systems ideal for introduction and early adoption of new technologies.

Accent lighting and the 50W MR-16 halogen is the performance target for the base EFO unit which employs a quartz metal halide lamp as the source. Potential replacement of the 50W MR-16 was considered the best chance to make large energy reductions because of its widespread use. Research into exterior barrier coatings and ballast drive techniques were recently explored as part of the HEDLight program. Exterior coatings were able to keep lamps running hotter and act as protection barriers increasing lumen output, improving CRI, and extending lifetime. Ballast efficiency improvements were realized for both DC and AC ballasts based on optimized circuit design and component choice.

Potential Technical Enhancements and Suggested Future Work

1. External thin film coatings on quartz metal halide should be further investigated because they can improve efficiency, lamp life, and CRI.
2. High efficiency ballasts should be developed further because increases in system efficiency will increase the marketability of discharge systems.

R&D and Technical Challenges

1. Integrated design and application of multi-layer coatings on the exterior of lamps to improve efficiency, lifetime and CRI. The lamp and coating need to be designed in concert so that the returned energy is accounted for properly and any spectral effects are balanced. This is more challenging than IR halogen lamps because areas of complex geometry or areas of extreme thermals can have a large impact on lamp performance and life.
2. Advanced electronic ballast designs and algorithms must be developed to reduce the losses on electronic ballasts, these changes should be robust so that efficiency is maintained throughout life of the lamp.
3. Dimming capability while maintaining efficiency, color and lifetime. Lamp and ballasts must be developed together so that lamp performance at different levels is acceptable. Ballast controls must be mated to existing electronic dimming systems.
4. Development of optimized instant light performance for systems (lamps, sockets, ballasts, fixtures). New lamps with high pressure and ballast with high voltage starters and high current warm up cycles must be designed together. Integrated design of new sockets and fixtures is necessary in order to handle the higher voltage.
5. Multi-layer coatings on the interior of lamps to enable increased wall loading, brighter lamps, and therefore smaller fixtures. Research is needed to define the type of coating and method of application to reduce the corrosive effects of metal halides on lamp interior walls. Coating micro geometry must be optimized to prevent cracking or pitting which may lead to failures.
6. Improved processes and equipment for applying multilayer coatings to arc tubes and lamp components. Discharge sources are much more complicated than halogen lamps and require more sophisticated coating machinery to get uniform coatings on their complex geometry.
7. Expansion of full spectrum doses. Searching through the vast possibilities of metal halide dose combination takes time and rigorous statistical discipline. Many experiments need to be run for life and photometric performance to quantify the interactive effects of these new systems.
8. Development of reduced wattage and size of quartz MH lamps. Maintaining high efficiencies and long life while reducing lamp size will require a breakthrough in combating the effect of high wall loading. Inner barrier coatings are the most likely choice for enabling reduced wattage discharge lamps.

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5.5 Recent Developments in Dose Optimization and Design of Low-Wattage Quartz Metal Halide Lamps

Timothy R. Brumleve, APL Engineered Material, Inc

Focus of the Paper and Presentation

This paper describes recent developments in low-wattage (<70 watt) metal halide (MH) lamp and ballast systems with high color temperatures and increased efficacy (>80 LPW). Advancements in lamp dose chemistry, coatings, electrode materials, fill gas optimization, and ballast design are discussed as methods that helped improve light source performance.

Background

Recent developments in low-wattage MH lamp and ballast systems have achieved improved color rendition and luminous efficacy – two important performance parameters for wider-spread adoption of MH systems. These efficient light sources approach daylight "full spectrum" output that is a result of dose chemistry and lamp design optimization, including a balance between electrode materials, fill gas composition, and pressure. New photometry metrics for achieving targeted spectral response are used to achieve the high color temperatures in the 5000^{o} and higher Kelvin range. High temperature coating materials for inhibiting oxidation of molybdenum (Mo) sealing foils and for preventing reaction of metal halide dose materials with arc tube walls are critical in these performance improvements. The advancements in this area have shown some significant results for specific applications. Knowledge of high-temperature materials chemistry is key to enhancing performance and life in all HID lamp systems. Improvements in HID luminous efficacy, light source size reduction, and reduced system costs can only be achieved through better envelope, electrode and sealing materials, coatings, and a systems approach to arc tube/ballast/optical systems design.

Current Research Summary

Research has developed new 68 watt to 70 watt DC and AC light sources of high luminous efficacy (>80 LPW), high color temperature (CCT of 5000^{o} to 6500^{o} Kelvin) with a good spectral match to daylight reference spectra (D5000 to D6500). Simplex and Designed Experiment techniques were used to optimize the dose chemistry and arc tube design. Thermal imaging and modeling were proven to be effective design tools for limiting high temperature chemical reactions of the dose within the arc tube in both quartz MH and ceramic MH lamps, and for extending lamp life. In addition, two new photometry metrics were used for achieving the optimum targeted spectral response. Specific design goals were achieved through the use of a new Modified Lumens (Percent Efficiency) metric and a new χ' metric (a measure of the match to the spectral target).

Internal chemical barrier coatings, with the potential to reduce or eliminate salt–wall reactions, enable increases in wall loading, higher wall temperatures, increased metal halide vapor pressure, longer life and improved lumens maintenance. High temperature coating materials for inhibiting oxidation of molybdenum sealing foils in quartz metal halide lamps can eliminate seal failures, increase lamp life and reduce costs for arc tubes burning in air.

The results of this research improved lamp performance and life in the target systems studied to date. However, more research is needed to more fully understand fundamental aspects of high temperature materials chemistry in HID lamps, to optimize dose chemistry and thermal design, to develop novel coatings and to elucidate lamp-ballast interactions in MH lamps of both low and high wattage.

Potential Technical Enhancements

1. Efficacy improvements. Approaches to achieving breakthroughs include dose chemistry optimization, improved thermal design of arc tubes, improved ballast designs, and high-temperature internal chemical barrier coatings.
2. Wattage and lamp size reduction. Approaches to achieving these goals include dose chemistry optimization, improved thermal design of arc tubes, oxidation resistant molybdenum foils, and high-temperature internal chemical barrier coatings.
3. Lamp and system cost reduction (via manufacturing or replacement/maintenance cost reductions). Approaches to cost reduction include oxidation resistant molybdenum foils and improved ballast designs.

R&D and Technical Challenges

The following challenges continue and expand upon the approaches which have been described.

1. Dose chemistry and lamp design. Apply Simplex Optimization and Designed Experiment techniques to optimize the following types of low-wattage MH lamps with the following goals: percent efficiency greater than 90, CRI greater than 90 and χ' (chi prime) less than 20 for color temperature of 3000^o to 3400^o Kelvin, while improving luminous efficacy by more than 10 percent over existing designs. Apply the same tools to other low, medium and high wattage quartz MH and ceramic MH lamps to achieve similar levels of performance with high color temperature goals of 4500^o to 6500^o K. Although powerful, statistical optimization techniques can be greatly improved through a better understanding of the fundamental high-temperature chemical processes and the plasma physics of the arc and lamp/ballast system. Better thermodynamic and physical models of these phenomena will guide statistical approaches.
2. Oxidation resistant Mo foil. Develop new mounting and supporting technology to enable application of oxidation-resistant Mo foils. Prove and test concepts of air-filled outer jackets and elimination of hydrogen getters for reduction of sodium loss and for reducing manufacturing and lamp costs. Fundamental investigations of the coating process (rheology, chemical composition, fusion temperature) are

also needed to improve the protection of the Mo foils at the "knife edges," to reduce pin-holes and to improve coverage uniformity.

3. Ballast design and performance. Continue studies of lamp-ballast system interactions and the role of electrode materials and fill gas pressure and composition to achieve extended performance and life. This challenge demands a true "systems" approach including theoretical models and extensive experimental and statistical approaches on specific target HID systems.

4. Photometry metrics. Define new color quality metrics such as the χ' (chi prime) and spectral “holes” concepts. Publish and refine metrics to facilitate creation of industry standards.

5.6 ALITE: A Model for Support of Pre-Competitive Research in Lighting Technology

John J. Curry, National Institute of Standards and Technology

Focus of the Presentation

This presentation focused on an overview of the ALITE program model and general information about the ALITE-I and ALITE-II programs and their outcome.

A paper for this presentation was not requested, but reports on the ALITE-I program are available from the Electric Power Research Institute (EPRI), and the ALITE-II report will be available in the future.

Background

The ALITE program concept originated at the Airlie Conference in Virginia in 1995. Industry, government, and university researchers laid out a vision for ALITE to "support pre-competitive research in the basic science of commercial light sources to achieve major breakthroughs in performance and efficiency." There were two consecutive rounds of funding and research involving, at various times, each of the three major lamp manufacturers, three universities, and two government laboratories. The programs were managed by EPRI with funding from electric utilities and the participating lighting companies. The ALITE programs ran from 1997 to 2005.

Research Summary

Both ALITE-I and ALITE-II programs focused on an improved understanding of power balances in gas discharge lamps. A detailed accounting of the power balance is necessary to determine where significant savings are available and what problems should be addressed to increase luminous efficacy.

ALITE-I focused on low-pressure mercury light sources, and included novel low-pressure barium light sources. This included fluorescent, compact fluorescent and electrodless fluorescent light sources. The outcome of ALITE-I was an improved numerical design tool for fluorescent lighting.

ALITE-II focused on infrared losses in HID lamps and novel molecular low-pressure light sources (fluorescent). The outcome of ALITE-II is an improved understanding of the power balance of HID lamps.

Program Outcomes and Benefits

Although the ALITE program was affected by problems with funding continuity, it did establish a model for pre-competitive research in lighting technology. The program leveraged the technical guidance only available from industry scientists, with the physical resources and scientific experience of the National Laboratories, to support qualified university research programs.

A second important advantage of ALITE was that it helped address a need in the U.S. strategy for lighting technology because it supported pre-competitive research. Pre-competitive lighting research programs are more common in Europe and in Asia, where there are several strong university lighting research programs, as well as much larger consortium programs such as the Electrode Program and the COST 529 consortium in Europe. There are some strong university research programs in the U.S, but if these are not properly funded, the expertise may eventually disappear or go overseas.

In summary, any attempt to establish a coordinated effort on advancing HID technology should consider the advantages of the ALITE model, with DOE playing the coordinating role in bringing industrial scientists together with academic and government scientists.

6. Workshop Discussions

The following section provides an overview of the Workshop discussions. After the paper presentations, prepared written discussions were presented followed by a facilitated open roundtable discussion. Section 6.1 presents the two prepared written discussions, and Section 6.2 summarizes the potential for metal halide improvements based on the attendees' comments and open discussion.

The presented papers provided a good background for the discussions. They covered a number of existing technologies and presented ideas and topics that could significantly improve lamp performance and increase energy savings potential. As with the papers, the discussion focused on MH technology because it holds the most opportunity for improved performance, energy savings, and market acceptance. The prepared written discussions provided some additional ideas not presented in the papers, and also acted as a lead-in to the open roundtable discussion, thus why the written discussions encompass many thought-provoking questions.

6.1 Prepared Written Discussions

Two prepared written discussions were presented. The first discussion was by Walitsky and Ryan, and the second by Boling. These written discussions are provided below.

6.1.1 Discussion of HID Papers for the November 15th DOE Workshop Paul Walitsky and William Ryan, ICF Consulting

The companies represented at the Workshop are leading the way to finding improvements in HID technologies, and the papers presented provide a good preview of the current state of HID technology.

The opening paper by Jerzy Janczak of Philips Lighting addresses the integration of lamp and ballast as a way to gain system efficiency improvements. However, the following questions should be considered concerning integration of systems:

1. What about the third component of the HID lighting system, the luminaire? The two-pin based system described by Philips will have an advantage in moving toward an optimized optical system by consistently centering the lamp in the focal point of the reflector. However, the integration of the lamp, ballast and luminaire has the best chance of improving the total system efficiency. In addition, has any thought been given to expanding this feature to general lighting; thus improving the coefficient of fixture utilization? How is system efficiency measured per foot-candle delivered to the workplace as the customer is paying for lighting delivered in watts and dollars?
2. DOE is looking for significant improvements in system efficiency that would result in large wattage savings and compelling motivation for market change. Considering the trend in the market toward dedicated lamp and ballast pairs, what would be the implication of developing an entirely new system? This system approach would include optimized optics, ballast design, and lamp

around a new arc tube voltage standard. What are the implications of such development? How would a new "system-driven development" affect the cost, payback, size wattage saving, lighting quality, and lumen output?

3. The Philips paper also discussed the trend toward lower wattage HID lamps. There are currently several companies that have gone below the 39 watt to the 25 watt integrated package and the 20 watt mini-lamp, but the paper appeared to hint that even lower wattages are possible. The question arises, what market could be a target for a very low wattage HID lamp? If the 25 or 20 watt MH as a replacement for the 75 watt halogen, then what is next? An even lower wattage replacement for the 60 watt A-lamp incandescent? Is that not where compact fluorescent (CFL) has a strong market presence? To what economic or energy-efficiency gain? The cost structure of the CFL is now competitive with incandescent when energy, replacement, and labor costs are considered. One would think that a low wattage HID would have to be priced very competitively to make an inroad to that market. How do you see the low wattage HID replacing household lamps? Is this not the target of light-emitting diode (LED) technology as well? What other lamp market segment is a low wattage HID product suitable to replace with an acceptable return on investment?

The paper by Walter Lapatovich of Osram Sylvania presented a review of chemistry and physics of HID technology. Additionally, it provided an in-depth understanding of the processes involved in generating additional avenues for exploration. Based on the paper the following area should be considered for further discussion:

> The paper included exhaustive discussion regarding attempts to utilize the ultraviolet (UV) that escapes the arc tube and use it to generate additional lumens. Similarly, an effort was noted to reflect back the infrared (IR) and use it to heat up the arc. Because there is so much more IR then UV generated outside the arc tube in either the quartz or ceramic, why not use the IR to generate light? There are several anti-Stokes law phosphors that generate visible light when excited by IR. While physics limits this phenomena to one photon released for every two absorbed (and in practice perhaps one to three would be considered very good) it seems that exploration of this area might generate some interesting results. This was explored in fluorescent with disappointing results, but there is much more IR in HID than in fluorescent, especially in the ceramic configuration. Phosphors are already found on the outer bulbs for color correction, why not for lumen enhancement? Has this been investigated? What are the drawbacks of this approach?

While looking for new concepts within old technology, exploration of the arc tube material might prove useful. The ceramic arc tube is composed of polycrystalline alumina. This is a translucent material which transmits about ninety percent of the visible spectrum. Is there a way to increase the transmission yet retain the properties of high temperature and resistance to chemical attack? One of the causes of the loss in transmission is the grain boundaries of the alumina. Why not use single crystal material? Sapphire was used in the early development of the HPS lamp. Transmission was enhanced but brittleness and cost were a factor. Now that some 40 years have passed there may be enough improvements to give this material another look. Another material used for IR laser pumps was yttria. Yttralux tubes were made by GE for this use. Would a combination of an IR transmitting material and IR phosphors produce something worthwhile?

Considering the electrical properties of the arc and ballast, considerable attention has been paid to the areas around the electrodes. If one were to change the arc tube operating voltage from the 125-130 volt area to perhaps 250 volts, what would happen? The current would drop in half and the arc would be lengthened, would we need to lower the work function as far? Are there any advantages from a light generation standpoint? Would the ballast configuration benefit from a lower amperage requirement?

Finally, Gary Eden of University of Illinois presented some new and intriguing concepts for exploration. The introduction of the microcavity plasma device surrounding the electrode is an interesting concept. We noted the use of stainless steel for the cathode section. It has been known that reactions of the rare earth halides with iron containing materials can have detrimental effects on the life and maintenance of luminous efficacy of HID lamps. (Residual iron on the tungsten surface will quickly result in tube darkening). Has there been any study of such effects in the use of the microcavity plasma over perhaps 10,000 hours or longer?

6.1.2 Discussion on Exterior Optical Coatings on QMH HID Lamps

Norm Boling, Deposition Science, Inc

At the HID Workshop, Brumleve and Buelow talked about "coatings" on HID lamps. The coatings to which they referred are generally well known in HID circles. They included, as examples, coating on electrodes and coatings on the inside of the HID lamp. The latter have been looked at extensively as a way to prevent or slow chemical attack. These are good areas for research and should be addressed in DOE funding considerations, specifically interference filters vacuum-deposited on the HID lamp. These coatings are made up of many layers, the number and thickness of which are determined by optical design guided by the end use. Generally they function by interference and not absorption.

Although complex, with many vacuum-deposited layers, these coatings are routinely used on halogen lamps (roughly 20 million per year) to reflect IR back to the filament. Therefore, the deposition technology and economics necessary for depositing them on halogen IR lamps are already well established.

These coatings can change the physics of HID lamps to the extent that HID lamps incorporating them should be viewed as a new type of lamp. Because of this, the lamp, ballast and coating must be studied as a system. Simply applying these coatings to existing lamp/ballast systems will usually yield ambiguous, or even negative, results.

The potential technical enhancements include: color modification, efficiency enhancement, wall temperature control, wall emissivity control, arc stability, improved electrode degradation, and controlled chemical reactions with envelope.

The R&D and technical challenges for lamp coatings are that most lighting companies are generally not working on and are not knowledgeable in the area of interference filters. And, most commercial lighting companies would not pursue this research on their own.

6.2 The Potential for Metal Halide Performance Improvements

Through the course of the Workshop attendees discussed a number of performance improvements that could be achieved. Table 6-1 below provides a baseline reference of the current status of MH lamp performance, followed by Table 6-2 that projects potential MH performance improvements. Figure 6-1 below also shows the spectra of current ceramic and quartz metal halide lamps.

Table 6-1: Current Status of Metal Halide HID Technology

Wattage Range	Low Wattage (≤70)		Medium Wattage (100-250)		High Wattage (300-400)	
MH Lamp Type	**Quartz**	**Ceramic**	**Quartz**	**Ceramic**	**Quartz**	**Ceramic**
Ballast Type	CWA	Electronic	CWA (Pulse Start)	Electronic	Magnetic	Electronic
Ballast Efficiency	73%	86%	78%	90%	87%	93%
Lamp Efficacy (LPW)	69	85	85	86	110	88
System Efficacy (LPW)	50	73	66	77	98	81
Initial Lumens	3,450	3,300	8,500	8,600	42,000	36,000
Lumen Maintenance	55%	80%	65%	75%	74%	85%
CCT Shift (Degrees Kelvin)	600	200	600	200	600	200
Lamp Life in Hours	20,000	12,000	15,000	16,000	20,000	15,000
Warm Up (to full output)	1-2 min	1-2 min	1-2 min	1-2 min	4 min	2-3 min
Restrike (to strike the arc)	8 min	8 min	10 min	2-4 min	15-20 min	4-6 min
Cost	$42	$26-36	$49-80	$26	$20-40	$50-60

Sources: Lamp and ballast information obtained from Philips Lighting Company, Osram Sylvania Inc. and Venture Lighting catalogs and personal conversation with Kent Collins Bath of Philips Lighting Company, New York. Pricing information obtained from www.bulbs.com (tier three end-user costs) and www.grainger.com (online catalog discounted at 20 percent) and Home Depot shelf pricing.

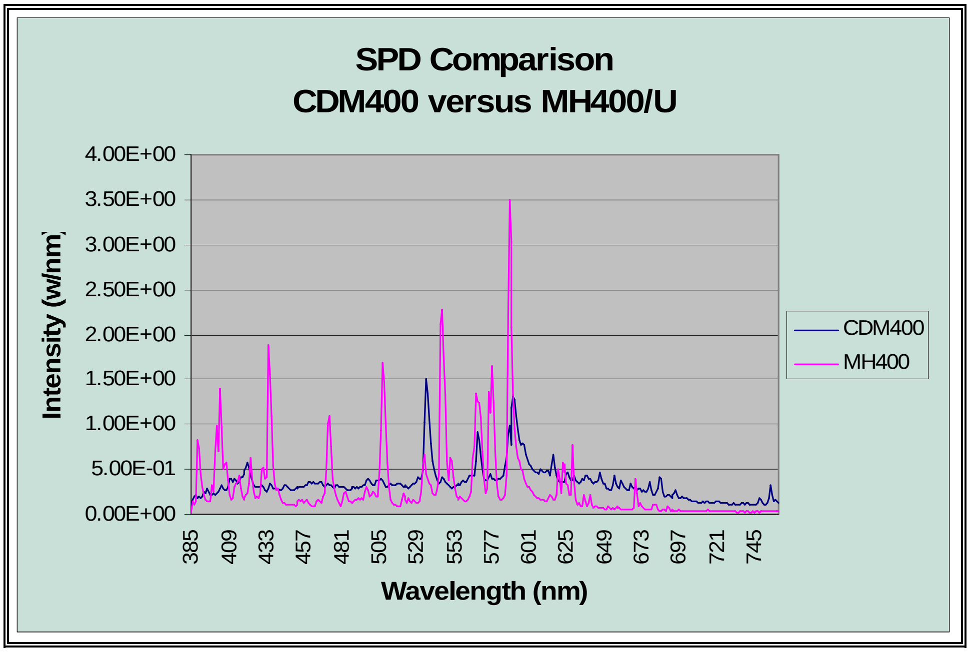

Figure 6-1: Ceramic (CDM) vs. Quartz Metal Halide (QMH) Lamp Spectra
(Source: Jerzy Janczak and Hans Schellen, Philips Lighting Company, Appendix C)

The performance improvements shown below in Table 6-2 are based on the expert opinion of the attendees, taking into account theoretical maximums and what is practical and foreseeable with additional research to overcome existing technical barriers. Improvements from the existing MH technologies typically range from 10 to 50 percent. The achievable improvement levels will significantly vary on the wattage size of the lamp and the technical approached used to enhance the performance. For example, lower wattage lamps offer some of the greatest improvements; the attendees stressed that to optimize the performance improvement, the lamp and ballast need to be developed together as a system approach.

Table 6-2: 5-10 Year Outlook of Potential Advancements through Additional R&D

Wattage Range	Low Wattage (≤70)		Medium Wattage (100-250)		High Wattage (300-400)	
MH Lamp Type	**Quartz**	**Ceramic**	**Quartz**	**Ceramic**	**Quartz**	**Ceramic**
Ballast Type	Electronic	Electronic (Integrated 70 w)	Electronic	Multi-lamp Electronic	Electronic	Multi-lamp Electronic
Ballast Efficiency	95%	95%	95%	95%	97%	97%
Lamp Efficacy (LPW)	100	125	110	130	120	135
System Efficacy (LPW)	95	115	100	125	110	130
Ballast Efficiency	95%	95%	95%	95%	97%	97%
Initial Lumens	7,000	8,750	27,500	32,500	48,000	54,000
Lumen Maintenance	90%	95%	90%	95%	90%	95%
CCT Shift in Degrees Kelvin	300	75	300	75	300	75
Lamp Life in Hours	20,000	25,000	25,000	30,000	25,000	30,000
Warm Up (to full light)	30 sec	30 sec	1 min	1 min	1 min	1 min
Restrike (to strike the arc)	<1 min	< 1 min	<2 min	<2 min	<2 min	<2 min
Other Potential Improvements	Coatings*	Continuous dimming	Coatings*	Continuous dimming	Coatings*	Continuous dimming

Source: High Intensity Discharge Lighting Technology Workshop, November 15, 2005 presentations and discussions of industry experts.
*Coatings: improved coatings could increase LPW (lumens per watt).

7. R&D Discussions

As part of the Workshop discussions, the attendees were asked to list specific R&D topics that are critical to achieving the performance levels outlined in Table 6-2. The attendees organized their thoughts and collaboratively came up with the following eight areas for R&D:

- System Approach for Restrike
- Smooth/Continuous Dimming
- Characterization of Optical Processes: Photoassociation, Infrared Emission, and Metal Halide Spectra
- Ballast Systems
- Coatings (Interior and Exterior)
- Chemical Fill Optimization
- Arc Tube Material (Quartz, PLA, Saphire, Yttrium Oxide)
- System Optimization (lamp/ballast/luminaire)

The attendees feel that these eight topics can yield significant energy savings and/or overcome major technical barriers that impeded wider adoption of MH technology.

The information presented below is based on the speakers' papers and presentations, and the open roundtable discussion. The information provides a background on each topic, potential impacts on efficacy, source size, other attributes; and the potential cost effectiveness and market acceptance.

7.1 System Approach for Restrike

7.1.1 Background and Description

The Workshop attendees quickly brought up the problem of hot restrike, which is a major issue with HID lamps. This phenomenon occurs when the lamp is extinguished while hot. The arc will not strike immediately (to provide light) leaving the user in the dark for up to 20 minutes depending on the lamp and ballast system used. This problem is caused by the high pressure of the hot gas within the arc tube and the high voltage needed to re-ionize this gas at this high pressure. With existing lamps the gasses need to cool, decreasing the pressure in the lamp, before the arc can restrike.

A number of approaches have been used to address the hot restrike issue. In many HID installations a second halogen lamp is installed in the same fixture and designed to illuminate if the HID extinguishes while hot. The halogen lamp then extinguishes once the HID lamp light output is restored. Another solution is a special lamp/ballast system that applies a very high voltage across the arc tube and restrike the lamp in a short time interval. However, this solution requires a specially designed lamp, socket, and ballast to provide the high voltage and to prevent arcing in the socket or within the lamp leads or frame. Alternatively, doubled-ended lamp configurations have been employed so that a higher voltage may be applied without concern about arcing.

The R&D challenge is therefore to explore other methods of shortening the hot restrike time via novel lamp and/or ballast designs. One suggested approach presented by Eden is to employ an ionization device within the lamp. These devices are called microplasma injectors and are capable of enabling a more rapid hot restrike within the lamp. They are also effective in reducing the ignition voltage of a cold lamp, thereby minimizing electrode sputtering and extending lamp life.

7.1.2 Impact on Lamp, Ballast and System Efficacy

Overcoming the issue of hot restrike would probably have little impact on lamp efficacy, but there may be some minor efficacy gains possible in the ballast, and lumen maintenance could improve. However, restrike continues to be one the major issues limiting wider adoption of efficient MH technology. Attendees mentioned that overcoming restrike issues will most likely lead to wider adoption of MH technology, and achieve overall energy savings in commercial buildings, and also enable penetration into residential applications.

7.1.3 Impact on Source Size Reductions

If fully researched and brought to market over the next five to ten years as the attendees discussed, the “microcavity solution” presented by Eden could lead to a decrease in source size. However, the full impact of this device on lamp or ballast size needs further exploration.

7.1.4 Impacts on Other System Attributes or Applications

The attendees indicated that overcoming hot restrike issues through means that do not require high voltages will also provide lamps that are safer. Eden's proposed investigation into the "microcavity solution" is a step in the right direction of restrike with lower voltages.

7.1.5 Cost Effectiveness and Industry/Market Acceptance

Attendees reemphasized that a major barrier to widespread acceptance of HID and specifically MH lamps in commercial and residential sectors are the issues of hot restrike and rapid ignition. The user and the market are accustomed to incandescent technology that provides light instantly at the flick of the switch and can be turned on and off without delay of reignition. Overcoming these barriers would certainly aid in more rapid penetration of these lamps.

Employment of any device or methodology that improves restrike will impact the ballast as well as the lamp. Initially it is expected that this would increase cost, but this may not be a major issue for purchasers if the efficacy and hot restrike benefits are significant. In the case of fiber optic distributed lighting systems, as presented by Buelow, component costs of ballast and lamp can be spread over as many as eight points of light, making these systems attractive avenues to introduce innovations and new technologies which may have higher initial costs.

7.2 Smooth/Continuous Dimming

7.2.1 Background and Description

The attendees all agreed that a barrier to increased market acceptance of HID technology is the lack of "true" continuous dimming capability. Two-step (aka bi-level) dimming has been available for several years using electromagnetic ballasts. Two-step dimming was developed and widely used rather than continuous dimming because continuous dimming with magnetic ballasts is very difficult.

The problems with two-step dimming are: 1) users cannot pick a particular light level, and 2) lamps may shift color during dimming. In addition, high pressure sodium (HPS) can only dim to 30 percent, and dimming below 50 percent has not been readily available with MH. Designers and users need the dimming capability to push beyond 30 percent to as low as 10 percent light level. As for dimming to less than 10 percent, the attendees pointed out that fluorescent systems with full range dimming (0 to 100 percent) are less than one percent of the fluorescent market. This implies that full range dimming systems could be sold at a premium without affecting market acceptability.

Commercial designers and engineers generally prefer dimming capabilities in conference rooms, multipurpose and classrooms, the hospitality industry, and retail. HID two-step dimming has also been used in warehouse lighting, strictly for energy savings. Continuous dimming is also a prime requirement where daylight harvesting is used. The environmental movement is making great strides in developing methods for daylight optimization. This requires dimming capability for the artificial light sources. Currently these applications are restricted to fluorescent (at a cost premium) or halogen and incandescent sources.

Development of true continuous dimming without color shift would open up a significant market, which currently cannot take advantage of the energy saving potential of MH lighting. However, color shift due to dimming needs to be overcome.

7.2.2 Impact on Lamp, Ballast and System Efficacy

While dimmed, the lamp and ballast efficacy will not increase. Actually, due to inherent losses in the ballast, the efficacy will slightly decrease. However, in terms of energy use there will be savings because lamp and ballast systems are using less energy while dimmed.

7.2.3 Impact on Source Size Reductions

Dimming capability will ideally be controlled from the ballast and would not have an impact on lamp source size. With respect to magnetic ballasts, dimming features add size to the ballast. However, as electronic ballast circuits continue to get smaller and smaller, it does not seem reasonable to suggest that dimming controlled by such circuitry would impede the move toward ballast size reduction.

7.2.4 Impacts on Other System Attributes or Applications

Dimming MH lamps results in less electricity consumed and thus less heat generated. Papers presented at the Workshop indicate that more than half of the energy required to power the lamp is lost as heat. Reduction in power reduces the heat generation and thus reduces ventilation and air-conditioning requirements for the building system.

The reduction in full power usage may also lengthen the life of the lamp and ballast. This reduces maintenance costs and replacement costs.

Dimming systems will also permit end-users to participate in utility load shedding programs. During peak demand periods, utilities may contact selected customers and request or require load reductions; in return users may receive a reduction in over all electric rates. Dimming capability enables a customer to participate without having to shut down operations.

7.2.5 Cost Effectiveness and Industry/Market Acceptance

Architects, designers, and engineers have been asking for continuous dimming and see this as one of the key attributes that would enable them to specify MH. A dimmable MH lamp with no shift in color opens up the retail, educational, commercial and other markets to the possibility of daylight harvesting and architectural dimming for MH.

7.3 Characterization of Optical Processes: Photoassociation, Infrared Emission, and Metal-Halide Spectra

7.3.1 Background and Description

The attendees focused on the fact that IR losses are significant and a small improvement in this area could yield substantial efficacy gains for the lamp. Figure 7-1 below from Lapatovich and Chen's paper and Workshop presentation shows total IR losses for a 100 watt ceramic metal halide lamp at approximately 53 percent. Smith, Bonovallet and Lawler report radiated near-IR (wavelengths 0.7-2.5μ) losses at 10 percent of input power ("*Infrared Losses from a Na/Sc Metal Halide High Intensity Discharge Arc Lamp*" P. 1519, J Phys.D Appl Phys, 36, 2003]. Metal halide lamps with rare earth salts are reported to have higher near-IR losses of 25-27 percent (Jack and Koedam, *"Energy Balance for Some High Pressure Gas Discharge Lamps,"* J Illum. Eng Soc 3,323, 1974).

These radiated near-IR losses are significant and is the reason the Workshop attendees focused on this issue as one needing further research. Coupled with the IR losses further into the IR region and thermal IR generated from the arc tube, a significant part of the input power is lost in the form of IR radiation. Theoretically these losses can be captured to increase the efficacy of the lamp and small improvements can yield significant system efficacy gains.

Another process not understood at present is the absorption and emission of visible light by diatomic and triatomic fragments of the MH salts with which MH lamps are dosed. Measuring these spectra should enable MH lamps with higher efficacy to be engineered.

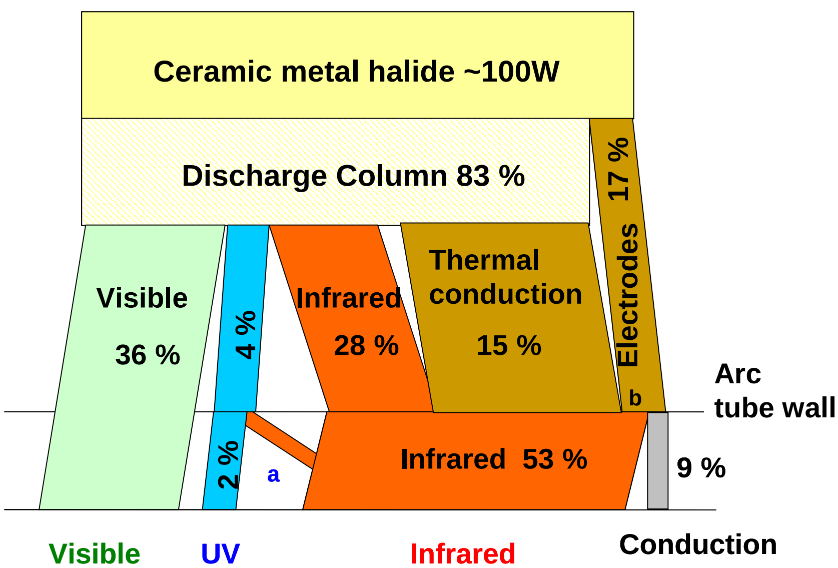

Figure 7-1: Approximate Power Flow in a Modern Ceramic Metal Halide Lamp
(Source: Lapatovich and Chen, Osram Sylvania: *Efficacy Limits of White Light Metal Halide Lamps, 2005* – Appendix C)

In addition to IR losses, Eden reported that photoassociation phenomena may also contribute to substantial absorptive losses in HID lamps. Photoassociation, defined as the absorption of a photon by a colliding pair of atoms, has only recently been able to be measured. These new techniques to measure photoassociative spectra can open the window into understanding how absorptive, and thus IR, losses occur within the arc tube plasma. It is also likely that photoassociation and the IR losses mentioned above are linked. That is, the visible photon absorbed by photoassociation is likely to be converted to IR emission through a transient molecular interaction.

All of this work leads to the conclusion that if it is possible to approach the lamp efficacy of 200 lumens per watt mentioned by Lapatovich and Chen, researchers and industry must have a better understanding of where the energy supplied to the lamp goes and how it is emitted. Only with such understanding will it be possible to develop methods to capture and perhaps utilize this energy in the visible spectrum.

7.3.2 Impact on Lamp, Ballast and System Efficacy

Discussion during the Workshop indicated that photoassociation may account for as much as 10 percent of the energy loss. Understanding this loss mechanism and determining where, at present, the energy lost to photoassociation reappears raises the possibility of capturing this energy for visible light generation. A 10 percent gain in light output would be a significant step toward raising the efficacy of the lamp component of the system.

Understanding the distribution of the IR losses can lead to the development of mechanisms to either reuse the IR for further temperature control of the arc or to enhance visible emission. Knowledge of the IR spectra and the absorption and emission spectra of MH salt molecular fragments may also help in salt selection and the selection of salt ratios within the dose, thus raising the lamp and system efficacy.

7.3.3 Impact on Source Size Reduction

As the source size gets smaller heat management becomes more of a challenge. The importance of understanding IR emission magnifies as arc tube and ballast sizes are reduced. Characterization of the IR generation spectra and sources can provide guidance to the development of further source size reduction schemes. Without this knowledge further source size reduction will be a slower process depending on empirical information rather than an understanding of the scientific principles involved.

7.3.4 Impacts on Other System Attributes or Applications

With the new techniques mentioned by Eden industry now has the tools to evaluate photoassociation phenomena of different salts. This will help understand IR losses for different salts, but could also be used to understand photoassociation in particular parts of the spectrum, which may be a way to further improve color rendition. These new laser experimental techniques can also be applied to determining the optical spectra of metal halide molecular fragments, thus allowing the metal-halide dosage to be optimized by simulation rather than by an empirical approach.

7.3.5 Cost Effectiveness and Industry/Market Acceptance

Given that 53 percent of the energy is lost in IR energy, learning how to recapture an even smaller percentage of those losses can yield significant efficacy gains and would be cost effective. It is anticipated that any lamp with a small percentage increase in efficacy would gain the attention of, and acceptance by, industry as long as there are no negative tradeoffs.

7.4 Ballast Systems

7.4.1 Background and Description

Although the lamp and arc tube chemistry often receive the initial attention when discussing efficacy improvements, attendees emphasized that the ballast is just as critical because the lamp and ballast need to operate as a system.

The introduction of solid-state ballasts has opened up the door for true continuous dimming, improved color control, smaller source sizes, and improved efficacy. The advent of the solid-state ballast, and advancement towards smaller and smaller packages, makes the integrated MH lamp possible, as was demonstrated at the Workshop by Janczak and Schellen. The initial wattage at 26 watts is a good first step. However, attendees wonder if and how this can this be expanded to higher and lower wattages. Higher wattages will raise the serious concern about heat management. If this can be accomplished then the large family of higher wattage Parabolic Aluminized Reflector (PAR) and halogen PAR are susceptible to retrofit with more efficient MH sources.

Electronic ballast advances further offer the possibility of being controlled by wireless technology. The Zigbee protocols now being developed optimize output in conjunction with sensors reading daylight and occupancy. These ballasts, if fully developed, take the system approach to building management to a new level of efficiency. They allow for load shedding control via the local electric utility or off-site facilities management.

7.4.2 Impact on Lamp, Ballast and System Efficacy

Further advancement of electronic ballasts can continue the trend of minimizing ballast losses. This may be achievable down to less than three percent from the current best level of six percent, thus achieving a system efficiency increase of five percent. In addition, the development of more cost-effective electronic dimming would yield savings from daylight harvesting and load shedding.

7.4.3 Impact on Source Size Reductions

The integrated circuit as a ballast mechanism is the key to the integrated lamp/ballast combination as shown in the Janczak and Schellen's paper. Continued development in this area could eliminate the separate lamp/ballast system. This would decrease lamp and ballast "source" size and increase the number of market applications such as existing track lighting systems and small diameter recessed downlights. For example, the lamp and ballast together could easily fit in the head of track lighting fixture.

7.4.4 Impacts on Other System Attributes or Applications

7.4.4.1 Multi-lamp Ballasts

Solid-state circuits also lend themselves to the possibility of being able to control different types of lamps. Multi-lamp ballasts would enhance the system approach, contribute to energy savings and reduce costs. A multi-lamp ballast would also reduce electrical distributor inventory because there would be fewer different ballasts needed, and this could also potentially save manufacturing and shipping costs for the original equipment manufacturer (OEM).

7.4.4.2 Control of the Arc

Minute variations in current control can have significant effects on the arc and its properties. Controlling the ballast response to input voltage via solid state circuits provides the ability to reduce variations. However, further research and development is important in order to prevent electrode damage (which can limit life), and control species segregation (which results in color separation) within the arc and prevent acoustic resonance, which can destroy a lamp prematurely if the arc comes too close to the arc-tube wall causing the tube wall to overheat. Providing appropriate resonance shifts during life can improve color mixing and prevent non-passive failure in the MH lamp.

7.4.4.3 Color

With quartz glass metal halide arc tubes, metal ions may migrate through the arc tube wall with some ion species (especially Na^+) migrating at high rates. In metal halide lamps containing NaI, the migration of Na^+ through the wall is the well-known "sodium loss" process. This migration of positive ions will cause a build-up of free halogen (e.g. iodine) within the arc tube, leading to operating voltage rise and arc constriction. Typical lamp ballasts may not be able to compensate for these effects, leading to increased lamp power dissipation, color shifts and shortened lamp life. However, with appropriate feedback to the ballast circuitry, it may be possible to compensate for these changes.

In ceramic arc tubes, migration/diffusion of metal ions through the wall is minimized, but primary cause of color shift may be the segregation of salts within the arc stream. This could be attributed to line voltage variations. Electronic ballast stability controls can eliminate or greatly minimize this possibility. Color shifting now reported to be between 75^o and 200^o Kelvin could be further improved, or even reduced to an indistinguishable level.

7.4.4.4 Lumen Maintenance

Lumen depreciation has improved from less than 80 percent to 85 percent, and now 90 percent. Ballast control of the arc seems to be a fruitful path for developing further advances. Electrical current variations can cause electrode losses, and thus reduced lumen maintenance. These electrical current variations can also cause the arc to fluctuate and move towards and damage the arc tube wall. Ballast control could keep the arc stable, minimizing arc tube wall damage, and increasing lumen maintenance.

7.4.5 Cost Effectiveness and Industry/Market Acceptance

Electronic ballast improvements can be achieved in a cost effective manner and be accepted by the market if they demonstrate superior system (lamp/ballast) performance. As the industry use of MH systems advances, the contributions of the ballast in addressing the needs of the market become more apparent. Dimming, color control, improved lumen maintenance, size reduction, protection from end-of-life non-passive failure and longer life are all demanded by the user.

7.5 Coatings (Interior and Exterior)

7.5.1 Background and Description

Coatings received a significant amount of discussion during the Workshop. Coatings can reduce IR losses and improve efficacy as described below. Three types of coatings were discussed; barrier coatings, color-corrective coatings, and reflective coatings. This included silica coatings for oxidation protection of Mo sealing foils in quartz MH lamps.

The Brumleve and Buelow papers both discussed the need to control wall reactions, both in quartz and ceramic arc tubes. Reactions of the metal halide salts with silica (quartz), causes lumen loss and reduced lamp life. These reactions consume and reduce scandium and other rare earths found in current dose mixtures. Reactions with tungsten can also occur, causing electrode erosion. Similar reactions were also reported by Hilpert et al (Proc.6th Int. Symp. on Molten Salt Chemistry and Technology, Hrsg:Chen Nianyi, Qiao Zhiyu, Shanghai University Press, Shanghai China 2001, pp140-145) involving alumina arc tubes. Barrier coatings on the inside of the arc tube may provide a means of reducing these reactions.

The papers discussed earlier concerning IR losses were concentrated on understanding where the IR is coming from and at what wavelengths. Color-corrective coatings of IR absorbing phosphors (anti-Stokes law phosphors) on the inside of the outer bulb may offer a means of capturing the IR to generate white light. This was discussed by Walitsky and Ryan during the Workshop discussion.

During the Workshop, Boling initiated a discussion on reflective coatings on the outer wall or arc tube. These coatings are similar to those used in halogen lamps such as the infrared-coated (IRC) halogen. These coatings reflect back IR photons which have transited the arc tube wall back into the arc to increase energy available for light production. These type coatings can also act as filters thus differentiating which wavelengths are transmitted and which are reflected. The filter layer is composed of 40-60 layers of film which total about 4 microns total thickness, each layer being about 1000 angstroms thick. As these coatings are applied to the outer bulb they can be used in quartz or ceramic lamps to theoretically increase efficacy.

However, as discussed during the Workshop, more research is needed to fully understand the benefits of the different coatings, investigate the use of color-corrective coatings that have not been used on MH lamps, and improve adherence of the coatings.

7.5.2 Impact on Lamp, Ballast and System Efficacy

The possibility of minimizing wall reactions with barrier coatings could result in the opportunity for higher wall loadings and vapor pressures allowing for different salt mixtures to be investigated. These can lead to higher lumen output quartz lamps and possibly higher output ceramic lamps with improved lumen maintenance, and maintained efficacy.

Reflective coatings increase the arc temperature without requiring additional input power thus improving the lumens per watt. However, the cost of producing and installing such coatings has been a barrier to their adoption.

For many years phosphor coatings have been used on the inside surface of the outer bulbs to color correct MH and MV lamps. These coatings of yttrium vanadate or yttrium phosphate-vanadate and magnesium germanate have been effective and cost competitive. On the other hand, anti-Stokes law phosphors are currently expensive at current usage rates. They have been considered in fluorescent systems but are not known to be used in MH systems. However, given that 28 percent of the input power is transmitted directly to IR energy, a small percentage improvement can yield significant efficacy gains.

Interference coatings can increase the photons in the arc thus "fattening the arc." As photons are brought back into the energy field additional photons may be emitted in the visible range. Thus, there may be an increase in lamp efficacy. However, the reintroduction of photons back into the arc may also have an effect on the ballast performance.

7.5.3 Impact on Source Size Reductions

The use of reflective coatings to increase vapor pressure without increasing input watts leads to the possibility of smaller source sizes. In his paper, Buelow presented preliminary findings showing improved life of metal halide lamps when exterior reflective coatings are added. These improvements could be linked to a more even bulb-wall thermal distribution. If the hot spot temperature can be reduced through this method, then smaller lamps can be run at higher power and still have the same hot spot, which should lead to similar lifetime.

In addition, by reducing wall reactions, arc stability is improved which relaxes the requirements for ballast control. This may also lead to a reduced ballast size.

IR coatings on the outer wall will affect the color of the lamp and the output, but would not have a direct influence on the source size. However, if output is raised significantly then manufacturers could choose a lower wattage lamp to produce the same output as the higher watt lamp used previously and capture the energy savings.

7.5.4 Impacts on Other System Attributes or Applications

Interior barrier coatings on quartz arc tubes are likely to help reduce color shift. If coatings can reduce the wall reactions then dose chemistry may remain relatively constant. Ceramic arc tubes do not appear to have wall reactions of the magnitude seen in quartz. Therefore coatings may not have the same impact with a ceramic system in controlling dose chemistry.

Reflective coatings may help in lumen maintenance in both systems. In ceramic some loss of salts occurs at the grain boundaries of the polycrystalline alumina. A coating could minimize this reaction. By keeping these areas from darkening over time lumen maintenance could be improved.

Color-corrective coatings which contribute to lumen output may also be able to produce lamps with different visible spectra. This may be valuable to consumers and purchasers wanting higher color temperature lamps.

7.5.5 Cost Effectiveness and Industry/Market Acceptance

Adherence to the arc tube wall and the complexity of applying the coatings are the two main barriers to wider investigation and use of coatings. This was discussed by Buelow and Brumleve during the Workshop. Unless science and research can help overcome these challenges, the use of internal coatings may suffer from significantly increased costs. This, of course, would limit market acceptance. The discussers suggested that different methods of application should be investigated and researching radically different methods may provide some valuable in-sight; keeping in mind that coatings have the potential for extending lamp life, enhancing performance, and reducing lamp manufacturing costs.

7.6 Chemical Fill Optimization

7.6.1 Background and Description

The chemical fill, or dose mixture, used to generate light in HID lamps has evolved from the mercury lamp of the 1930's to the sodium-mercury lamp of the 1960's to the rare earth mixtures now used in metal halide lamps. The rare earth iodides including scandium iodide and sodium iodide have been a mainstay of the arc chemistry for many years. The search for more efficacious lamps and/or better color rendition has led to adding additional iodide salts to the mix.

The rare earths have multiple energy bands and thus the opportunity for emission spectra covering multiple wavelength ranges. Dysprosium, holmium and other rare earths present a dazzling array of such choices. However, empirical work is slow, tedious, and time-consuming resulting in uneven results requiring long testing times.

The rewards of finding the right mixture can lead to optimization of the emission spectra where it is most needed to increase useable visible light. Brumleve discussed two methods of statistical modeling which are applicable to this problem. Juggling eight individual rare earths leads one to believe that this may be the only reasonable way to find the optimum dose.

Research is needed to assess the trade off between efficacious output and improvement in color control and color rendition. In addition, as discussed in Section 7.3, Eden mentions that laser spectroscopy can now be used to investigate photoassociation in different chemical fills. Laser spectroscopy can also be used to determine the optical spectra (absorption and emission) of metal halide fragments.

7.6.2 Impact on Lamp, Ballast, and System Efficacy

Optimizing the dose mixture is a primary factor in increasing the efficacy of the lamp; thus a lot of discussion focused on this topic. If the dose mixture is optimized not only is lumen output maximized but lumen maintenance is also improved. System efficiency improves in direct proportion to dose mixture advances.

7.6.3 Impact on Source Size Reductions

An optimized dose mixture will theoretically allow wattage and lamp size reductions for equivalent brightness. Optimized dose mixtures is one of the areas lamp designers investigate to reduce source size.

Smaller sources will lead to more commercial applications. The smaller size lamp also has better optical control, further improving the system efficiency.

7.6.4 Impacts on Other System Attributes or Applications

Optimized dose mixtures should also improve color rendering and possibly color shift. Generally as CRI improves lumen output suffers, but the CRI could approach 95 to 97 without loss of output if the right dose mixture is found.

Improved lumen maintenance will also allow designers to specify a fewer number of fixtures per space, because designers design to mean lumens not initial lumens. The higher the mean lumens the fewer fixtures one needs to light a space to meet lighting requirements. Fewer fixtures will also lead to compliance with watts per square foot ordinances.

7.6.5 Cost Effectiveness and Industry/Market Acceptance

The cost of newer salt mixtures should not be significantly higher than current mixtures. While rare earths are not inexpensive, their cost structure is to some extent already built into lamp cost. In some cases, new salts could be used that will increase cost, and in some cases different ratios of individual salts will be used. The labor to prepare mixtures is automated which is already in the cost structure.

Higher output, improved color rendering, and improved lumen maintenance are exactly what the market wants. Market acceptance should be immediate. In addition, optimized dose mixtures that lead to source size reduction will open up new markets for MH lamps – specifically retail, hospitality and other commercial spaces.

7.7 Arc Tube Material (Quartz, PCA, Saphire, Yttrium Oxide)

7.7.1 Background and Description

Until the1960's quartz was the only material used to contain the arc. This material offered good resistance to temperature and was able to keep the lamp intact for thousands of hours. In the late 1950's, Dr. Coble and General Electric developed a high pressure sodium (HPS) lamp using polycrystalline alumina as the arc tube material rather than quartz. This lamp had the advantage of being significantly more energy efficient generating light in an area of high sensitivity to the eye. Lumens per watt went from 60 to almost 100 lumens per watt. The disadvantage was the color and color rendering, although mercury vapor had serious drawbacks in color rendition as well. Metal halide lamps emerged in the 1960's and used quartz arc tubes. This development brought whiter light and higher coloring rendering. In the 1990's MH lamps with ceramic (polycrystalline alumina) arc tubes were introduced, which provides better lumen maintenance, higher efficacy, and significantly reduced color shift compared with quartz arc tubes.

Some of the attendees believe there may be additional lumens to be gained from the ceramic arc tube by increasing the transmittance of the arc tube material. Visible radiation emitted from the arc must transit through the wall of the arc tube and thus experience some losses. Polycrystalline alumina has multiple grain boundaries. These boundaries act as sinks for the photons attempting the transit. Elimination of the boundaries will, in theory, reduce this photon trap.

Single crystal alumina, also known as sapphire, is a material without grain boundaries. Polycrystalline alumina has a transmittance of approximately 90 percent. Quartz transmission nears 100 percent, but because quartz tubes cannot reach as high a temperature as polycrystalline alumina the ceramic lamps are more efficient than the quartz lamps even with a lower transmission of the arc tube material. However, single crystal alumina will approach 100 percent. Coupling this gain with the higher arc temperature of ceramic could produce a significant jump in efficacy. Lamps with this material have been made in the past and are currently used in research applications, but have not been seen in commercial applications.

Other materials such as yttrium oxide have also been the subject of experimentation. Infrared transmittance may be enhanced with such a material. Coupling an improved IR transmitting material with anti-Stokes law phosphors described in Section 7.5 may offer an area for further development.

7.7.2 Impact on Lamp, Ballast and System Efficacy

Improved transmission of photons through the arc tube wall would yield higher lumen output for the lamp. Theoretically a 10 percent increase is possible; practically, five percent or more increase would be significant. A single crystal material should mean reduced reactions between the metal halide salts and the arc tube wall, and arc stability could improve and yield additional efficacy gains. This increase in lumen output would be achieved without an increase in input power.

7.7.3 Impact on Source Size Reductions

An increase in system efficacy will result in a reduction in wattage to obtain similar lumen output, or higher lumen output for the same wattage. Choosing to keep light levels constant can result in a lower wattage lamp which often means a smaller arc tube and source size. This means that improved lumens per watt will have a favorable impact on source size reduction.

7.7.4 Impacts on Other System Attributes or Applications

Single crystal arc tubes should improve lumen maintenance as wall reactions will be minimized. This will keep the dose mixture near its' desired ratios for longer periods of time. With improved transmission one would expect improved color rendering as there is less absorption of the various wavelengths transmitting the arc tube wall. With no grain boundaries to absorb material, the color shift, which is minimized in polycrystalline alumina compared to quartz, should be virtually eliminated.

7.7.5 Cost Effectiveness and Industry/Market Acceptance

Single crystal arc tubes are expected to be more expensive than polycrystalline alumina tubes. Market acceptance will require balancing the cost versus the value of the improvement. At this point it is not possible to predict the impact on cost resulting from manufacturing volume of a single crystal arc tube and whether market acceptance will ensue.

7.8 System Optimization (lamp/ballast/luminaire)

7.8.1 Background and Description

The attendees presented two major issues with the historical development of metal halide lamps: 1) all current improvements of metal halide performance has been built on mercury vapor (MV) technology that evolved more than 50 years ago – i.e. a "patchwork" of improvements to relatively sub-par technology; and 2) lamp, ballast and luminaire manufacturers have historically, and in many cases still do, develop their products independently with minimal communication. The result is a system that produces products, but the products' performance is not nearly optimized.

To date the electrical operating characteristics of MH lamps are based on MV technology. However, the development of a new MH lamp and ballast system with improved electrical parameters combined with other advances (such as arc tube, fill chemistry, etc) could yield a more efficient system. For example, a new generation of MH systems could target a higher voltage arc tube, thereby reducing the current which reduces the complexity of the ballast, its size, and cost.

In addition, Buelow's paper demonstrated how integrating the lamp, ballast, and luminaire development during the design process can yield an optimized system. The attendees agreed that this process would have significant advantages.

Some attendees feel that the future lies in integration of the development cycle for all three components. In order to maximize the parameters of the lighting system, the lamp ballast and luminaire must all be developed as a system. The R&D components described in the preceding sections are all interdependent. An R&D effort that does not consider the entire system will be looking backwards instead of into the future.

7.8.2 Impact on Lamp, Ballast and System Efficacy

Ryan suggested lamp and ballast efficacy could achieve a 30 percent gain if developed together, and investigating more optimized electrical parameters rather then using those of the standard MV systems. Regardless, a systems approach to design would yield additional efficiency gains.

In addition to the source efficacy, workplane illuminance efficiency would also benefit from an optimized systems approach. Developing the luminaire in conjunction with the lamp would optimize the lumen delivery to the workplane. This is demonstrated in Buelow's paper, and is also becoming more important as exterior luminaire distribution is being restricted by Dark Sky Legislation and the overall movement for reduced glare in interior and exterior applications.

7.8.3 Impact on Source Size Reductions

A systems approach would help reduce the source size of the lamp, ballast and luminaire. This would benefit the practical application in terms of space requirements. Issues of heat management, optical focus, voltage and current control all become intensified as the components are reduced in size. However, system optimization is the key to successful source size reduction and quality performance. The integrated lamp ballast combination shown by Jerzy and Schellen would not be possible without optimization of the system.

7.8.4 Impacts on Other System Attributes or Applications

System attributes such as lumen depreciation, color shift, useful life and end-of-life phenomena all benefit from system optimization. The ballast can affect the lamp and the arc; the luminaire will also impact overall system efficiency and practical application.

It may also be possible to build ballast technology which could signal approaching end-of-life phenomena such as “non-passive failure modes.” Such optimization would have beneficial effects in safety considerations and potentially open new markets to MH where such phenomena are a major concern.

7.8.5 Cost Effectiveness and Industry/Market Acceptance

All Workshop participants showed that system optimization is the “golden” key to efficiency, cost effectiveness, and market acceptance. All of the companies represented are familiar with the principle that optimization helps to reduce manufacturing costs. In addition, the operating cost of an optimized system should actually be lower than one in which the components are developed separately and are not matched to each other. Market acceptance will depend on the advantages perceived by the designers and specifiers as they incorporate new systems into their designs. Retrofit opportunities will also depend on financial returns along with improved properties.

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Energy Savings through Controllable, High Efficiency Ceramic HID Systems – Both Lamp and Electronic Ballast Considerations

Gary Eden, University of Illinois
Metal Halide Laser Spectroscopy and Microcavity Plasma Devices: Tools for Improving HID Lamp Performance

Walter Lapatovich, Nancy Chen, Osram Sylvania
Efficacy Limits of White Light Metal Halide Lamps

Roger Buelow, Fiberstar, Inc.
Recent Lifetime Increases and Photometric Improvements of Quartz Metal Halide Lamps from Exterior thin Film Coatings and Improved Ballasts

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Appendix D. HID Lighting Technology Workshop Registrant List

APPENDIX A

HID Lighting Technology Workshop Agenda

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

2005 HID Lighting Technologies Workshop

High Intensity Discharge (HID) Technology Workshop
Department of Energy
Conventional Lighting Technologies
DOE EERE-Building Technologies and NEMA

November 14-15, 2005
Radisson Hotel Reagan National Airport

November 14

Registration and Evening Reception sponsored by NEMA — 6:00 – 8:00 pm

November 15

Welcome and Introductions – Jim Brodrick — 8:00 – 8:15 am

Background – Jim Brodrick — 8:15 – 8:45 am

Workshop Goals and Objectives – DOE — 8:45 – 9:00 am

Energy Savings through Controllable, High Efficiency Ceramic HID Systems — 9:00 – 9:30 am
Jerzy Janczak, Philips Lighting

Metal-Halide Laser Spectroscopy and Mircocavity Plasma Devices: Tools for Improving HID Lamp Performance — 9:30 – 10:00 am
J. Gary Eden, PhD, University of Illinois,
Department of Electrical and Computer Engineering

Break — 10:00 – 10:15 am

Efficacy Limits of White Light Metal Halide Lamps — 10:15 – 10:45 am
Walter P. Lapatovich, Osram Sylvania

Lifetime Increases and Photometric Improvements to Quartz Metal Halide Lamps from Exterior Thin Film Coatings and Improved Ballasts — 10:45 – 11:15 am
Roger Buelow, Fiberstars Inc.

Recent Developments in Dose Optimization and Design of Low-Wattage Quartz Metal Halide Lamps Timothy R. Brumleve, APL Engineered Materials, Inc.	11:15 – 11:45 am
ALIGHT Program John Curry, NIST	11:45 – 12:00 pm
Lunch	12:00 – 12:45 pm
Prepared Written Discussion of Papers – Discussers Oral presentation of prepared discussions on papers and additional HID R&D topics	12:45 – 1:30 pm
Facilitated Interactive Discussion – Paul Vrabel/Scott Graves, ICF Consulting Additional opportunities and challenges not described in the papers	1:30 – 2:15 pm
Break	2:15 – 2:45 pm
Summary of Key Opportunities and Challenges	2:45 3:00 pm
Facilitated Interactive Discussion – Paul Vrabel/Scott Graves, ICF Consulting Assessing the opportunities based on cost-effectiveness, wattage size, and system efficacy	3:00 – 3:45 pm
Next Steps and Closing Comments – Jim Brodrick	3:45 – 4:00 pm

APPENDIX B

Paul Walitsky and Paul Vrabel
Background Paper:
General Technology Overview of the Current Status of High Intensity Discharge Lamp Technology 2005

GENERAL TECHNOLOGY OVERVIEW OF THE CURRENT STATUS OF HIGH INTENSITY DISCHARGE LAMP TECHNOLOGY 2005

OCTOBER 27, 2005

Paul Vrabel, LC
Paul Walitsky, CHMM
ICF Consulting

Current High Intensity Discharge Technology

The High Intensity Discharge (HID) lamp family is composed of three distinct lamp types: Mercury Vapor (MV), High Pressure Sodium (HPS), and Metal Halide (MH). Low Pressure Sodium (LPS) while technically a low pressure discharge lamp it is often considered by industry a part of the HID family. LPS serves in particular applications as if it were an HID lamp. Table 1 summarizes the different characteristics of each lamp type including different types of Metal Halide lamps.

Mercury Vapor

Mercury vapor is the oldest of the HID family – first introduced in the 1930's. MV technology, while a breakthrough at the time, has been superseded by more efficacious technology. However, MV lamps are still used primarily because of their low cost and longevity.

Mercury vapor lamps will often burn much longer than their published 24,000+ rated life. The problem is that they have high lumen depreciation, but this is not always a concern of the purchasers. In addition, the initial purchase cost is very low compared to other HID technology, which is appealing to homeowners and landscapers. MV spectrum has a strong green component, which combined with low initial cost makes it attractive for landscape lighting.

Mercury vapor lamps are responsible for 17 percent of the electricity consumed by the HID lighting installed in the US.[2] However, MV only constitutes 8.5 percent of the HID shipments as reported by NEMA.[1] MV is considered so inefficient that the production of Mercury Vapor ballasts will discontinue January 1, 2008 as determined by the Energy Policy Act of 2005.

Sodium

The High Pressure Sodium lamp was perfected in the early 1960s by GE and Westinghouse Lamp companies. It rests on the development of Polycrystalline Alumina by Dr Coble of GE in the 1950s. Polycrystalline Alumina allowed the lamp engineers to use corrosive sodium along with the mercury to produce a much more efficient source of light.

High pressure sodium is widely used in highway, street, parking lot, and area lighting. HPS lamps consume 32 percent of the electricity used for HID lighting and constitute 34 percent of the shipments in 2002 according to the NEMA numbers.[1] This is most likely due to the fact that HPS initial cost is good when comparing the value of efficacy and life.

High pressure sodium lamps range in efficacy from 80 to 125 lumens per watt, which is very good compared to MV and better than Metal Halide. However, the drawback of HPS is its color appearance and color rendering properties. The yellow-orange color is sometimes considered unfavorable especially when a "whiter" light is desired. HPS has a color rendering of 22 (out of an index of 100), which is very low compared to other light sources. For example, Metal Halide HID lamps range in color rendering from 62 to 95.

"White" High Pressure Sodium lamps were developed in the 1980s in an effort to provide a high color rendering and "whiter" light source that would be more attractive for commercial applications. However, the color temperature was very "warm" in the 2200 to 2700^{o}K range, which is too warm for the desired temperatures of 3000 to 4000^{o}K for commercial applications. The initial interest was to develop a "white" light HPS lamp and maintain the efficacy. However, the price of providing better color rendering and white light has been a loss of system efficacy. Currently manufacturers are producing white HPS but have not pushed the technology beyond the original intended target of retail produce display.

Metal Halide

The metal halide lamps can be categorized by the type of arc tube construction and the mode of starting. Arc tubes are either quartz or ceramic (aluminum oxide), and the starting mode is either pulse or probe start.

Quartz arc tubes were the first type used, but ceramic arc tubes were introduced in the early 1990s. Ceramic arc tubes offer the ability to operate at higher temperatures with less salt losses, thus curtailing color shift during life. Research in quartz lamps continues to make advances in electrode configuration, gas control, and electronic control[7].

Quartz arc tubes for metal halide lamps were first introduced in the early 1960's. Today, quartz is the most popular arc tube and lowest cost for metal halide lamps. However, quartz metal halide lamps are subject to large color shift over life due to salt losses, and have high lumen depreciation. In addition, metal halide lamps are sensitive to burning position. This is due to the effects of heat and gravity. The horizontal position brings the arc close to the wall where some cooling occurs. This affects the arc and also unbalances the chemical equilibrium. However, the metal halide lamp brings a more complete spectrum to the emission range of the lamp, gives better color and improves the color rendering properties. MH sacrifices some lumens per watt in achieving these improvements over HPS.

Ceramic arc tubes are manufactured as cylinders or ball-shaped. Because the ball shaped vessel more closely follows the natural contours of the arc there is some increase in efficacy of the lamp. Ceramic arc tubes operate at higher temperatures, have lower temperature gradients and have a different salt mixture. These salts produce a different emission spectrum. Benefits are less color shift, higher color rendering, and improved lumen maintenance. In addition, ceramic arc tubes result in less color variance among lamps during manufacturing, and can be manufactured in much smaller sizes. The smaller size means lower wattage and lumen lamps, and greater optical control because the arc tube is a smaller "point" source.

Ceramic Linear Arc Tube[9]

Spherical Ceramic arc tube (Osram)

The other primary difference in metal halide lamps is the mode of starting -- pulse start versus probe start. Conventional metal halide lamps have three electrodes inside the arc tube. One at either end which the arc uses as touch points when operating. However to start the lamp, a spark is initiated across the short gap between the “probe electrode” and the operating electrode – i.e. probe-start. The electrical breakdown started here generates ions which travel to the opposite electrode and thus initiate the arc. When the lamp heats up a bimetallic switch cuts the “probe electrode” out of the circuit. This was the standard method of starting metal halide lamps for about 30 years.

Pulse start lamps eliminate the internal starting probe and add the ignitor to the ballast circuitry, which improved performance. The introduction of the pulse start technology has lengthened lifetimes of metal halide lamps by up to 50 percent and yielded system efficacy gains of greater than 25 percent. A 320 watt pulse start lamp can produce almost as much light as a standard 400 watt probe start lamp. There are also improvements in lumen maintenance and color stability. See Table 1 for performance benefits. Warm-up time is reduced to as low as two minutes, which is a major benefit for interior applications. Over the years this technology has advanced through the wattage range from 70 to 150 watts to 400 watt lamp and down to 20 watts at the low side. In lower wattage lamps the trend is definitely toward electronic ballast configuration.

Ballasts

The HID ballast market is dominated by core-and-coil electromagnetic (aka magnetic) ballasts, however electronic ballasts are available.

Magnetic ballasts, or core-and-coil, are an inductor consisting of one or multiple copper coils stacked on a core of steel laminations. These two components are joined with a capacitor. This assembly transforms the electrical power into a form appropriate to start the lamp. These ballasts are generally large and heavy. There are five basic circuits for magnetic ballasts:

Reactor – A single coil ballast can be used when the input voltage to a fixture meets the starting and operating voltage requirements of an HID lamp. Reactor ballasts only perform the current limiting function. This ballast and the High Reactance Autotransformer are used for low wattage HID lamps (35-150 watt).

High Reactance Autotransformer – Used when the input voltage does not match the requirements of the lamp, this ballast transforms the input voltage to the lamp in addition to limiting the voltage. Two coils are used. This ballast is used for the lower wattage ranges.

Constant Wattage Autotransformer – The CWA ballast uses a capacitor in series with the lamp to correct high current draw. The capacitor allows for greatly improved lamp wattage control. CWA is the most common ballast used. It is used for the higher wattage HID lamps. (175-2000w).

Constant Wattage Isolated – This ballast is primarily used in Canada to meet safety requirements. It electrically isolates the secondary coil from the primary coil. It prevents the socket shell from being energized on phase-to-phase input voltages. Because the voltage in Canada can be higher than in the US, (Canada often uses 377 volt), this ballast helps to prevent shocks. This ballast is primarily used in Canada.

Regulated Lag – This is a three coil ballast. It has a reactor ballast with a two coil voltage regulator circuit. This ballast provides the best lamp wattage regulation and has less energy losses, but is larger in size and more expensive. It is used in heavy industrial operations such as Auto manufacturing plants or steel mills where long wire runs are used. It also helps to lengthen lamp life and thus reduces maintenance costs.

Pulse start ballasts have the same configuration but add an ignitor to start the lamp. This allows for separation of the starting and operating functions. The logic in choosing a ballast circuit for the pulse start lamp is the same as for probe start ballast circuits described above. The ballast ignitor allows the elimination of the ignitor in the lamp itself. In balancing cost and energy efficiency the CWA pulse start ballast is the best choice for the mid to high wattage pulse start lamps.

Electronic HID ballasts were first introduced in the mid 1990's offering the possibility of true dimming, (continuous decreases in power and light compared to step dimming), system control, and miniaturization -- all of which lead to energy savings.

The electronic circuits convert the input energy into higher frequencies than capable for magnetic ballasts. This leads to improved lumen maintenance, longer lamp life, color quality control, and improved system efficiency. Electronic ballasts can keep low wattage ceramic MH lamps at precise control over long periods of time, improving lumen maintenance by compensating for variations in input parameters due to aging.

Electronic ballasts can also accommodate control systems integrating daylight dimming, occupancy control, and variable task demands. Electronic ballast on dimming circuits tied to photo-sensors can determine what light output is needed. According to Denny Beasley of Delta Power Supply, 33 percent power dimming became available about three years ago. The dimming improves lumen maintenance so designers need not specify as many lamps per square foot, or can use lower wattage lamps to maintain desired light levels, thus reducing energy requirements.

Table 1: HID Lamps and Performance

	Mercury Vapor	High Pressure Sodium	Probe Start Metal Halide	Pulse Start Metal Halide	Ceramic Metal Halide
Wattage Range	40-1000	35-1000	50-2000	50-2000	20-400
System Efficacy (LPW)*	39	94	51	68	87++
Lumen Maintenance (Mean life)	50%	90%	65%-75%	70%-80%	85%-90%
CRI	22-45	21-25	65-70	62-96	81-95
CCT (^{0}K)	3700-6800	1800-2700	3000-4200	2900-5000	2900-4200
Color Shift (^{0}K)	+/-100	+/-100	+/-500	+/- 500	+/-200
Warm up time (minutes)	5-7	3-4	5-7	2	2
Life (hours)	24,000+	24,000+30,000	10,000-20,000	6,000-20,000	9,000-20,000

using 400 watt lamps,
++ using electronic ballast

Applications

Mercury Vapor

Mercury vapor has limited use, but is readily available. In addition to landscape lighting, there is sign lighting, street lighting, and highway sign lighting that utilizes mercury vapor, but this use is decreasing. MV can be found in do-it-yourself, hardware, and farm stores due to its low cost and long life.

High Pressure Sodium

Street, highway, area (parks), and parking lot lighting are the most popular applications for HPS. HPS is also common for warehouse, building façade and some indoor manufacturing. However, the number of interior applications is reducing due to the poor color of HPS and the advances in MH. In addition, more municipalities are using MH instead of HPS for urban and suburban lighting. This is due to the desire for "whiter" higher color rendering illumination for public areas, especially shopping and commerce areas. It is easily understood that people like higher color rendering lamps and "whiter" light. Research has also shown that motorists have better peripheral visibility under metal halide compared to high pressure sodium lamps.[13,14,15]

Metal Halide

Metal halide leads in the number of HID lamps sold per year. MH can be found in many exterior applications including street, highway, area, facade, and sign lighting. MH is also the preferred lamp for sports venues from baseball fields to tennis courts. Common interior applications include many "high-bay" applications where the ceiling is usually over 15 feet. The high lumen output, good color properties, and ability to optically control the light make MH the lamp of choice for "high-bay" retail, gymnasiums, warehouses, manufacturing, lobbies, and other high ceiling applications. The advantages of white light, high CRI, and better lumen maintenance of the ceramic HID lamp with electronic ballast are a solution to all of the disadvantages of HPS.

Recent miniaturization of MH lamps down to 20 watts, made possible with ceramic arc tubes, is opening up new applications for MH technology where other efficient light sources do not work. The most practical is the replacement of halogen spot lights used for accent lighting in retail applications. Historically, halogen is the preferred lamp of choice in retail accent, spot, and flood lighting because of good color properties and the ability to control the direction of the light.

Electronic Ballasts

Electronic Ballasts are recommended for driving ceramic metal halide lamps. The electronic ballast can maintain the superior color properties, including high color rendering index and efficacies of 90 or more lumens per watt (in the low wattage lamps). In the medium wattage ceramic metal halide, which is now becoming available, electronic ballast operation is needed to maintain color and lumen maintenance.

Electronic ballasts are now available with multi-voltage capability and the ability to recognize input voltage variations and make adjustments to keep the lamp input voltage constant. This helps maintain color, light levels, and overall proper performance.

Recent Advances and Trends

Recent advances in HID technology are focused on miniaturization and wattage range expansion of MH lamps. Smaller wattage lamps, less than 50 watts, with better color control are being introduced to the market for commercial applications. In addition, there is a push to introduce ceramic technology into lamps above 400 watts – again for better color control.

Ceramic Metal Halide Lamps

At the low wattages there is 20-watt mini metal halide and an integrated (lamp/ballast) 25-watt metal halide, which was introduced in the past year. These lamps can replace 75 and 90-watt halogen lamps in the retail sector. The primary benefit is energy savings and long life. Standard PAR Halogen lamps have rated lives between 2000 and 3000 hours. The 25-watt integrated HID lamp has a rated life of 10,500 hours. However, the 25-watt integrated lamp cannot be dimmed, which is a major limiting factor.

Longer life and improved color rendering continues to be a focus of development as well. A 39-watt ceramic metal halide with a 12,000 hour rated life was recently announced -- said to be the industry's longest life 39-watt. In the same wattage range, color rendering is moving steadily upward with a 95 CRI at 3000^{o}K in PAR and T-6 shape MH lamps.

At the higher wattage range, 400-watt ceramic MH lamps have been introduced. This advancement is for improved color consistency in sports and arena lighting where color is critical for television. In addition, 320-watt ceramic pulse start lamps have been introduced for energy efficiency and better color. The 320-watt lamp shows mean lumens in a horizontal configuration of 22,000 lumens versus 23,000 for one of the 400-watt Probe start configurations.[16]

Quartz Metal Halide Lamps

The most recent advances in quartz technology were the introduction of pulse start lamps in the 1990's. Pulse start lamps continue to be introduced in more wattages for more applications. The main advantage of pulse start being energy savings.

At higher wattages, quartz technology still leads the market. For example, an 875-watt pulse start has an 80 percent mean lumen rating and a rated life above 20,000 hours. A 920-watt energy saving metal halide is designed as a direct replacement for the 1,000-watt lamp.

In quartz arc tube technology, understanding effects of varying inner arc tube gas pressure and electrode composition, and control gear may lead to improvements in this technology. Recent research indicates that there may be avenues to further increase efficiency and lumen maintenance of these lamps.

Ballasts

The electronic ballast with voltage control and microcircuit technology offers possibilities of true dimming down to 33 percent and possibly even lower levels. This will lead to increased use of the technology in areas where daylight harvesting requires a dimming lamp component. The emphasis on daylight harvesting is gaining momentum due to US Green Building Council LEED® for new and existing construction and energy codes. Control technology will be needed to support this trend and ballast manufacturers are investigating.

Ballast and lamp companies are also conducting forums to educate the design community that electronic ballast and ceramic technology is the key to sustainable lighting design where HID systems are needed. While cost is higher, the flexibility, improved performance, and efficiency have a decided economic advantage. This is especially true in the retail environment.

Luminaires

Although this report is focused on the lamp and ballasts it is important to make a brief mention of the luminaire, especially because of the impact on energy consumption.

Manufacturers are continuing to introduce new luminaries with better optical control. One reason is to meet cutoff requirements by "Dark Sky Legislation" and LEED® to reduce light trespass and light pollution. These luminiares are generally more efficient than previous generations. In addition, the reduction of lamp size due to ceramic arc tubes has fixture manufacturers designing luminaires that more efficiently distribute the light from these lamps.

The miniaturization of MH lamps and availability of smaller electronic ballasts has yielded fixtures that are smaller, lighter, and more conducive for interior commercial applications especially retail. One manufacturer[5] for example, produces a system that splits the light from a 100-watt metal halide lamp out through four down lighting fixtures, and in the process is more efficient than the four 60-watt halogen PAR lamps it replaces. This reduces required lamp watts by 140 watts per fixture and reduces heat generation and air-conditioning load. Smaller electronically ballasted fixtures are easier to install on track lighting systems, and small ceramic arc tubes allow for better optical control so designers can exactly place the light where needed.

Other Trends

Another trend impacting the HID market, is the introduction of high-output T5 fluorescent (T5HO)lamps. T5HO lamps are being used in high-bay retail to replace 400-watt ceramic metal halide fixtures. Usually a six lamp T5HO luminaire will replace one 400-watt metal halide. This retrofit is sold on energy savings (361 watts vs 455 watts), instant on, and better color properties. Although this retrofit is gaining in popularity, many lighting designers debate which technology is more applicable – both systems have their pros and cons. Pulse-start quartz lamps would also provide energy savings but not provide the color and instant-on benefits. Ceramic metal halide lamps provide the color and energy saving benefits but do not have better starting times.

Opportunities

Low-wattage ceramic metal halide lamps are opening the door for significant energy savings in retail applications where incandescent and halogen have dominated. Replacing halogen PAR lamps is one application, but there is also the opportunity to impact the (halogen) MR16 market. Further advancement in lamp size reduction, color consistency, and dimming all need to be addressed to truly compete in this market.

Development of ceramic discharge lamps for wattages above 400 watts will open up the sports and high mast (highway) markets as well. Sports lighting can be a future beneficiary of improved system efficiency.

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APPENDIX C

HID Lighting Technology Workshop Papers

ENERGY SAVINGS THROUGH CONTROLLABLE, HIGH EFFICIENCY CERAMIC HID SYSTEMS – BOTH LAMP AND ELECTRONIC BALLAST CONSIDERATIONS

Jerzy Janczak and Hans Schellen
Philips Lighting Co.

Abstract

High Intensity Discharge (HID) lamps and systems have existed for more than 50 years, leading to the most energy efficient light sources available. Lamp development efforts have led to white light sources with following properties:

- Efficacies of ~100 lm/W
- Long lamp life of >15000hrs
- Good lumen maintenance
- Excellent color control of +/- 200K in color temperature

Ballast developments have focused more and more on electronic ballasts with advantages of:

- Very good lamp power control
- High efficiency +10% compared to conventional magnetic ballasts
- Low in weight and volume
- Simple wiring

An overview of the history of HID developments, the latest state of the art technology and the potential for the future is given. It is Philips' strong belief that major steps in further improvement of energy efficiency must be achieved through system developments: i.e. lamps and ballasts should be developed as a system to achieve the highest energy benefit, potentially leading to:

- Compact well designed white light systems
- Energy savings of up to 30% compared to conventional lamp and ballast combinations
- Dimmable systems, with maintained color performance
- Lamps with integrated ballasts

The final effect will be greater availability of high efficiency HID systems with the associated energy savings and application flexibility.

Background

Lamp Technology

High Intensity Discharge (HID) lamps and systems have existed for many years. A brief overview of HID lamps is shown in the table below.

Table 1: HID lamp overview

Type	Introduction	Positive	Negative
Mercury Vapor	'50's	Long Life Reliable	Color Rendition Efficacy
High Pressure Sodium	'60's	Long Life Efficacy	Color Rendition

Quartz Metal Halide	'70's	Color Rendering Efficacy	Lumen Maintenance
Ceramic Metal Halide	'90's	Efficacy Color Rendering Maintenance	Dimmable

HID lamps gained their popularity in the market place as one of the most efficient point sources of light, which allow distribution of light easily where it is needed as well as having long life well suited for their application. Generally, HID lamps are applied in professional applications where total cost of ownership is the main consideration:

Lowest energy cost through good efficacy and lumen maintenance
Lowest installation and maintenance cost through life

Typical drawbacks of HID systems are:

Lumen maintenance of Metal Halide (MH)
Systems are big and bulky with complicated wiring

Currently, the market is dominated by High Pressure Sodium (HPS) and Quartz Metal Halide (QMH) lamps. Key characteristics of HPS lamps are given below.

Table 2: Characteristics of HPS lamps

Wattages	Efficacy	CRI	CCT
35W – 1000W	65 – 140 lm/W	10 - 25	1900 – 2100K

Due to high efficacy, long life and reliability and excellent lumen maintenance, HPS lamps are most prevalent in street and outdoor applications. Poor color rendition and low CCT have stopped broader penetration of HPS lamps to other applications. The main characteristics of QMH lamps are given in Table 3.

Table 3: Characteristics of QMH lamps

Wattages	Efficacy	CRI	CCT
35W – 2000W	70 – 110 lm/W	60 - 85	3000 – 5000K

Good initial efficacy and color rendering as well as "white light" can be considered as strong points of QMH lamps. The lumen maintenance of QMH lamp is fair. The weakest characteristics of QMH lamps are the spread in its color and lumen maintenance, which varies from lamp to lamp and can be influenced by lamp power, lamp life and burning position. Attempts by many companies on several fronts have not successfully addressed this variation, much of which is intrinsic to the interaction of the quartz material and the metal halide salts used. QMH lamps are found in major applications in industrial and retail lighting.

The visible spectra of HPS and QMH lamps are shown in Figure 1 and Figure 2, respectively.

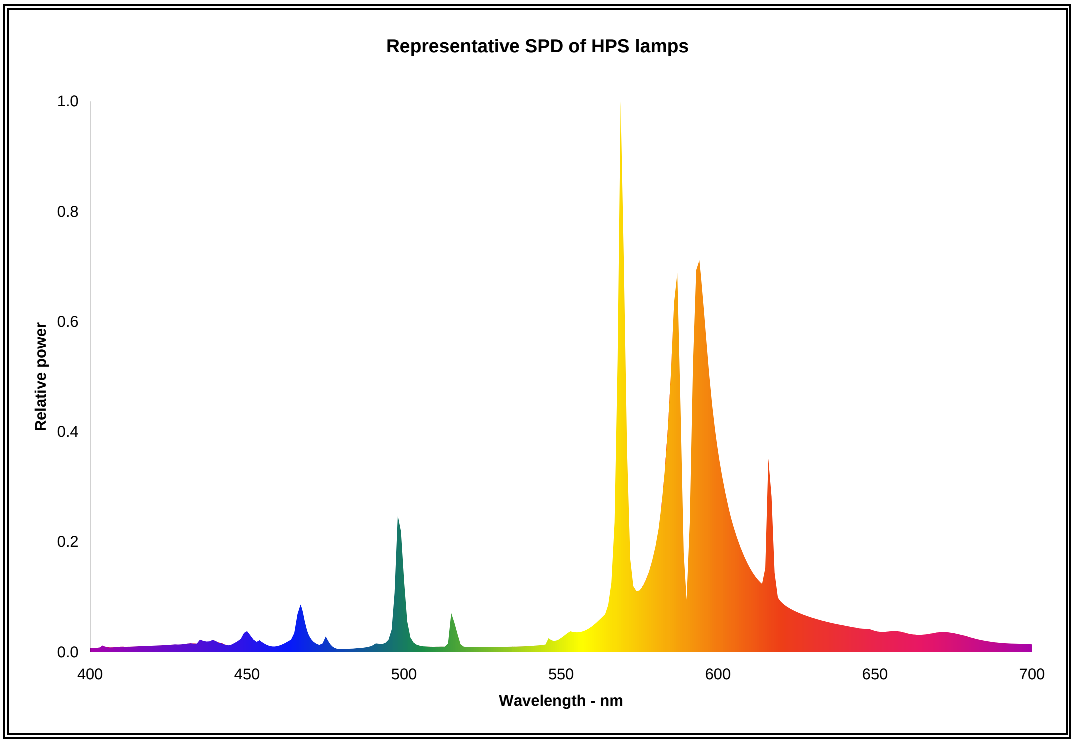

Figure 1. HPS lamp spectrum

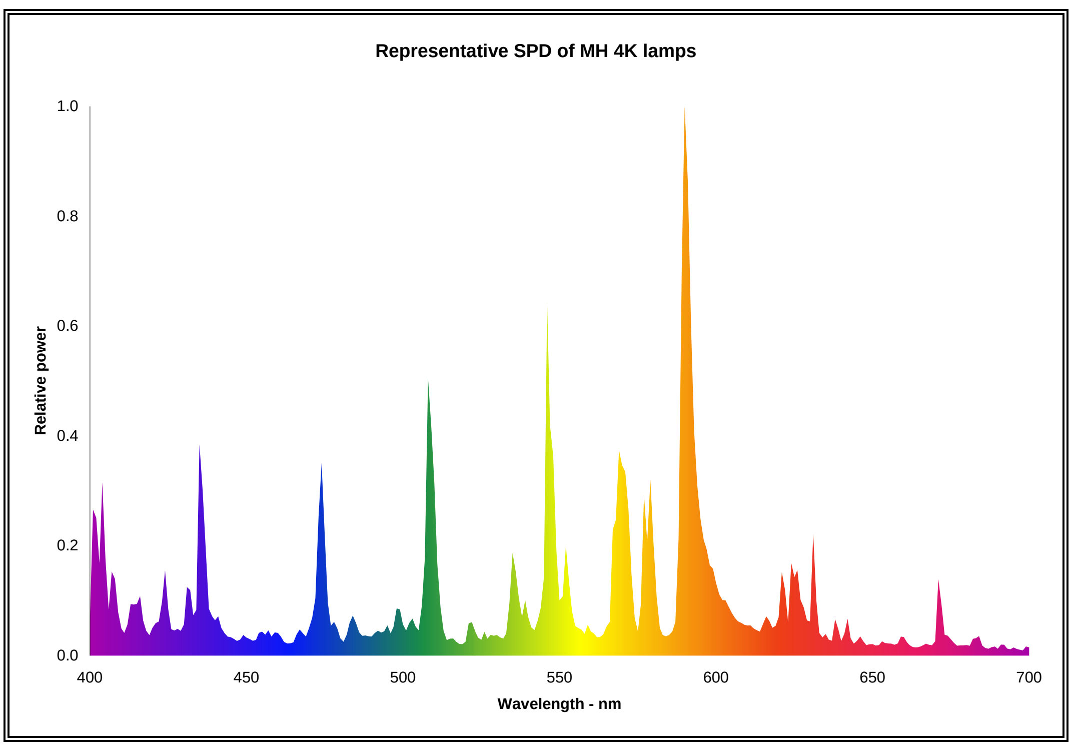

Figure 2. QMH lamp spectrum

Ballast Technology

Although introduction of the first HID system reaches back to the 1930's, the majority of HID systems are still currently powered in a conventional fashion, by magnetic ballasts. There are a number of negative aspects related to the operation of HID lamps on conventional magnetic ballasts.

The first limitation is related to their 50/60Hz lamp operating frequency. The decay time of typical HID plasma is in the range of 20 – 200 μs, which is much shorter than the time corresponding to the current zero crossing of the mains. This consequently leads to the occurrence of reignition peaks that may limit lamp performance, especially under dimming conditions. Many problems associated with conventional operation of HID lamps, especially metal halide lamps, are directly related to this reignition behavior.

While lamp radiation is modulated with double line frequency (100Hz or 120Hz), small asymmetries can produce a light flicker component at the line frequency. Those asymmetries may originate from dissimilar lamp electrodes, but also from vertical operation of the HID lamp. Light modulation is more critical at 50 Hz than 60 Hz, since the human eye sensitivity significantly decreases with increasing frequency in this region. For 50 Hz operation, the flicker level of 1.5% causes serious complaints, whereas for 60 Hz operation corresponding threshold level lies approximately at 5%.

Conventional magnetic ballasts feature relatively poor power control characteristics, relative to electronic ballasts. Consequently variation of the input line voltage as well as differences in the lamp design or changes of lamp characteristics during life, will strongly influence luminous flux, color characteristics and in many cases lifetime of the lamp itself. Attached figures (Figure 3. and Figure 4.) depict graphical interpretation of above mentioned characteristics.

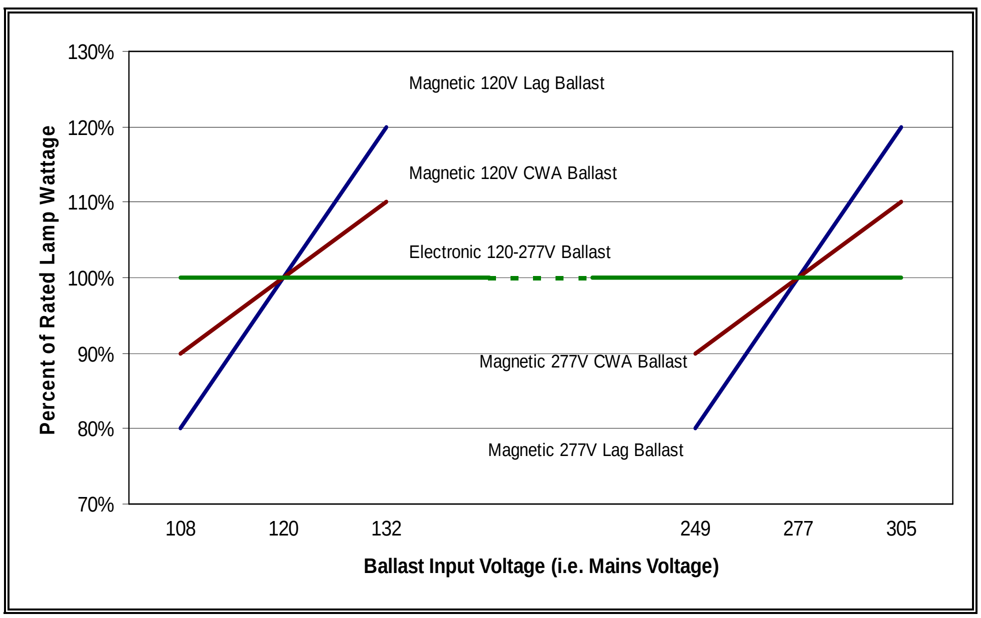

Figure 3. Lamp wattage regulation; magnetic vs. electronic, as a function of line voltages

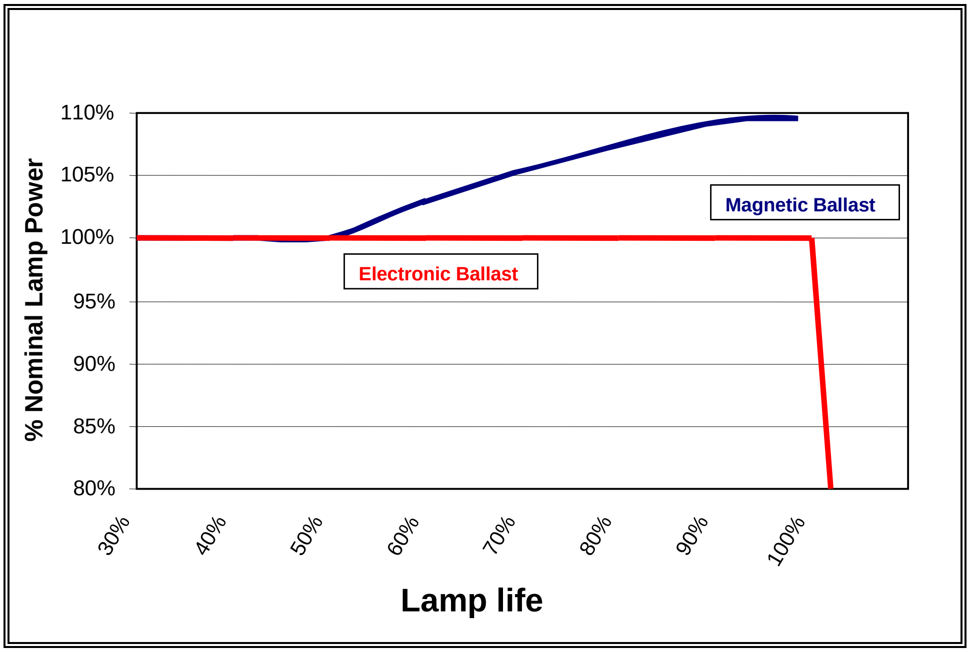

Figure 4. Lamp wattage regulation; magnetic vs. electronic,
as a function of lamp life (Metal Halide lamp example).

Run-up on conventional gear is relatively slow, which is due to the low lamp voltage and to the power that the conventional circuit can deliver during this phase of operation. As a result, run-up phase may last from one to several minutes, before luminous flux will reach 80 – 90% of its steady state value. Conventional ballast systems consist often of several components: the magnetic ballast, a capacitor and sometimes a separate starter (HID lamps may need a starting pulse up to 5 kV).
Until the mid 1990's, the progress of HID systems development with electronic ballasts was rather slow. From the electronic ballast point of view, unavailability of advanced technologies and high cost did not allow them to penetrate faster in HID lighting applications.

As far as development of HID lamps is concerned, the fact that MH lamps were mostly developed as retrofit for existing conventional ballasts, did not allow more aggressive introduction of novel technologies.

Existing Technology

Since our focus in this paper is on HID lighting systems powered by electronic ballasts, this chapter will discuss the current status of Electronic ballast options and Ceramic Discharge Metal Halide (CDM) lamps, which are considered the most advanced existing HID "white light" technologies.

Differences in performance between electronic and conventional operation

Given an existing lamp, upgrading from conventional magnetic to electronic ballasts may change overall the lamp-ballast system efficiency; however, there will be no fundamental increase in lamp efficacy. In contrast to conventional operation, on electronic ballasts the lamp power factor is almost unity and the time-dependent fluctuation of the plasma temperature will be absent. This can lead to small variations in the relative intensities of spectral lines. As a result of this, changes in efficacy will be rather insignificant (less than ~3%). The changes in CCT will be also rather small (at the most 200K – 300K). In some cases the CCT is lower, caused by the lower peak plasma temperature, which results in less blue radiation. A big advantage of electronic operation is the elimination of line frequency flicker, which is related to the current zero crossing on conventional gear. Since the plasma cooling effect at the current zero crossing will be amplified by lower lamp power, prospects of dimming on electronic gear are significantly improved. In fact dimming with conventional gear is generally limited to a two level switching between 100% and 50% power operation. These switching systems are typically complex in wiring. The opportunity for dimming will be much greater with electronic operation due to high di/dt, very accurate lamp power control in steady state operation, and flexibility of run-up current control, improved lamp maintenance under dimming conditions may be expected. Currently, there are available HID systems with electronic ballasts that allow dimming range of 100% – 60% and 100% – 30% for MH and HPS lamps respectively.

Electronic ballasts have the following main advantages:

- Excellent power control independent of line voltage and lamp setting
- Better ballast efficiency leading to lower losses in the ballast
- Greater compatibility with the demands of dimming
- Fewer components next to the lamp, which simplifies wiring (only 1, for magnetic is typically 3)
- Further increase of system efficiency due to power factor of almost unity
- Lower in weight and volume than conventional gear

Generally speaking, the efficiency of conventional magnetic ballasts is in the range of 84% – 86%, whereas most recently introduced electronic ballasts may reach efficiency of 90% – 92%. For some dedicated applications electronic ballast efficiencies may even reach 96%. The table below shows the relation of lamp and system power, to achieve comparable illumination level for incandescent and CDM HID lamps, powered by conventional magnetic and electronic ballasts.

Table 4: System power @120V, incandescent vs. CDM (lamp watts)

Type	P1	P2	P3
Halogen Incandescent	75W (75W)	100W (100W)	150W (150W)
CDM on conventional	NA	56W (39W)	72W (50W)
CDM on electronic	26W (20W)	45W (39W)	56W (50W)

Furthermore, electronic ballasts allow the installation of substantially more fixtures on one circuit, thereby lowering installation costs for new constructions.

Table 5: Lamp watts/number of fixture per 20A circuit @120V

Type	P1	P2	P3
Halogen Incandescent	75W/25	100W/19	150W/12
CDM on conventional	NA	39W/22	50W/20
CDM on	20W/69	39W/40	50W/32

electronic			

Ceramic discharge MH lamps – current status

Philips introduced the first Ceramic Discharge Metal Halide lamp in 1995. The following picture in Figure 5 shows a typical ceramic and quartz metal halide arc tube. The ceramic and quartz refers to the wall material of the arc tube, the light emitting part inside the glass bulb of an HID lamp.
CDM lamps have been produced for 10 yrs with excellent color properties. The ceramic arc tube material is much more resistant to the lamp chemicals at much higher temperatures leading to lamps giving white light with excellent color rendition and efficacies. The ability to operate ceramic arc tubes at higher temperatures than quartz ones is a fundamental advantage of the ceramic system, and one that cannot be compensated for, by quartz designs. Together with the good control of the dimensions of the ceramic arc tube material compared to quartz, this leads to much less color variation initially and over the life of the lamps so that these lamps can be applied in many new, more color critical, applications. Dimensional control of the ceramic also leads to lamp powers that are not possible with quartz: 35W, 20W and even smaller wattages are possible, further extending the application possibilities of these efficient light sources since the arc tubes can be more compact.

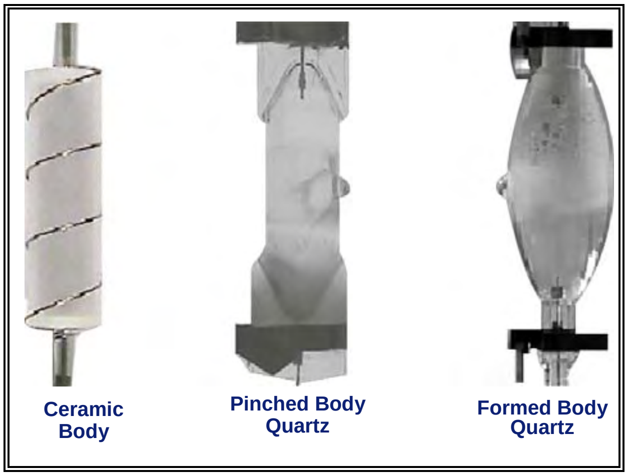

Figure 5. Shapes of discharge tubes; CDM vs. QMH

Due to excellent color and light technical properties, CDM lamps have gained very wide acceptance in the marketplace. Key characteristics of CDM lamps can be summarized in the table below.

Table 6: Characteristics of CDM lamps

Wattages	Efficacy	CRI	CCT
20W – 400W	90 – 95 lm/W	80 - 95	2700 – 4200K

Figure 6 shows comparison of CDM and quartz MH lamps spectra.

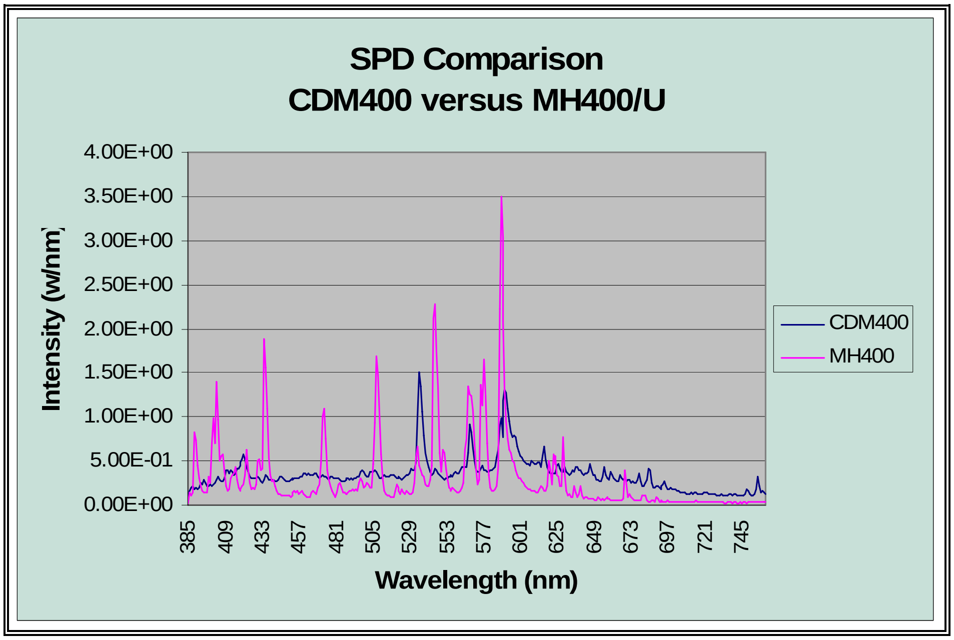

Figure 6. CDM vs. QMH lamp spectra

The benefits of Ceramic MH technology versus Quartz MH are listed in Table 7.

Table 7: Benefits of CDM vs. QMH (typical values, 20-400W)

Feature	QMH	Typical Ceramic Improvement	CDM
Color rendering R8	3000K, CRI of 65-75 4200K, CRI of 80 – 85	10 points	2700K, CRI of 81 – 85 4200K, CRI of 92 – 95
Lamp efficacy	80 – 90 lm/W	7 lm/W (~10%)	90 – 95 lm/W
Color stability	+/- 300 – 400K	+ 50% – 100%	+/- 200 – 250K

Graphical representation of color consistency of CDM lamps is shown in Figure 7.

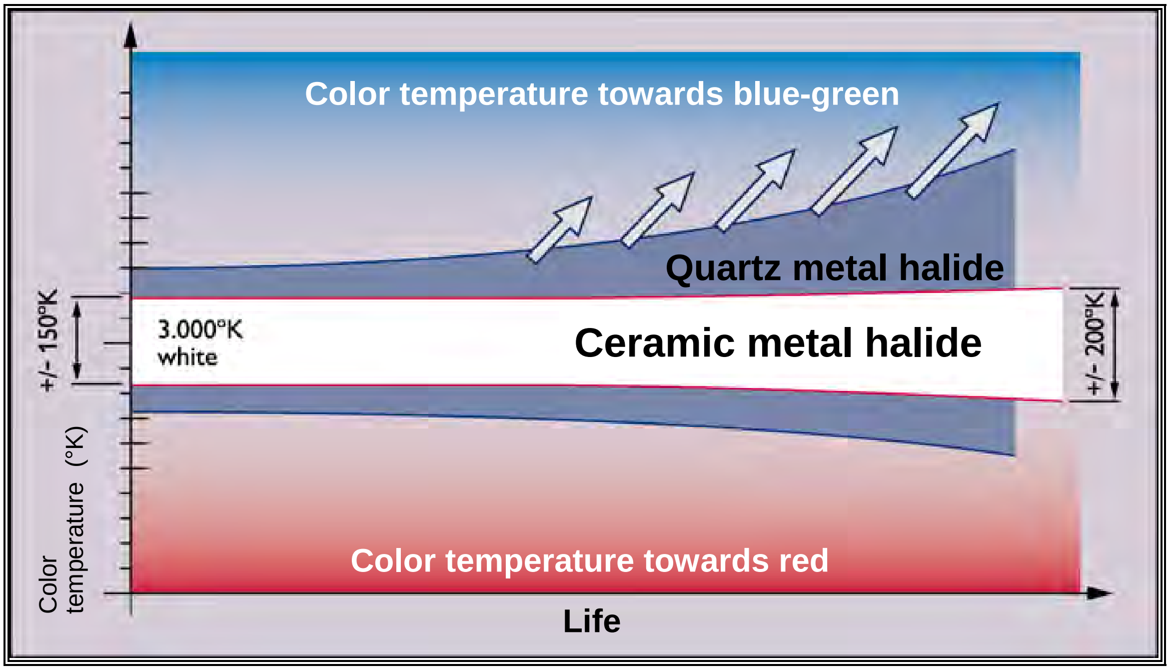

Figure 7. Color consistency of CDM vs. QMH lamps over life

Considering the data discussed above, regarding efficiency improvement of electronic ballasts as well as Ceramic MH lamps, it is becoming very clear that by combining both technologies, significant energy savings can be achieved and new, efficient systems may become possible that were not in the past.

Current Research and Potential Technical Enhancements

Within Philips Lighting it is our sincere conviction that lamps and ballasts should be developed concurrently as systems to achieve the highest energy benefits:

- Our experience shows that ballast efficiency improvements on their own can have negative effects on the lamp efficiency by the change of the spectrum. Efficacy improvements should focus on the total system because the total system energy use counts.
- Dimmability is only good if the color of the lamps is kept under control
- System development can lead to systems with integrated ballasts for further ease of use and spread of the application potential of HID systems

New electronic ballast developments

Current research for electronic ballasts is dedicated to further size reduction, increased efficiency and extended ballast functionality. Most recent years have brought significant size reduction of electronic ballasts. Continuous development in the area of semiconductors and passive components as well as new ballast topologies enable significant size reduction of electronic HID gear.

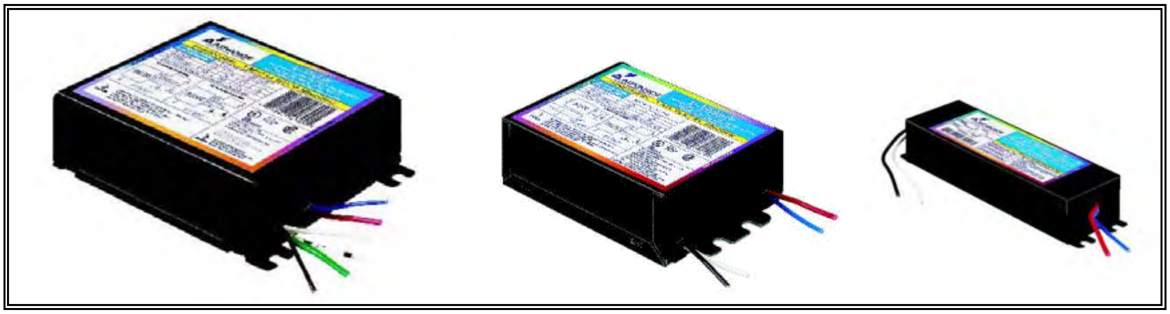

Figure 8. Progression of E-HID ballast miniaturization for MH lamps.

Typical progression of E-HID ballast volume in most recent years is depicted in the table below.

Table 8: Volume progression of E-HID ballasts (cm^3) for MH lamps

Wattage	1998 – 2002	2003 – 2004	2005 – 2006
39W	420 cm^3	170 cm^3	105 cm^3
70W	420 cm^3	330 cm^3	205 cm^3
100W	420 cm^3	420 cm^3	310 cm^3
150W	1100 cm^3	650 cm^3	420 cm^3

This significant size reduction contributed to novel, more efficient topologies and more robust components that may withstand higher ambient operating temperatures. Together with compact lamps and lower wattages, more compact ballasts allowed the design of more efficient, smaller and more aesthetically pleasing luminaries as shown in Figure 9.

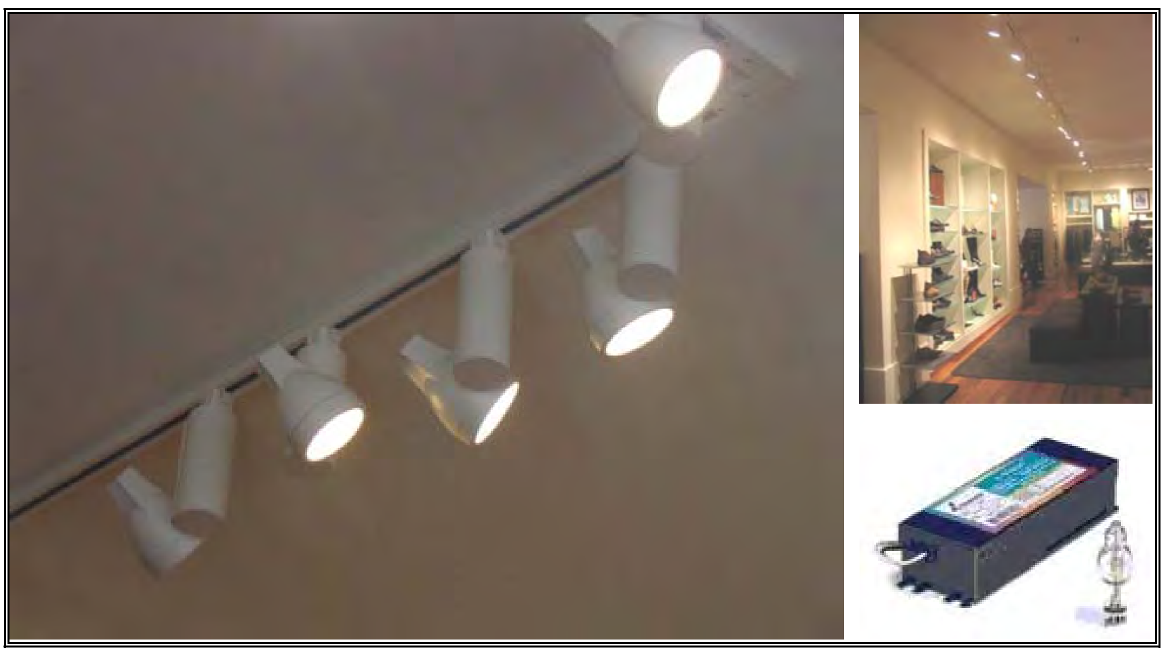

Figure 9. E-HID 20W NI system introduced by Philips in 2004.

New E-HID ballast development is targeted to other areas as well. A lot of emphasis is put on lower ballast cost and also lower ballast cost per socket. We plan to introduce an E-HID ballast to operate 2 HID lamps independently on one driver.

Also, implementation of microprocessor technology as well as new sophisticated control and communication protocols allow easier and more flexible dimmability of HID lighting systems. Currently, 0 – 10V control protocols are readily available in 250W – 400W systems. Dimmable ballasts for lower wattages are in an advanced development stage and will be introduced in the next couple of years. It is worthwhile to note, that introduction of new generation of CDM lamps, one that is suitable for dimming application, is an important factor in making possible the extension of dimming HID systems to lower wattages. This innovative HID lamp will be discussed in more detail in the following section of this paper.

The new area of E-HID ballast development is related to advanced control algorithms, which are based on wire-less communication. This novel technology should further expand capability and penetration as well as ultimate flexibility of dimming HID lighting systems.

Future CDM lamp development

Further improvements of CDM lamps will be achieved by implementation of new ceramic arc tube shapes (see Figure 10 for examples), new fillings and integration with electronics. Leading to:

- Higher efficacies going up to 120 lm/W
- Lumen maintenance improvements to >90%
- Dimming with constant color
- Much shorter restart time after lamp turn off
- Compact lamps, well aligned in the luminaire for less glare

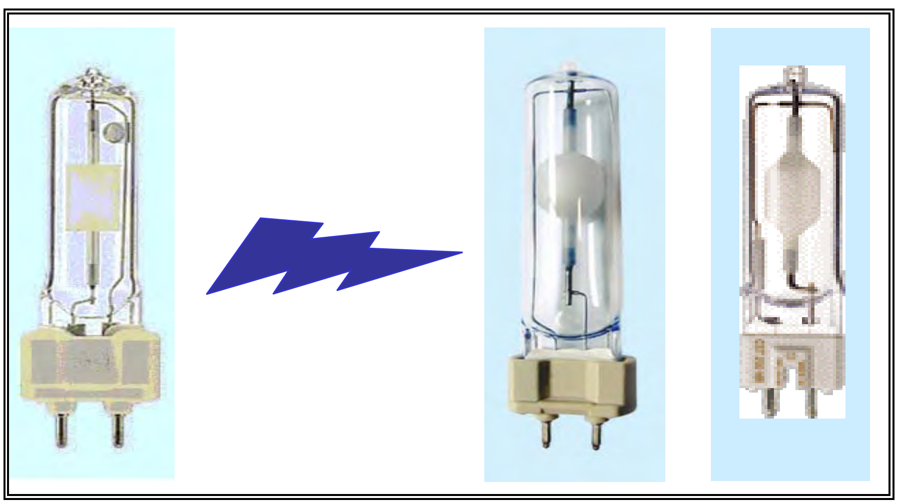

Figure 10. Evolution of cylindrical to other tube shapes in CDM lamps.

Improved lamp lumen maintenance over life will proportionally increase mean lamp efficacy. This improvement will directly translate to further enhancement of energy savings potential. A product now under development will introduce a new generation of CDM lamps. This lamp features:

- reliable dimmability down to 50%
- increased lumen output and hence mean efficacy

- improved lumen maintenance
- improved color rendering

Graphical representation of key lamp characteristics is shown in Figure. 11

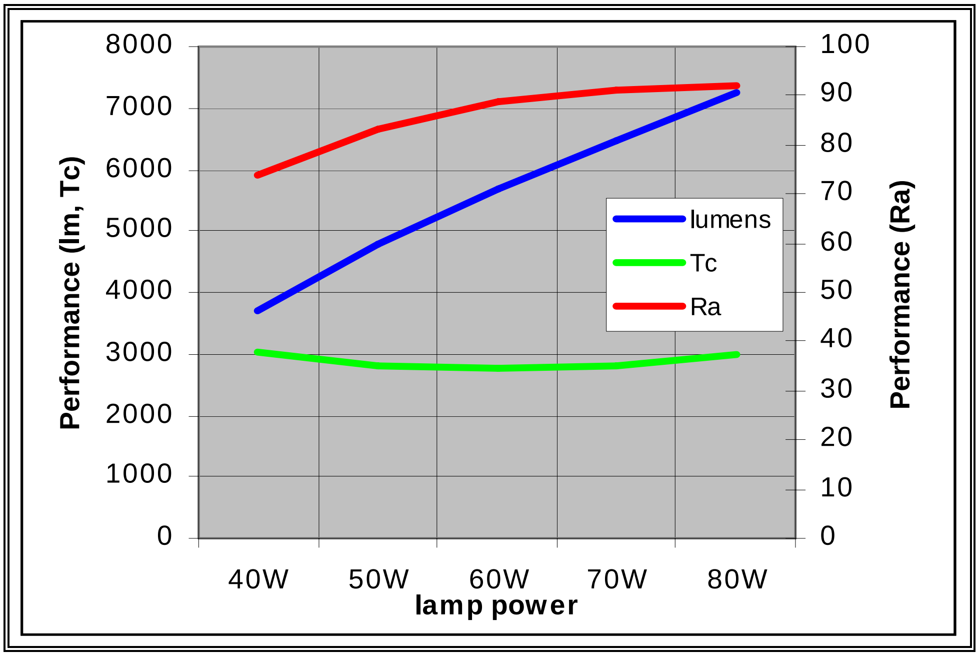

Figure 11. Key characteristics of new generation dimmable CDM lamp.

A remarkable characteristic of this lamp, that during dimming down to 50%, it maintains CCT within 200K and color rendering stays above 75. This product is not ready for market introduction, but is much more than a general concept. We believe it represents the future of white lighting by ceramic, electronically driven and controlled metal halide systems.

Future/New Lamp – Ballast system development

During recent years some major developments in electronic ballast as well as CDM lamps have occurred. However, we strongly believe that the best chances to achieve ultimate performance of E-HID systems will be established by the combination of new HID lamp concepts with the appropriate electronic gear. Two examples to highlight this are the following.

The first example is related to a new lighting system for outdoor applications that is in the final stages of development. The lamp system is comprised of two types. One type is based on metal halide salts and generates white light. The second type is based on HPS technology and generates yellow light. Both types of lamps share the same dimensions and the same optical center in the reflector, which is very unique feature of this system. Lamp power is in the range of 60W – 140W. The key features of this system are following;

- compact lamp, base and ballast system: 50% smaller than conventional systems (see Figure 12)
- high efficiency lamp – ballast system with energy savings of 10-30%
- operation on electronic ballast only
- excellent life and lumen maintenance

The main benefits of this system are;

- maximum fixture design freedom
- precise optical positioning
- lowest cost of ownership
- greater application flexibility
- higher reliability

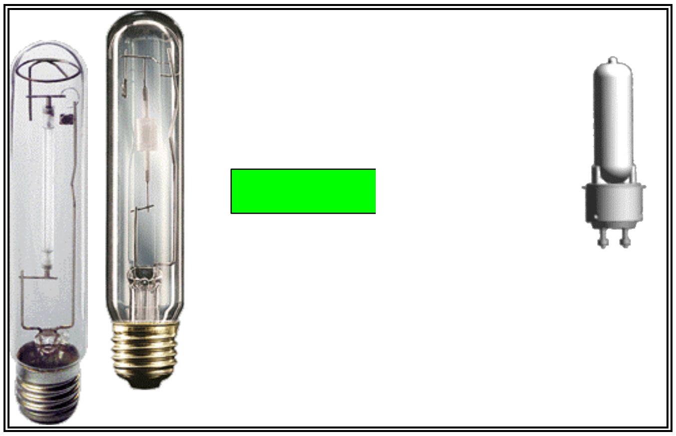

Figure 12. Size evolution of HPS and CDM lamps into one size.

This novel system will feature excellent maintenance and reliability over lifetime. One of the strongest advantages of this system is optimal matching of both types of lamps (MH and HPS) with the same fixture. The development focus was to achieve the highest system efficiency and this leads to two different ballasts: one for the "white light" and one for the "more efficacious, yellow light". Matching dimensions for the "white" and "yellow" light means that both lamps will fit the same fixture. Having a new base/holder for good alignment in the fixture this leads to less glare and roughly an extra 5% efficiency gain (examples shown in Figure 13)

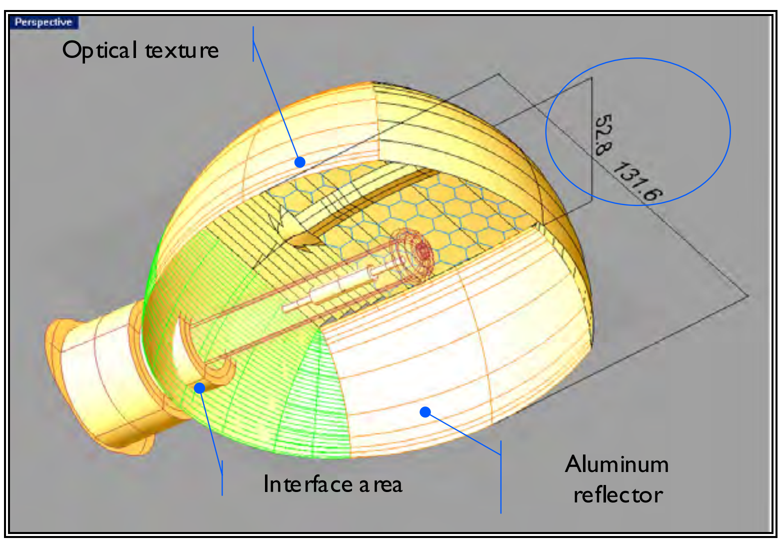

Figure 13. Lamp integration with the luminaire.

The second example is an integrated system introduced in the marketplace in the past few months. The combination of advancements in lamp and ballast miniaturization, has allowed development of

25W integrated Ceramic Metal Halide lamp in a PAR 38 reflector. It was already shown in Table 4, that this new integrated system, in terms of lumen package, would replace 75W incandescent halogen lamp, but offer 60% energy savings and 3 times longer life. As in the previous example, the key component of this system is integrated optics. A mechanical sketch of this system is attached below.

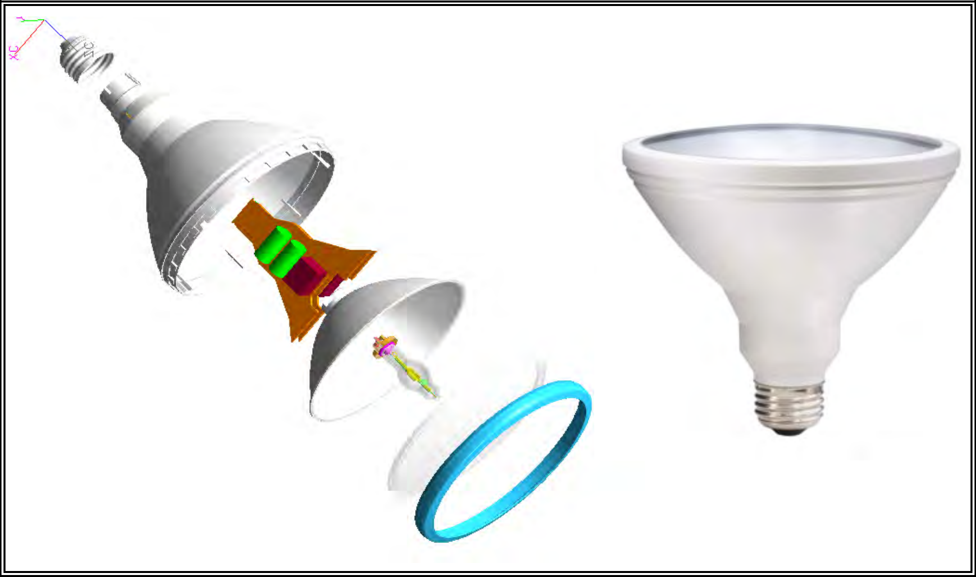

Figure 14. 25W E-HID integrated system.

R&D and Technical Challenges

As shown, HID and specifically Ceramic HID systems are very energy efficient white light systems but with still limited usage. In order to expand its application area, the following technical challenges for HID systems needs to be resolved.

- Achieving the highest efficacies (120 lm/W or higher) ***with*** an excellent maintenance (>90%) ***and with*** long life (20000hrs) ***also for*** higher powers (250 - 1000W).
- Dimmability of these systems with maintained color.
- Instant light during lamp start-up as well as warm restart. In this case Philips has successfully demonstrated practical solutions (automotive HID lamp and UHP projectors), however complexity and system price did not allow introduction of this system in general lighting applications. Not only cost is the main roadblock to expand this technology to general lighting. Sockets for existing indoor installations are only rated for not more than 5 kV, limiting available voltage for warm restrike of HID lamps.
- Achieving reliable life of electronic systems in outdoor applications, facing extreme temperatures conditions and for instance lightning strikes.
- HID systems and concepts discussed in this manuscript are a closed system. By closed system we mean that ballast and lamp are designed as a pair. A main challenge is to develop standards that would enable such closed systems to find applications with other lamps or ballasts, that were not part of the original optimized design. This is a big and very difficult challenge.
- Excellent color properties have been achieved for 3000K lamps, which established the benchmark. The challenge is to extend these excellent color properties to other color temperatures.

Thoroughly analyzing above challenges, the following top three priorities can be established:

1. ***Instant light and warm restrike of HID lamps***
2. ***Conversion of closed systems to commonly available open systems***
3. ***Initial cost of the system.***

Conclusions and Recommendations

With the support of several examples, this paper shows that the most significant energy savings in HID lighting systems can be achieved combining Ceramic MH lamps with Electronic ballasts. Even further improvements, in terms of system efficiency and lamp maintenance are possible, but this ultimate goal may be only achieved by combination of CDM lamps with dedicated electronic ballast and very precisely designed compact optical reflector, in other words: **focus on system developments.**

Philips Lighting has been actively working on the topics discussed in this article. We are strongly convinced that this work on E-HID lighting systems points the way to the future of white light, HID systems with the energy saving, color and dimming features that the market will demand. It is also believed that the success in the project, dealing with high efficiency Ceramic HID Systems -

both lamp and electronic ballast, will accelerate **the energy savings potential** of this new high – payoff technology.
The energy saving potential can be reinforced by:

- Further system efficiency improvements.
- Further maintenance improvements: lower lamp powers needed at the start.
- White light in more outdoor applications may lead to an improved feeling of safety and perhaps to the requirement of lower lighting levels.
- Lower wattages and integrated lamps will increase the application scope of these efficient light sources.
- Dimmability down to 50% of power leads to huge energy savings in low use hours.
- Control leads to better maintenance scheduling.

It is therefore recommended to support the development of these systems.

METAL-HALIDE LASER SPECTROSCOPY AND MICROCAVITY PLASMA DEVICES: TOOLS FOR IMPROVING HID LAMP PERFORMANCE

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Abstract

Despite the maturity of HID lamp technology, the optical properties of several metal-halide precursors with which lamps are dosed routinely, such as DyI_3, are poorly understood. Photoassociation, the absorption of a photon by a colliding pair of atoms, is also undoubtedly significant in the high pressure, broadband radiation environment provided by an HID lamp. This presentation will briefly discuss these processes and other important gaps in our understanding of *molecular* absorption and emission in HID lamps. The potential impact of a new class of plasma devices, known as microcavity plasma devices, on HID lamp performance, ignition and restrike, will also be described.

Background

In the four decades since the introduction of the metal-halide lamp, considerable progress in its efficiency (luminous efficacy) and lifetime, as well as the fundamental understanding of the plasma have been realized. Despite these advances, significant gaps continue to exist with respect to several processes that have a fundamental impact on lamp performance. Among these are optical emission and absorption processes associated with the metal-halide molecules and radicals that are routinely present in HID lamps.

Although the electronic and optical characteristics of the parent metal-halide molecules (MX_n, where M and X denote metal (or rare earth) and halogen atoms, respectively, and n is an integer ≤ 4) are themselves of interest, it is the dissociation fragments that are able to play a strong role in radiation transport in the cooler regions of the plasma (i.e., near the wall). Lamps are normally dosed with a multicomponent mixture comprising Hg, Ar, and several metal-halide salts. At the core of the arc, dissociation of the precursor metal-halide is essentially complete but the situation at the perimeter of the plasma is quite different. Mono- and di-halide fragments of precursors such as DyI_3 are present in significant quantities, making the optical properties of such radicals of importance to the performance of the lamp.

Another characteristic of HID lamp plasmas that appears to profoundly influence its properties and ultimate performance is the presence of large number densities of specific atoms. Even in those regions of the lamp plasma in which the molecular radical concentrations are high, the number densities of several atoms, such as Hg and I, are large ($\gtrsim 10^{18}$-10^{19} cm^{-3}). In the presence of an intense radiation field, photoassociation — the absorption of a photon by a colliding pair of atoms — is a loss process for which we must account. The next section briefly discusses a few such absorptive processes and their implications for HID lamps.

Laser Spectroscopy of Free → Bound Absorption (Photoassociation) and Metal-Halide Radicals

• *Photoassociation in HID Lamps*

Photoassociation is the process in which two atoms (A and B) approaching one another along an interatomic potential are able, when in the proper range of internuclear separation (R), to absorb a photon, thereby exciting the "collision pair" to an electronic state of the molecule AB (Refs. 1, 2). Figure 1 qualitatively illustrates the photoassociation process for Kr-F atomic pairs in which both atoms

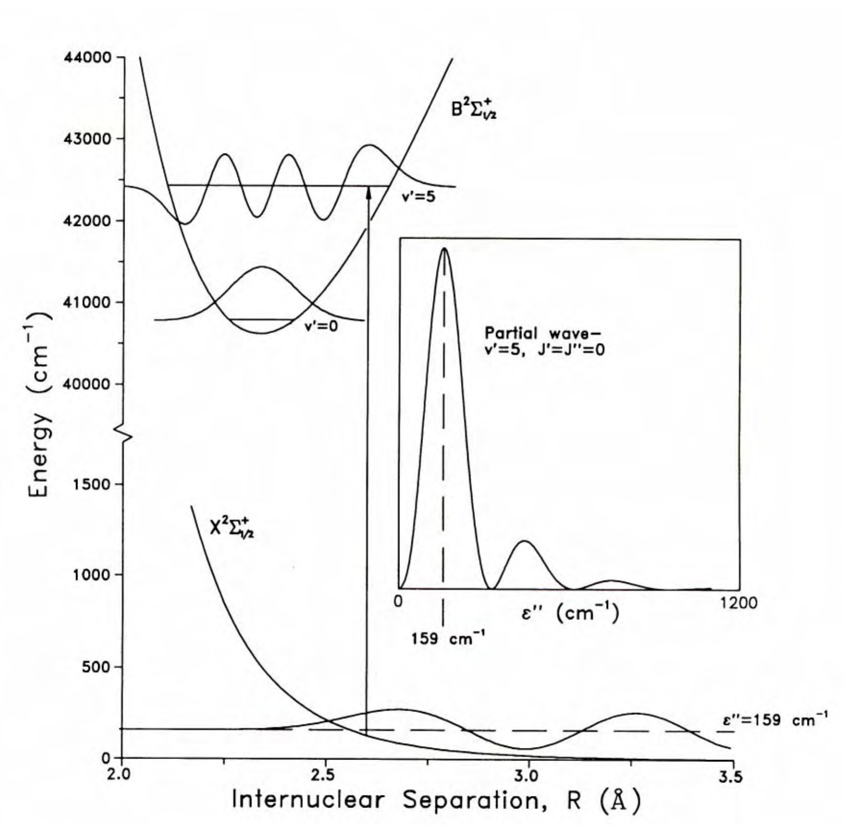


Figure 1. Generalized energy level diagram for the KrF molecule, illustrating the photoassociation of Kr-F thermal collision pairs.

are thermal and initially in the ground state.[1] There are several reasons as to why this process has profound implications for the efficiency of HID lamps. Photoassociation draws upon pairs of thermalized atoms and the photoabsorption rate varies as the product of [A] and [B] where the square brackets represent the number density of atom A or B. It is well known in the lamp community that, regardless of the radial position in the plasma, atomic species predominate and those typically having the highest number densities are Hg, I, and Ar. Furthermore, photoassociation occurs over a very broad spectral region, making it difficult to recognize its existence and distinguish photoassociation losses from other processes. As an example, Figure 2 shows the photoassociation spectrum of Xe-I atomic pairs

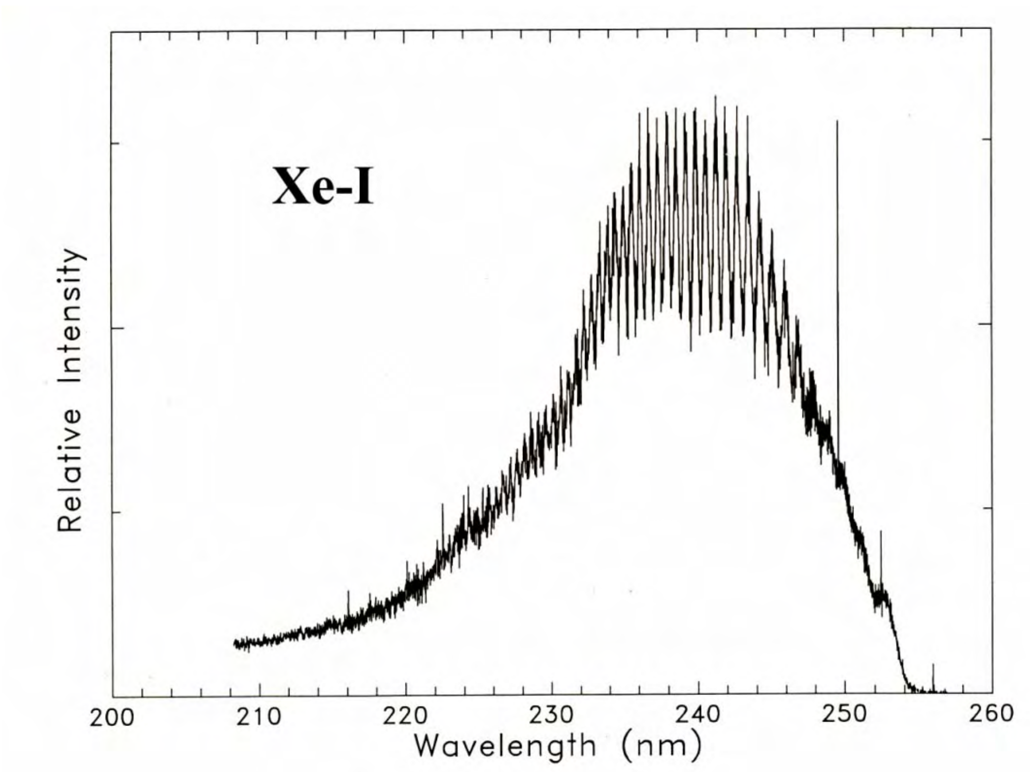
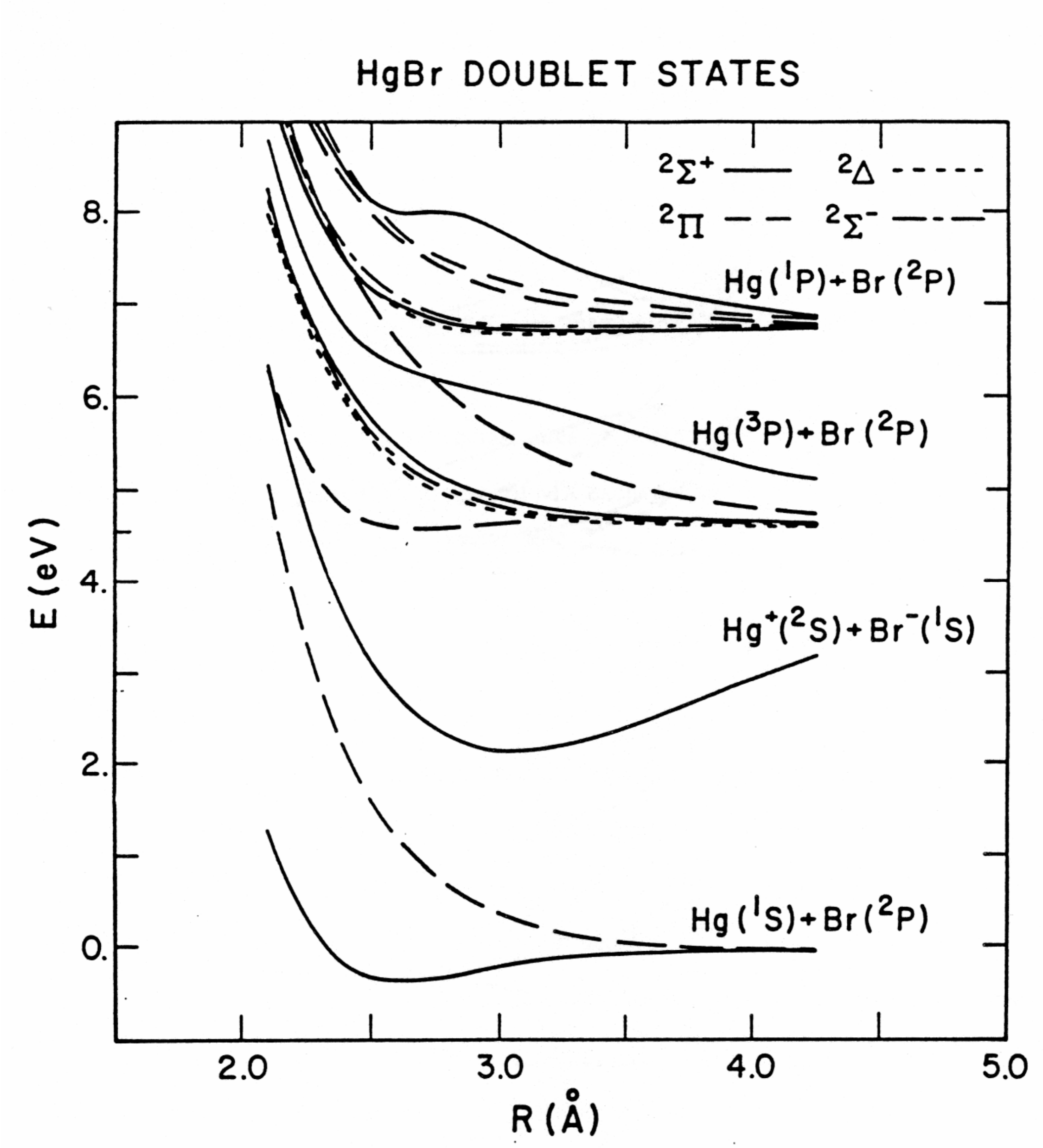


Figure 2. Photoassociation spectrum of Xe -I atomic pairs, thermalized at 300 K. These data were obtained at the University of Illinois by laser excitation spectroscopy.

that was recorded by a technique developed at the University of Illinois.[2] Notice that although peak absorption occurs in the vicinity of 240 nm, the spectrum extends from ~210 nm to □ 250 nm. Perhaps more importantly, as the gas temperature rises the photoassociation spectrum shifts progressively towards the red.

In summary, photoassociation has not been incorporated into HID lamp models to date but appears to play a significant (and, quite possibly, major) role in radiation transport. The spectral breadth of the radiation emitted by the plasma, combined with the large number densities of several atoms, indicate that photoassociation is likely responsible for substantial absorptive losses in HID lamps. Only recently has it become possible to measure photoassociative spectra and it is suggested that the Hg-I atomic pair be investigated. Figure 3 is a partial energy level diagram for HgBr which is illustrative of the structure of HgI. Pairs of Hg and I atoms moving along the $^2\Sigma$ or $^2\Pi$ ground state surfaces are available to absorb photons with energies in the 1.5 ~ 3 eV range, precisely the region with which we are most concerned for illumination. Furthermore, as the broadband emission moves radially outward from the core, it encounters cooler atomic pairs that absorb at longer wavelengths than do the pairs nearer the longitudinal axis of the arc. It is our conviction that experiments to measure the photoassociation spectrum for Hg-I pairs (and others such as Ar-I and Hg-Ar) will suggest pathways to further



improving the luminous efficacy of HID lamps.

Figure 3. Partial energy level diagram for HgBr (courtesy of P. J. Hay, Los Alamos National Laboratory). Photoassociation impacting HID lamp performance occurs between the $^2\Sigma$ and $^2\Pi$ ground states and the lowest $^2\Sigma$ excited state. The structure of HgI is quite similar to that shown here.

• *Absorption by Metal-Halide Radicals*

Despite the predominance of atomic species in operating HID lamps, metal-halide radicals are prevalent in the cooler regions of the plasma. Lamps are normally dosed with a variety of metal-halides, such as the iodides of Sc, Dy, and other rare earths. Unfortunately, very little is known of the structure of the precursors (such as DyI_3) and less regarding the dissociation fragments such as DyI and DyI_2. Such molecular species have long been known to exist but the optical emission and absorption spectra for these diatomic and triatomic radicals have not been available previously because of several experimental challenges.

A photoexcitation technique developed in our laboratory enables the measurement of both the emission and absorption spectra of metal halide radicals (MX, MX_2, …). As an example, Figure 4 shows emission spectra recorded in the 200-800 nm region when PbI_2 vapor is photoexcited at specific wavelengths in the ultraviolet (UV) by excimer lasers.[3] The specificity afforded by laser excitation and the variety of excitation wavelengths available make it possible to isolate the species of interest. In parts (c) and (d) of Figure 4, for example, emission spectra of electronically-excited PbI_2 in the 580-710 nm spectral region are readily observed whereas, to our knowledge, these emissions had not been reported previously.[3] Similarly, absorption spectra can be obtained with either a laser or lamp probe.

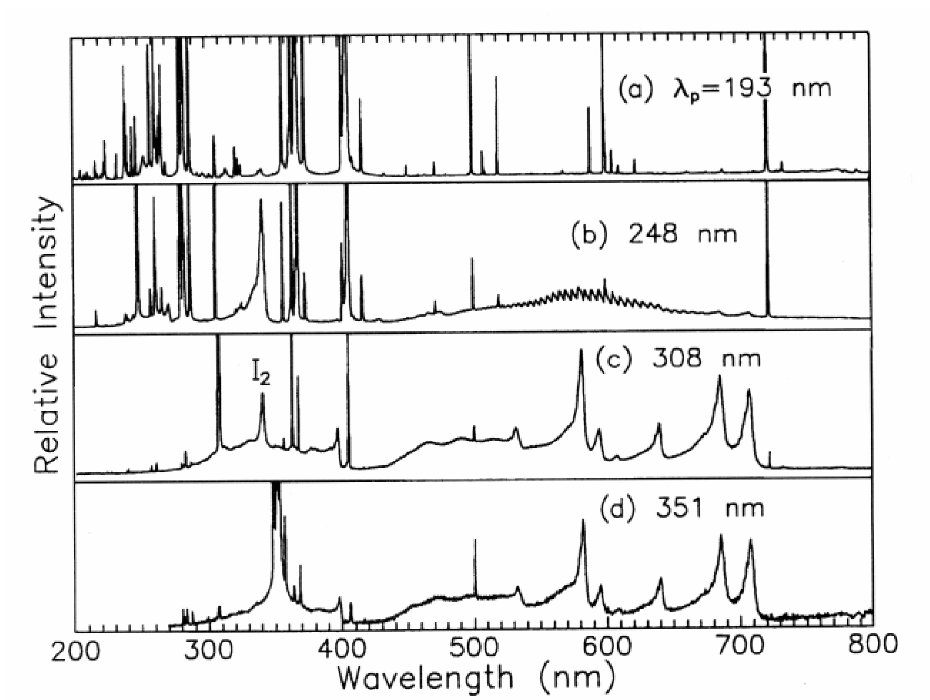


Figure 4. Emission spectra in the 200-800 nm region for PbI_2 vapor photoexcited at the wavelengths indicated. Notice in spectra (c) and (d) the existence of strong features in the 580-710 nm region that are attributed to electronic excited states of PbI_2. Similar experiments could be conducted for the rare earth iodides (such as DyI_3).

It is suggested that experiments similar to those of Figure 4, conducted for metal-halides often incorporated into HID lamps, such as the iodides of Sc and Dy, would be valuable in determining the role of radicals such as DyI_2 in attenuating and shaping(at the perimeter of the lamp) the emission spectrum produced in the arc core.

Microcavity Plasma Devices: Plasma Injectors for HID Lamp Ignition and Restrike

Over the past several years, a new class of plasma devices has been demonstrated and developed. Known broadly as microcavity plasmas, these devices are based on the confinement of a nonequilibrium plasma to a microcavity having a characteristic dimension < 500 µm. The unique characteristics of these confined plasmas make them of particular interest for the lamps that are the subject of this Workshop. Specifically, these devices are capable of operating at gas pressures up to, and well beyond, 1 atm. Also, specific power loadings of the microplasma of tens of $kW\text{-}cm^{-3}$ up to ~1 $MW\text{-}cm^{-3}$ can be obtained routinely on a continuous basis.

These properties of microcavity plasma devices are ideally-suited for assisting HID lamps, particularly with regard to ignition and restrike.[4] Figure 5 is a cross-sectional diagram of a ceramic assembly in which an array of microplasma devices is mounted immediately behind an HID lamp electrode. Each microplasma device comprises a stainless steel, cylindrical cathode having an i.d. of 400 µm and a screen anode. The anode-cathode gap is nominally 250 µm and the dashed line of Figure 5 indicates that the axes of the three microplasma devices are oriented so as to inject plasma into the
region above the electrode. Extensive measurements of the impact of plasma injection on the ignition of a high pressure discharge in Ar have been made and a few of the results are illustrated in Figure 6. The important point to be made is that the ignition voltage is reduced by *at least* a factor of two by injecting plasma into the region between the two HID electrodes. No aspect of the geometry of Figure 5 has been optimized and larger improvements are undoubtedly feasible. Also, these microplasma devices work reliably at gas pressures up to the highest values available with our current gas handling system (>1 bar), suggesting that this approach will also be valuable in improving the restrike characteristics of HID lamps.

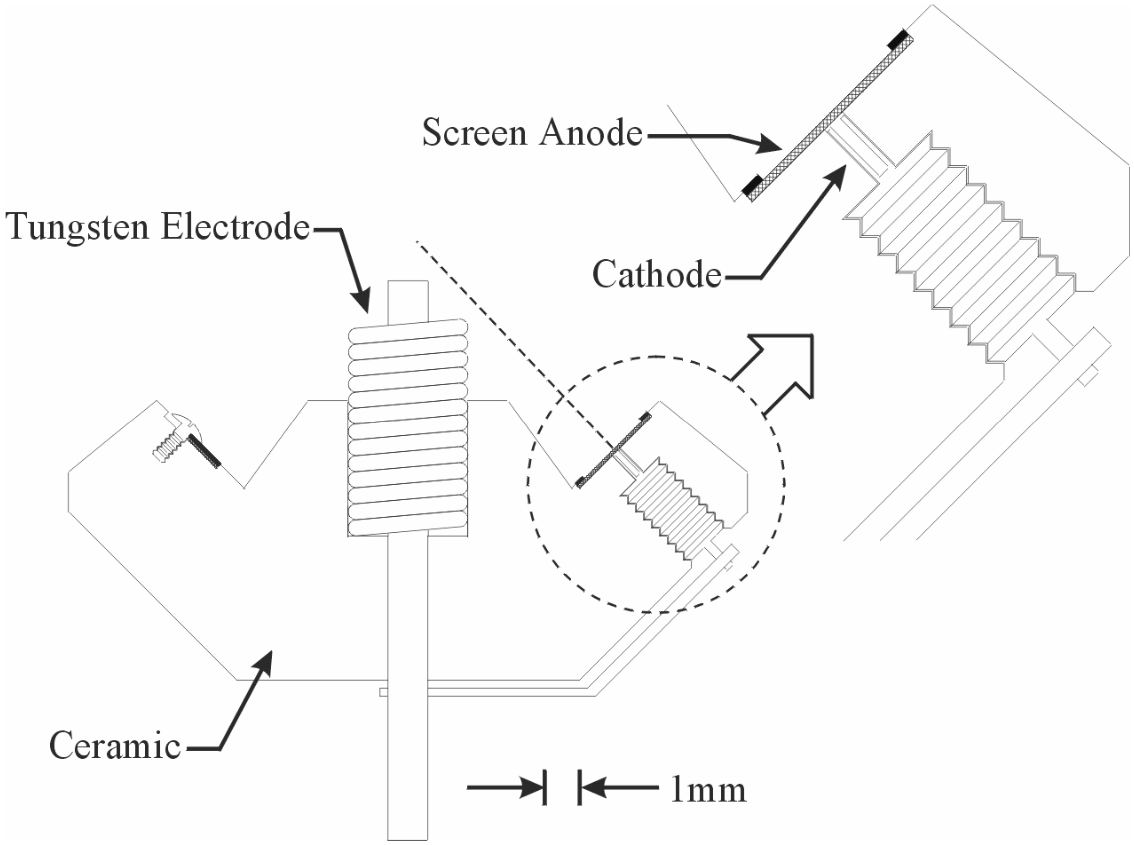


Figure 5. Schematic diagram (in cross-section) of an assembly in which three microcavity plasma devices are mounted immediately behind an HID lamp electrode. The dashed line indicates that the axis of the microplasma device is oriented so as to inject plasma into the region immediately above the electrode. The inset is a magnified view of a microcavity plasma device.

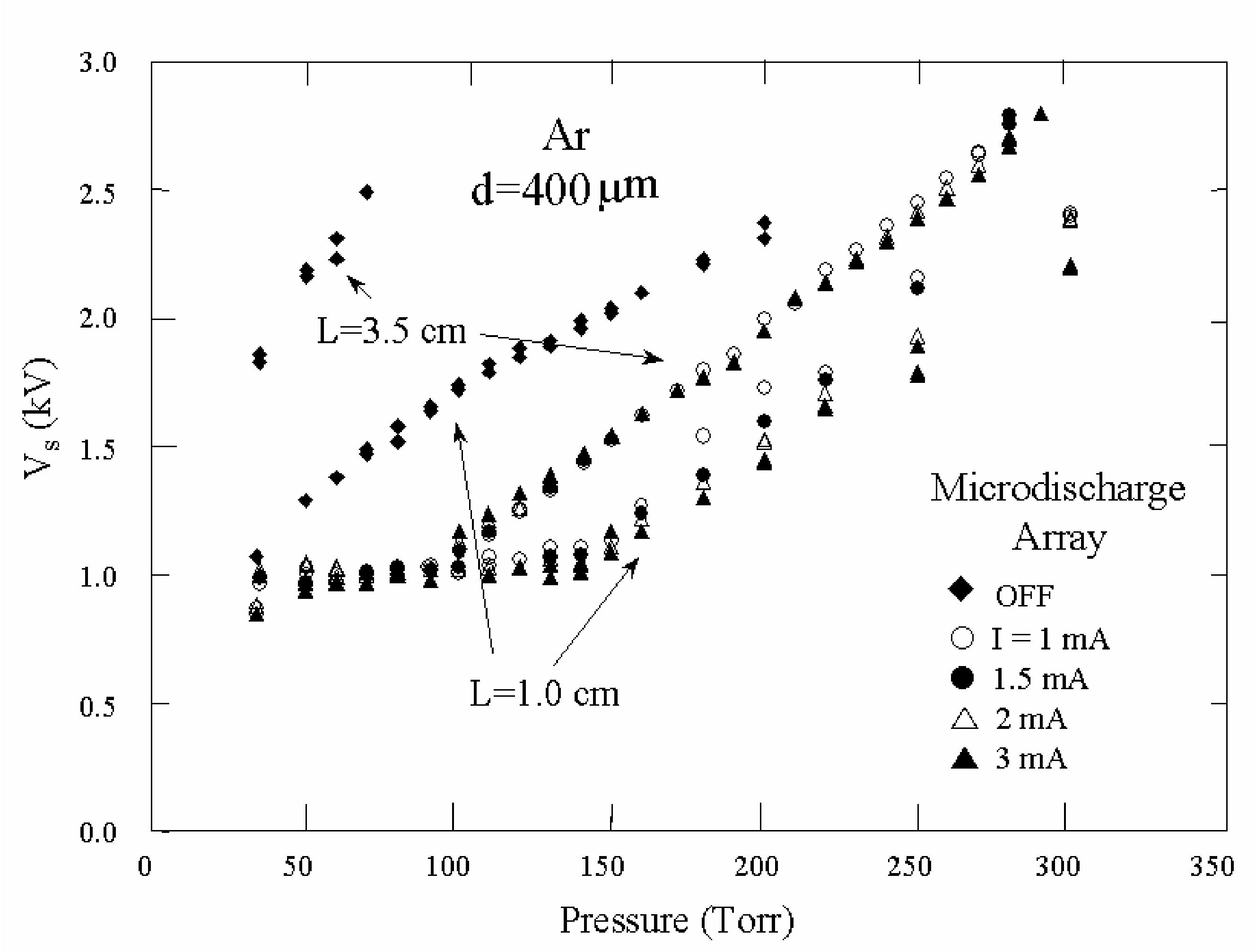


Figure 6. Data illustrating the reduction in the ignition voltage of a high pressure Ar discharge between two HID lamp electrodes by injecting plasma from an array of microplasma devices. Results are shown for a spacing (*d*) of 3.5 cm and 1.0 cm between the electrodes.

Conclusions

Advances in the engineering of HID lamps over the past two decades, in particular, have yielded an efficient illumination source but further improvements can be realized through a more detailed understanding of the photophysics in this complex environment. The combination of atomic densities exceed 10^{19} cm^{-3}, and an intense broadband radiation field are ideal conditions for photoassociation , which is expected to be a significant loss process in the lamp. Experiments to observe the optical properties of MX and MX_2 radicals present in the cooler regions of the lamp have also been described. Microcavity plasma devices are a new class of plasma sources that now provide the ability to inject plasma into the inter-electrode region of an HID lamp, thereby improving overall lamp performance and ignition and restrike characteristics.

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EFFICACY LIMITS OF WHITE LIGHT METAL HALIDE LAMPS

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Abstract

High-intensity metal halide discharge lamp performance, specifically the generated luminous flux and light color content, depends critically on the burner design. Factors influencing the design and consequent lamp efficacy include: lamp size, geometry, arc tube composition, fill chemistry, electrode design and excitation modes. The environment in which the burner is placed influences operation and longevity as well. Examples of this are burners used in gas filled outer jackets or reflector applications. Modern ceramic metal halide lamps operate in the regime of 100-110 lumens per system watt, with a general color-rendering index of about 85-90. Efficacy improvements are possible, but are bounded by a theoretical limit of approximately 450 lumens per radiated watt for a "white light source" suitable for general illumination. Thermodynamics further limits the approach to this global ceiling to a value of about 230 lumens per system watt. This is still a factor of two higher efficacy than is commercially realizable today. Possible pathways to achieving an efficacy increase are through novel chemical fills, radiation recapture, tailored excitation methods and careful thermal management. For example, modulation of the power at acoustic resonance frequencies can straighten the arc, modify the arc and wall temperature and condensate distributions, and suppress segregation. Waveforms can be asymmetric or pulsed, or even applied electrodelessly. The resulting expansion in choices for arc tube shapes, chemistries, and electrical excitation allows for potential gains in lighting performance. Potential benefits of system solutions include: higher efficacy, improved lumen maintenance, longer lamp life, improved optical coupling, safer or more environmentally friendly products and the ability to adjust light output color.

Background

The purpose of metal halide technology is to produce visible light efficiently, with good color content, in a compact, high luminance device. Metal halide lamps are often referred to as High Intensity Discharge or HID lamps. The high luminance is required for capturing and directing the light to a target area. This makes metal halide lamps suitable for luminaires which collect and direct the visible light for illumination at a distance. Depending on the optic and application the distance can be close (a few meters) or far (hundred meters).

Metal halide lamps are typically used in industrial and commercial applications. The illumination of parking lots, building facades, factory floors, exhibition centers, sports arenas (hundred meters), gymnasiums, airport halls and high ceilings of big box retailers (tens of meters) are typical installations. Retail installations for merchandise illumination (few meters) are growing as metal halide lamps move towards lower wattage and smaller lumen outputs. Metal halide lamps are not commonly used in residential applications despite their high efficacy.

As energy costs for commercial, retail and residential users increase, the system efficacy becomes very important. System efficacy is defined as the lumens generated by a lamp system divided by the electrical watts as measured at the wall. Frequently, the effect of the luminaire can be significant in delivering the flux to the target area. Percent of lamp lumens captured and directed toward target areas for HID luminaires can be as low as 56%.[i] Clearly in a system approach, one should consider the effectiveness of the optic as well. The focus of this paper, however, is to examine what are reasonable limits for the lamp efficacy itself and to suggest fruitful pathways towards improvements. By way of benchmarking, Waymouth suggested that HID efficacies could be as high as 300 lm/electrical watt.[ii]

Existing Technology

The efficacy of an installed lamp system in delivering lumens to a target area may be expressed as;

$$\eta_{system} = \eta_{ballast} \times \eta_{lamp} \times \eta_{optic}$$, dimensions of lumens/electrical watt, (Eqn. 1)

where η_j represents the efficiency of a particular energy or power conversion and the subscript j denotes the specific process. In the case of the lamp, η_{lamp} represents the lamp efficacy.

$$\eta_{lamp} = \frac{\int V(\lambda) \times S(\lambda) d\lambda}{W_{lamp}}$$, dimensions of lumens/lamp watt. (Eqn. 2)

Here, $V(\lambda)$ is the photopic response function and $S(\lambda)$ is the spherically averaged spectral power distribution (SPD) in radiated watts/nm. The integration occurs over all wavelengths, but because $V(\lambda)$ is zero outside of the range 380-780 nm, it acts as a sampling and weighting function over this interval (see Figure 1). Hence the limits of integration could be replaced by the visible limits of 380 to 780nm with no impact on generality.

The product of the lamp efficacy and the ballast efficiency is often quoted in the literature as the system efficacy in terms of lumens per electrical (wall-plug) watt. The effect of the optic is often ignored.

$$\eta_{system} = \eta_{ballast} \times \eta_{lamp}$$ (Eqn. 3)

Older magnetic ballasts operate with $\eta_{ballast}$ of about 0.85-0.88 (dimensionless, electrical watt out of the ballast/electrical watt into the ballast). Modern, electronic ballast efficiencies are about 0.90-0.92 already. Incremental improvements in the ballast efficiencies alone will not greatly affect the overall system efficacy.

Optic or luminaire efficiency has already been discussed and is outside the scope of this paper. However, it is clear from Equation (1) that optical efficiency factors approaching the present ballast efficiencies are desirable.

Finally there is the lamp efficacy, currently about 100 lm/W_{lamp} in metal halide (HID) lamps. Past research has been aimed at new chemical fills for the lamps that will improve the output in the visible region of the spectrum and boost the lumen output of the lamp. Examples are: the use of cerium halides to produce output at about 177 lm/W, but the color was greenish[iii]; the use of sulfur in place of metal salts to produce output at the level of 160 lm/W and again the output was greenish[iv]. Metal vapor lamps such as low-pressure sodium can produce 250 lm/W but the light output is monochromatic at 589 nm and unappealing as an indoor illumination source. Interior applications require high efficacy *and* white light to be appealing.

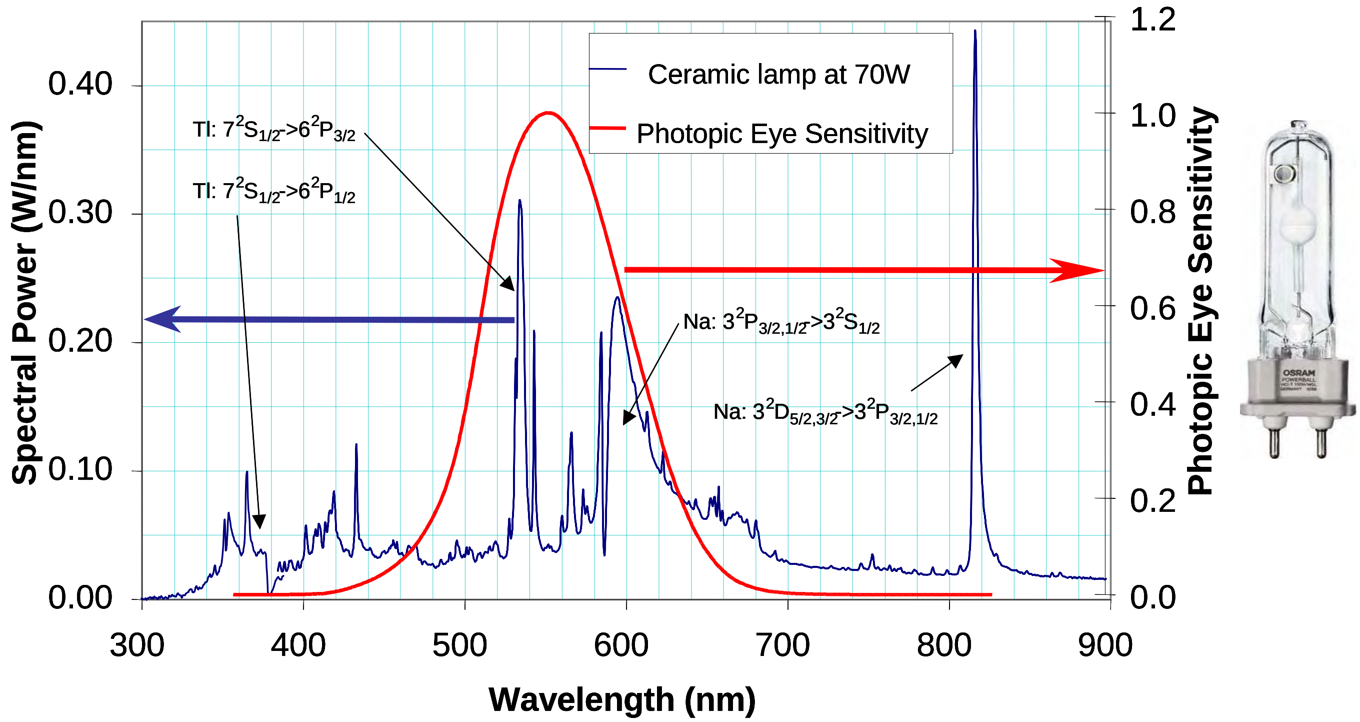

Figure 1. A modern ceramic metal halide lamp containing a mixture of rare and alkaline earth iodides along with sodium and thallium iodide and mercury. The spectral output is read on the left ordinate whereas the eye sensitivity curve is read on the right ordinate. The inserted photo (right) shows a typical lamp construction-pin spacing is about 12mm for scale.

Current Research

In this paper, we address the issue of limits on lamp efficacy when it is also constrained to a white light source. Also, we discuss what might be done to improve this efficacy factor, which seems to hold the most potential for gain in HID systems.

The expression for lamp efficacy, Eqn. 2, is re-written using a chain rule approach;

$$\eta_{lamp} = \frac{\int V(\lambda) \times S(\lambda) d\lambda}{W_{lamp}} = \frac{L(lm)}{W_{visible}} \times \frac{W_{visible}}{W_{lamp}} = \eta_{visible} \times \eta_{discharge} \qquad \text{(Eqn. 4)}$$

where L is the integral in the numerator, $W_{visible}$, is the spatially integrated radiated watts in the visible region, 380 to 780nm. The revised efficacy factor, $\eta_{visible}$, is used to interpret the work of McAdam[v] that has been replotted in Figure 2. These isoefficacy lines have been adjusted to the maximum of the photopic response curve of approximately 683 lumens/$W_{visible}$ at 555 nm.

Because a lamp can achieve a particular color point in an almost limitless number of ways (e.g. continuum source, three line source, selective radiator), the maximum visible efficacy, $\eta_{visible}$, may be achieved by any number of white light sources. All have the same limit regardless of how they achieve that color point. For example, in Figure 2, an incandescent source on the blackbody curve with a CCT of 3000K has the same visible efficacy limit as a discharge lamp at 3000K with the same chromaticity. [Incidentally, this holds true for LED sources as well.] The difference is in how each device converts electrical watts into visible radiated watts. This is the factor, $\eta_{discharge}$, in Eqn. 3.

For concreteness, the SAE, ECE specifications for white light are plotted in Figure 2[vi]. They also satisfy the general lighting need for white light sources that have (x,y) close to the blackbody locus. The isoefficacy line which crosses the blackbody locus but is almost parallel and is within the “white box” suggests a *maximum visible efficacy* of about 480-500 lumen/$W_{visible}$ is possible. Actual lamp efficacy is derated by the second factor in Eqn. 3.

The factor, $\eta_{discharge}$, discharge, is a measure of how effective a transducer the plasma is at converting the electrical power into visible light. Thermodynamics tells us that whenever power is converted from one form (electrical) into another (visible light) a price is paid in the form of heat. This is an expression of the inefficiency of the conversion process. Power conversion processes are never 100% efficient, so something less than 480 lm/ $W_{visible}$ will be achieved.

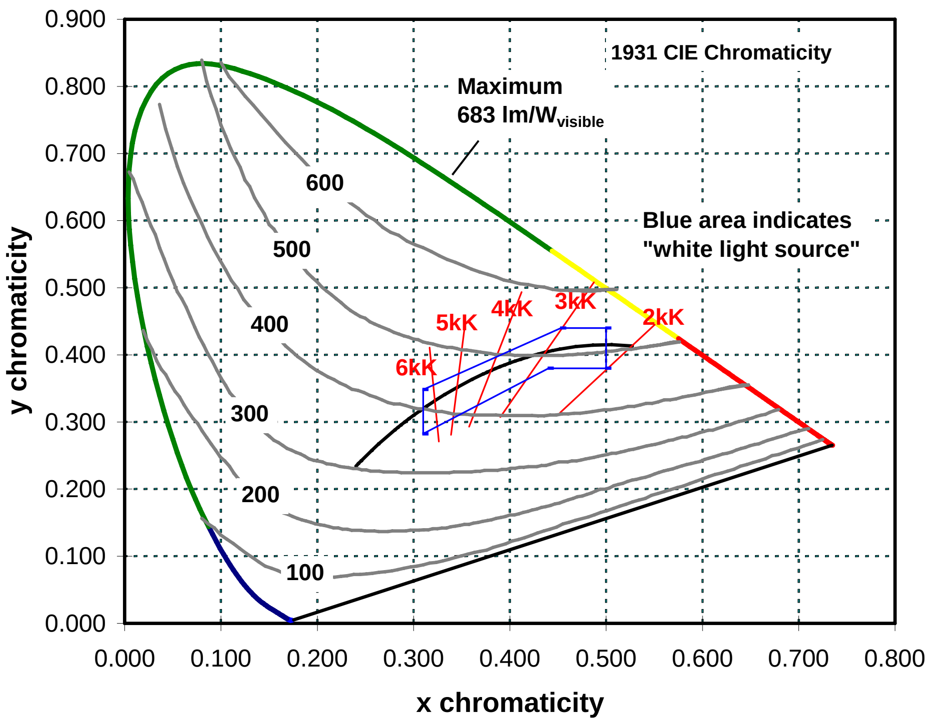

Figure 2. Contours of maximum efficacy for visible radiated power are plotted on the CIE 1931 chromaticity diagram. The Planck locus, lines of constant color temperature, and a box indicating "white light" are superimposed.

The discharge conversion efficiency, $\eta_{discharge}$, has been measured for many types of discharge lamps, although it is not expressed in such terms, but is presented as total visible watts radiated. Figure 3 below is a schematic diagram of the power flow in a modern metal halide lamp containing rare earth salt chemistry.[vii] Approximately 36% of the input electrical power exits as direct visible emission, hence for this type of lamp, $\eta_{discharge} = 0.36$. The greatest fraction of power is lost as heat. Thermodynamics insists we must give up some power as heat, but it does not demand 62%! Minimization of heat loss through careful thermal management and arc tube design is the first step to be taken to improve HID lamp efficacy.

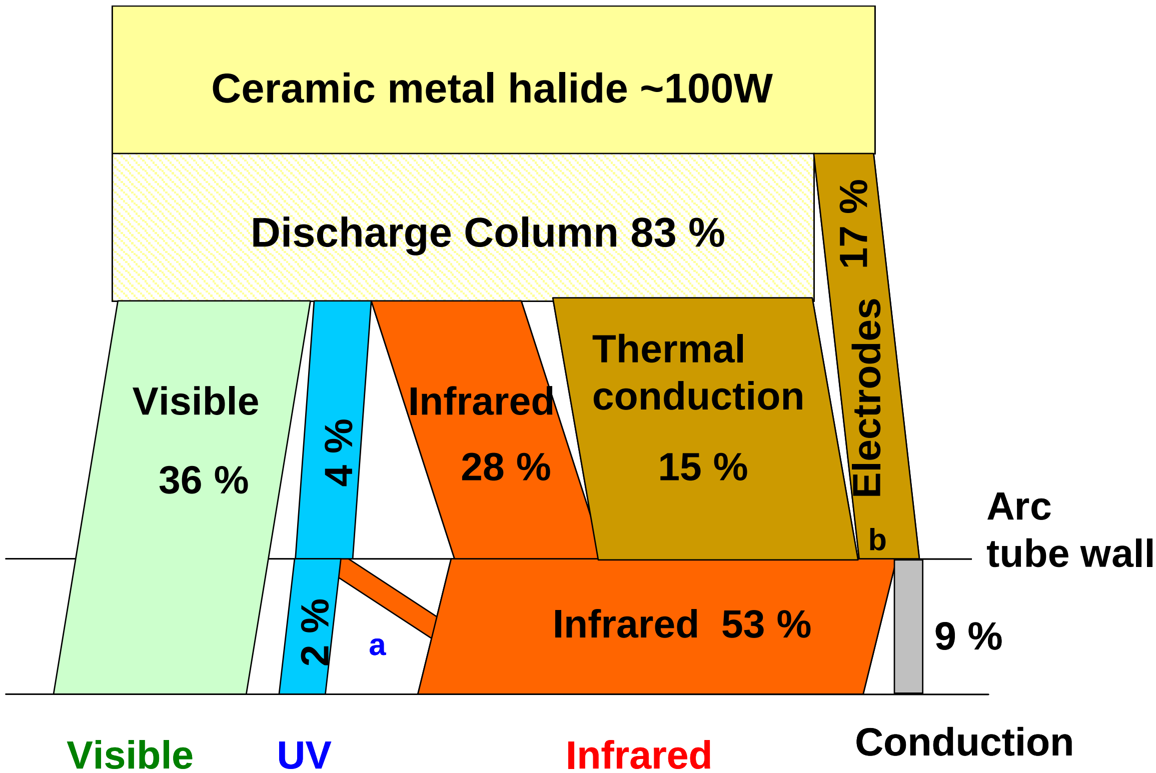

Figure 3. Approximate power flow in a modern ceramic metal halide lamp. The section marked 'a' indicates some UV absorbed by the arc tube wall and converted into heat. Likewise, the section marked 'b' indicates heat conducted through the electrical feed through and converted into heat in the capillaries.

Data measured on other lamps are reduced to terms used in this work and presented in Table 1.[viii,ix,x] These data show that lamps containing chemistries leading to multi-line emission from vaporized species have relatively high $\eta_{discharge}$ as do lamps containing significant resonance broadening or quasi-molecular components. The $\eta_{discharge}$ is lower for lamps with continuum emitters such as high-pressure xenon. This provides clues that chemistries that result in dense multi-line emitters, perhaps with a strong molecular component, could be highly efficacious systems.

Recall that a low-pressure mercury discharge for fluorescent lamps has an electrical to UV conversion, $\eta_{discharge} = 0.63$, suggesting that the electric discharge as a transducer can have a high efficiency. It should be possible in principle to improve metal halide discharges to approach, but not achieve, this level. Low-pressure lamps do not generate enough heat to vaporize the salts in metal halide lamps, consequently an improvement of, $\eta_{discharge} \cong 0.50$, is more likely. Such an increase in this factor would make metal halide lamp systems approximately 150-180 lm/$W_{electrical}$. Further increases can be obtained by pushing the $\eta_{visible}$ closer to its theoretical maximum. High pressure sodium lamps show that 400 lm/$W_{visible}$ is achievable, very close to the approximate 450-500 lm/$W_{visible}$ isoefficacy limit. If metal halide lamps can approach these limits, with suitable color content, system efficacy of 225-250 lm/$W_{electrical}$ is possible. Such lamps would be more than twice as efficacious as commercially available products today.

Lamp Type	Lamp Power	Visible Power	Eta (discharge)	Lumens	Eta (visible)	Eta (system)	CCT	CRI
	W(elec)	W(vis)	W (vis)/ W(elec)		lm/ W(vis)	lm/ W(elec)	K	
Metal halide, Na-Sc iodide [9]	400	136.2	**0.34**	39000	**286**	97.5	4860	65
Metal vapor, Mercury [8]	400	59.0	**0.15**	20800	**352**	52.0	5400	22
Metal vapor, High Pressure Na [8]	400	118.0	**0.30**	48000	**407**	120.0	2100	23
Metal halide, Na-Tl-In iodide [8]	400	97.0	**0.24**	34800	**359**	87.0	4500	67
Metal halide, Dy iodide [8]	400	128.0	**0.32**	32400	**253**	81.0	5250	85
Metal halide, Sn halide [8]	400	92.0	**0.23**	24000	**261**	60.0	4100	91
Inert gas, High Pressure Xe [10]	300	29.7	**0.10**	6900	**232**	23.0	5050	>90
Metal halide, Dy-Tm-Ho-Na-Tl-Ca iodide	70	20.7	**0.30**	6253	**302**	89.3	2820	81
Metal halide, Dy-Tm-Ho-Na-Tl-Ca iodide	35	9.8	**0.28**	3249	**332**	92.8	3140	79

Table 1. Experimental data are compared with regard to discharge efficiency and visible efficacy. Data taken from the references is numbered with square brackets, e.g. [8].

Potential Technical Enhancements

As mentioned above, recapture of excessive heat loss is one method of improving lamp efficacy. Clearly, some heat is necessary to raise the vapor pressure of the salts and provide suitable radiators. Careful thermal management as lamps are scaled, especially to lower wattages appropriate to indoor applications, is needed to ensure that only minimum heat is expended.[xi] Heat loss through the capillaries becomes significant as the wattage of the lamp decreases because electrode structures must be of finite size. One possibility is to utilize electrodeless excitation techniques, especially for low wattage lamps of small dimensions, and eliminate all heat loss through the electrodes and metallic feed-throughs.[xii]

Another approach to improving efficacy may be recapture of unwanted UV radiation. In the example given, the UV losses are only about 2%, but this will depend on the chemistry somewhat. Converting this with a phosphor coating on the outer jacket will yield at best a 1% increase in visible power due to conversion efficiency in the phosphor. An alternative to using powdered oxide-host phosphors is to use a fluorescing vapor in a second, outer jacket attached to the burner. The residual heat of the lamp is utilized to vaporize material in this annular chamber and recapture some of the unwanted UV as Stokes- shifted visible emission. Lamps of this kind (see Figure 4) have been made and tested with mixed results due to the low UV flux from the primary discharge.[xiii] Filling the annular region with sulfur vapor, for example, produces a very broad-band red emission from ground to excited state absorption in the near UV and blue followed by the Stokes-shifted fluorescence. The net effect is to lower the color temperature of the lamp by about 1000K.

One could imagine other materials with desirable emissive properties which require lower temperatures for vaporization. For example, some organic compounds (e.g. CH_3HgCl) can be easily vaporized and photoexcited into fluorescing states which subsequently emit useful light (about 550nm). For long term operation, the fluorescing species should be regenerated after the photofragment emits. Unfortunately, many organic compounds will revert to more stable forms of carbon and thus produce short lived devices.

It may be possible to recapture some of the infrared radiation from the arc tube itself with an anti-Stokes phosphor if one were available with high quantum efficiency. However, most phosphors have relatively narrow excitation bands (about 100nm or 0.1micron FWHM). The infrared emission from the arc tube (e.g. the 53% as depicted in Figure 3) is re-emitted in a very large bandwidth (10’s of microns) according to blackbody theory. The overlap between the phosphor excitation band and the IR emission is expected to be small. Additionally, for a typical arc tube operating at 1300K the peak in the emission is around 2.2 microns, so an optimum phosphor would convert two such photons into one photon at around 1 micron-also in the infrared.

Another possible avenue to improve the lamp efficacy is to alter the temperature profile of the gas within the burner. All of the lamps in Table 1 are passive, in that the temperature profile develops as a result of the energy balance between electrical input, radiation and heat flow out. The ballast or electronic control gear simply regulated the power to the lamp. More active control of the discharge through the modulation of lamp power at acoustic resonance frequencies may be used to improve lamp efficacy, via improvement of $\eta_{discharge}$ and/or $\eta_{visible}$.

For example, it has been observed that power modulation at acoustic resonance frequencies can straighten and center the arc (Figure 5) within the burner. Thermal losses due to the proximity of the hot arc to the wall are reduced, but in addition, the straightened arc also allows higher aspect ratio burners to be used at all, by reducing the danger of local arc tube overheating. Higher aspect ratio lamps are appealing because electrode heat losses are less significant. Arc straightening and centering also results in a more uniform arc tube wall temperature distribution, with warmer “cold spot” temperatures. The increased condensate temperature generally improves the efficacy of lamps containing typical metal halide fill chemistry.[xiv]

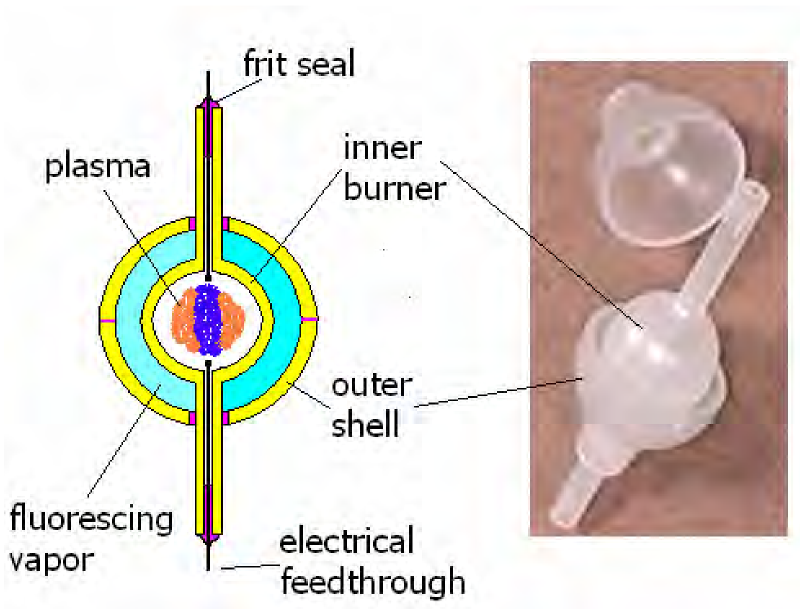

Figure 4. Construction of double-walled ceramic lamp for radiation recapture. Schematic on the left shows principal components. The photograph on the right shows key ceramic components. Lamps can also be made from vitreous silica.

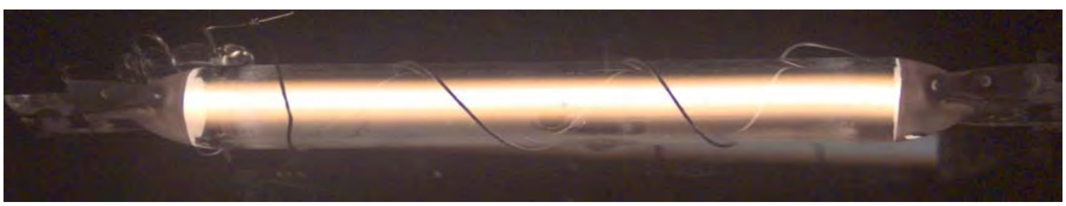

Figure 5. Straightened and centered arc of a horizontally operated, high aspect ratio (≈10:1), vitreous silica, metal halide lamp. This lamp contains rare earth iodides and is operated at about 340W. The spiral wire around the lamp body is an ignition aid.

High aspect ratio metal halide lamps typically exhibit segregation of vapor species when operated in a vertical orientation. Power modulation at longitudinal resonance mode frequencies can suppress this segregation.[xv] Again, this increases the usability of high aspect ratio burners. In addition to the efficacy increases discussed above, a few groups have implemented methods of controlling the segregation as a means of controlling the color characteristics of the emitted light.[xvi,xvii] Relocation of condensate has also been observed during excitation of longitudinal resonance modes. The condensate settles at particular locations, for example 1/3 and 2/3 along the length of the burner. The condensate temperature is thus elevated which may increase efficacy. Of course, the elevated temperature may enhance wall reactions, which may require a redesign of the burner. Even if the condensate temperature were subsequently reduced to previous typical levels, at least the overall burner temperature and heat losses would be reduced.

From visual observations it is apparent that the temperature profile of the arc is influenced by the power modulation. This suggests that acoustic power modulation might be used to modify the temperature profile towards improving lamp efficacy. For example, sharp profiles with higher peak temperatures in the core could increase the emission from particular atomic species, while broadened profiles may enhance emission from molecular species in the mantle.[xviii]

While there have already been many initial indications of benefits obtained by utilizing acoustic power modulation, there also exists the potential for more, for the resultant arc stabilization permits the use of alternative arc tube shapes and fill chemistries which otherwise would result in unstable lamps. The additional freedom in choices for lamp design might thus facilitate other advances in HID lighting technology.

Finally, we should consider discharges in different pressure regimes. Low pressure (torr) discharges generate little heat but are quite efficient in converting electrical power into radiation. These discharges are characterized by electron temperatures greater than gas temperatures. On the other end of the scale, at higher pressures (several bar), discharges convert 50% or more power into heat. These discharges are characterized by local thermodynamic equilibrium, one consequence being the electron and gas temperatures are equal. Little attention has been paid to intermediate pressure lamps (100's torr) where electron temperature is greater than gas temperature but the discharges are somewhat unstable. A combination of imposed stabilization techniques, such as acoustics, in this intermediate pressure range may lead to discharges which generate sufficient heat to vaporize interesting radiators, but limit heat losses and convert more electrical power into light.

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RECENT LIFETIME INCREASES AND PHOTOMETRIC IMPROVEMENTS TO QUARTZ METAL HALIDE LAMPS FROM EXTERIOR THIN FILM COATINGS AND IMPROVED BALLASTS

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Abstract

Distributed lighting systems offer a way to take advantage of the high efficiency and high brightness of quartz metal halide (QMH) lamps when a small lumen package is required, such as replacing halogen spot lights for retail applications. Tight beam distributions are produced out of small fixtures because brightness is preserved efficiently. Because only one high intensity discharge (HID) lamp and one ballast is required to produce up to eight spotlights, the market is less sensitive to changes in the costs of these components. This makes a distributed lighting system an ideal place to test advancements in arctubes and ballasts. Several recent tests are discussed, including life and photometric improvements from exterior thin film coatings and improved ballast efficiency. An outline for possible future improvements is presented.

Background

Fiberstars has been the market leader for remote source lighting for many years. Our product lines include high brightness fixtures for commercial use, high efficiency systems for interior spaces such as retail and color changing lights for pools. For the last five years, our main R&D focus has been on making energy efficient accent lighting systems. The result is a distributed lighting product called Efficient Fiber Optics, or EFO.

EFO research has benefited from several Federal programs. The Department of Energy (DOE) has been instrumental in helping remove the final barriers to bringing EFO into residential markets and broadening the addressable market in retail. Department of Defense (DOD) funding has come in the form of small business innovative research (SBIR) grants and broad agency announcement (BAA) funding. BAA funding has helped accelerate further development of EFO through a Defense Advanced Research Projects Agency (DARPA) program called High Efficiency Distributed Lighting (HEDLight).

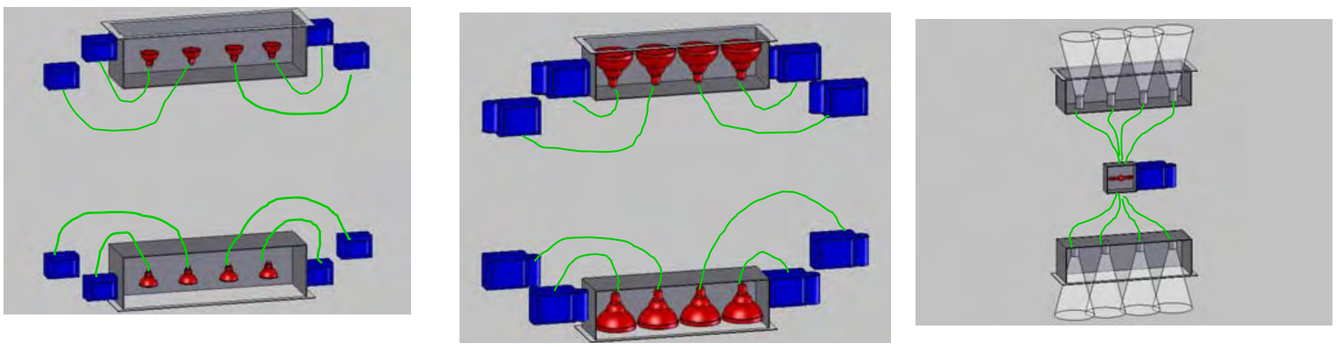
As research continues to improve the efficiency of distributed lighting systems, new Metal Halide lamp and ballast technologies are being explored. Often times these new technologies are also initially implemented by distributed lighting users (early adopters) since the nature of the system architecture spreads the cost of the lamp and ballast over several points of light.

Motivation, Financial Analysis

Understanding the inherent directed nature of light exiting large core distribution fibers, Fiberstars initially identified accent lighting and the 50W MR-16 lamp as the performance target for the base EFO unit. Potential replacement of the 50W MR-16 was considered to be the best chance to make a large energy reduction impact because of its widespread use. Considering recent developments, customers installing 50W MR-16s are now also considering 20W ceramic metal halide (CMH) sources. The financial decisions facing customers are always a motivating force to remain up to date on state of the art systems. 20W CMH lamps must now be included in comparisons when considering other energy efficient options.

First costs

For equal comparison, consider an eight spot system. Figure 1 shows a graphical representation / comparison for 3 different types of systems: a) halogen, b) ceramic metal halide and c) EFO. In this figure the lamps are red, the drivers are blue and the housings are a light grey.



a) Halogen b) Ceramic Metal Halide c) EFO

Figure 1: Schematic showing location of lamp (red), control (blue), housing (grey) for three different accent lighting systems.

Understanding the system architecture a comparison can be made between first costs. Figure 2 shows a comparison of first costs for a halogen installation, a 20W CMH solution and an EFO system. In order to make eight spots, the halogen and CMH solutions both require eight lamps (shown in shades of pink) and eight drivers (shown in shades of blue). Sometimes the halogen systems will have one large magnetic driver instead of several individual drivers, but this is rare. For each system, there is also a cost for the housings, wirings, and mounting brackets. This is shown in purple and is titled “Housing, etc.” For the EFO solution, the “housing, etc” category includes the distribution fibers.

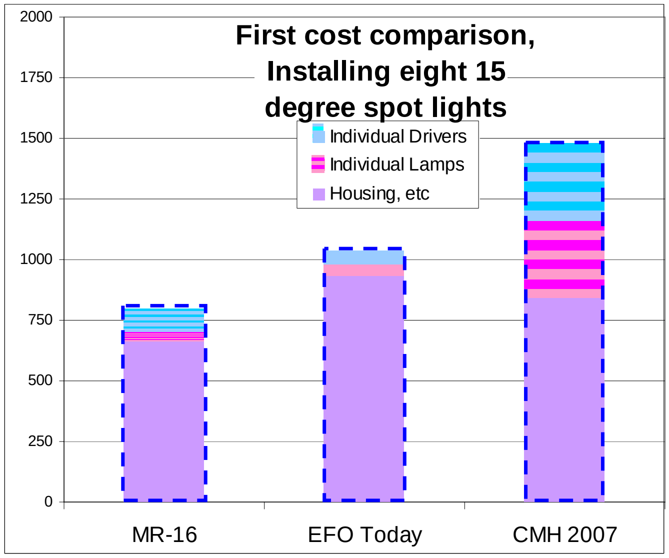


Figure 2: First cost comparison for the installation of eight 15 degree spot lights

Table 1 shows the assumptions / specifications for the systems being compared in tabular form. Note that two theoretical future CMH systems are listed in the table. A CMH fixture with lower costs for 2011 has not been identified but it is expected that future costs will come down on the order of the numbers shown. The 2011 projection is based solely on what would be a best fit for the industry, not based on any research currently underway and therefore should be considered a best case extrapolation with the understanding that market needs may drive a very different reality in 2011 in regard to performance and thus cost.

	Halogen, MR-16	EFO Today	CMH 2007	CMH 2011
	50W EXT	EFO EXT	20W CMH	12W CMH
Beam angle (no less than 15 degrees)	15°	15°	15°	15°
CBCP (target of 7000 CBCP)	7000	7200	10000	7200
Installed cost per point ($)	100	130	185	150
Lumens per watt in 15 degrees	3	35	15	20
Lamp life (hours)	4000	14000	10000	12000
Power per spot (W)	55	10	28	15
Source LPW	16	80	80	80
Cost (to end user) for new lamp ($)	5	48	40	20
Cost for eight spots, new lamps ($)	40	48	320	160
Cost (to end user) for a new ballast ($)		60	40	30

Table 1: Cost and performance assumptions

First year analysis

First costs are part of the story but post installation maintenance costs must also be considered when evaluating potential technologies and solutions. Figure 3 shows how the costs for the three types of systems stack up for the first year. Each re-lamp requires new parts (a new lamp) and labor to make the change. The new parts are shown in shades of pink, the labor in shades of yellow. There is also a section for the cost of energy in this first year, based on $0.10/kWH. This chart makes it easy to see how the costs of lamp replacement stack up.

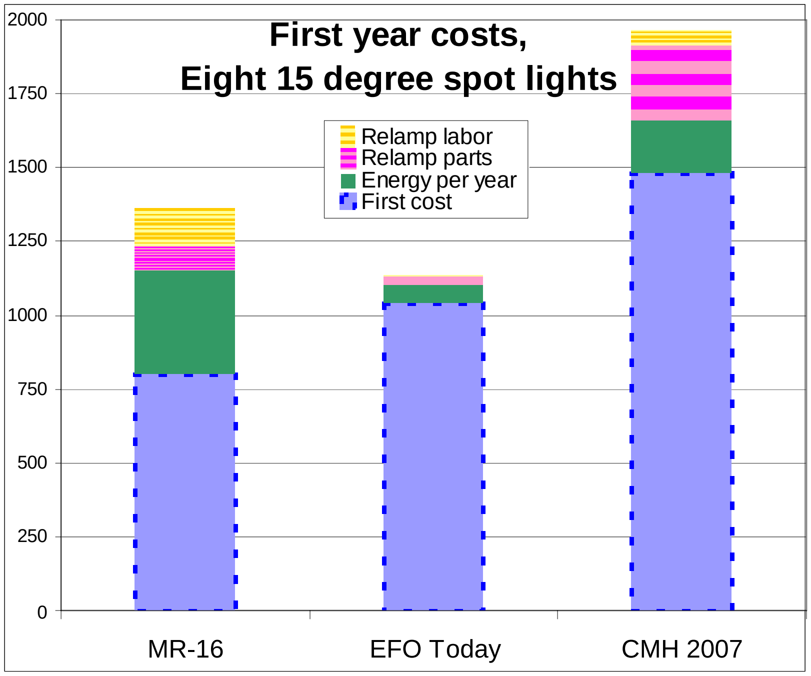


Figure 3: First year costs comparison for eight 15 degree spot lights

As is shown, the EFO distributed system has a lower overall cost at the end of the first year when compared to halogen and CMH.

Five year analysis

Consider the cost over time for 5 years. Figure 4 shows that after five years.   The re-lamp costs that are shown separately in figure 3 are now lumped together into a orange block for each year. It is shown that the EFO system has saved the customer about $2000 over 5 years for the eight spots.

Here, the effects of the theoretical future CMH development first described in Table 1 are best seen. If a 12W CMH lamp is developed which has lamp and ballast costs roughly half of the 20W lamp, and with longer life, it will also deliver significant savings compared to halogen, but still less than half of what an EFO system gives.

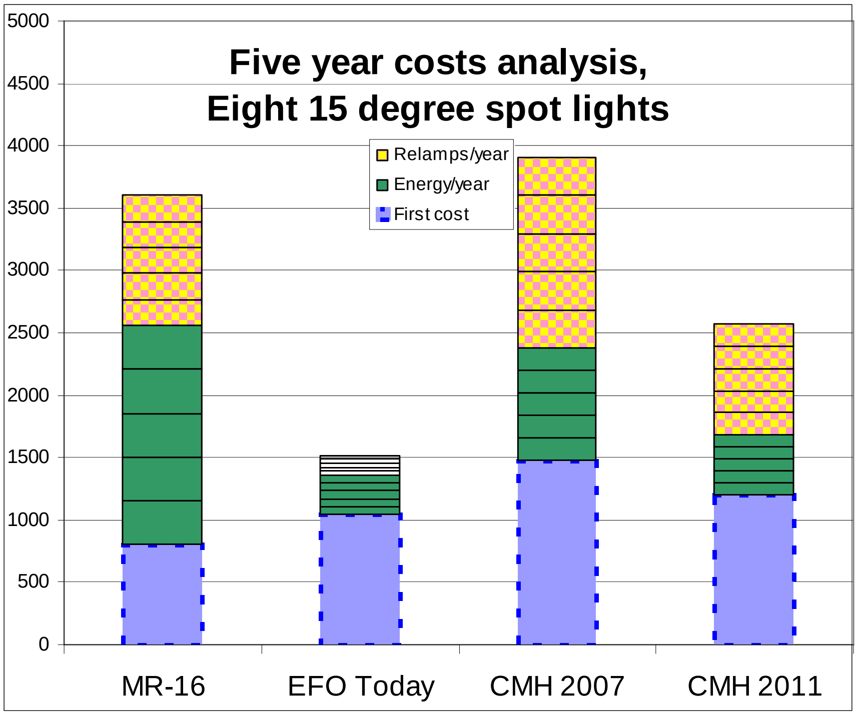


Figure 4: Five-year costs analysis for eight 15 degree spot lights

The cost analysis and the clear conclusion in regard to EFO are what led Fiberstars to dedicate research and development effort to develop a high efficiency, low cost distributed lighting system. It is the best way to save our customers money and energy in the long run.

Recent Advancements

Several advancements in the design and fabrication of high performance low wattage MH lamps were recently noted during research that was funded in part under the DARPA HEDLight program and through Fiberstars internal research. The effects of external barrier coatings and ballast drive techniques were explored.

Lamp external coatings
Fiberstars ran a series of lamp coating experiments where the outside of the arctube received a thin film reflector stack. These lamps saw significant improvements in life, color and lumen output. We are currently doing research to define and optimize these effects. Figures 5-7 show a summary of performance of uncoated to coated lamps.

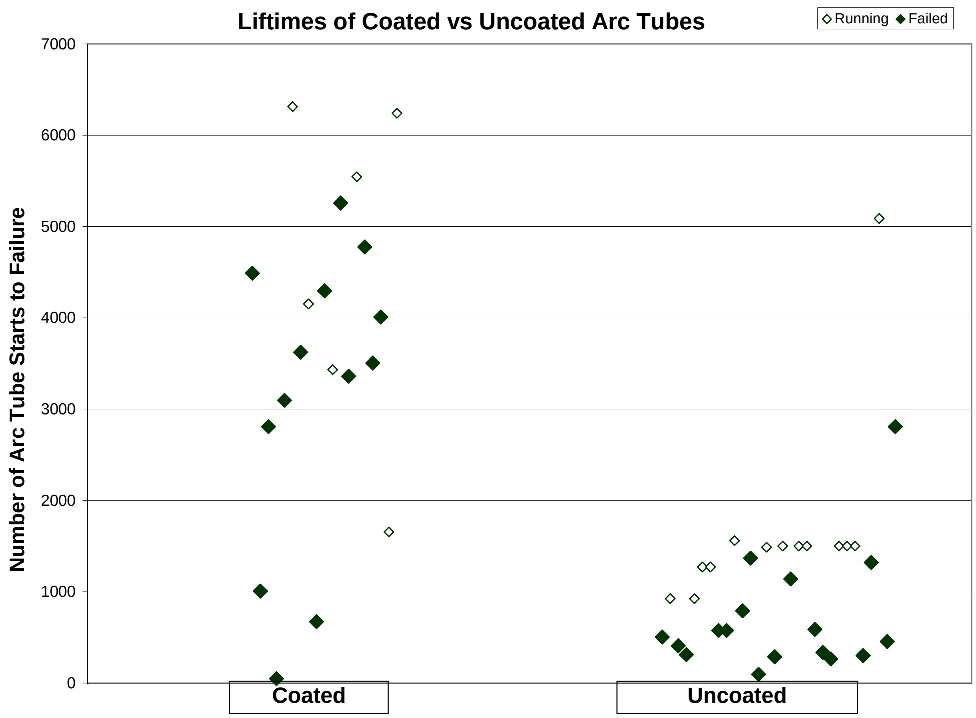


Figure 5: Lifetest using Fast Cycle 30 min On / 30 min Off

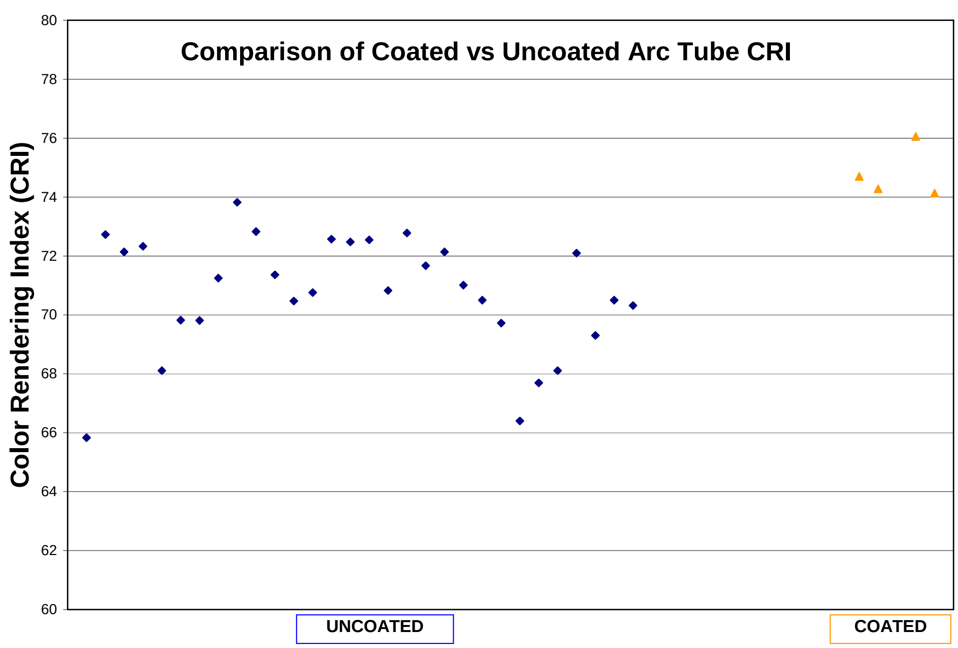


Figure 6: Color Rendering Index Improvement

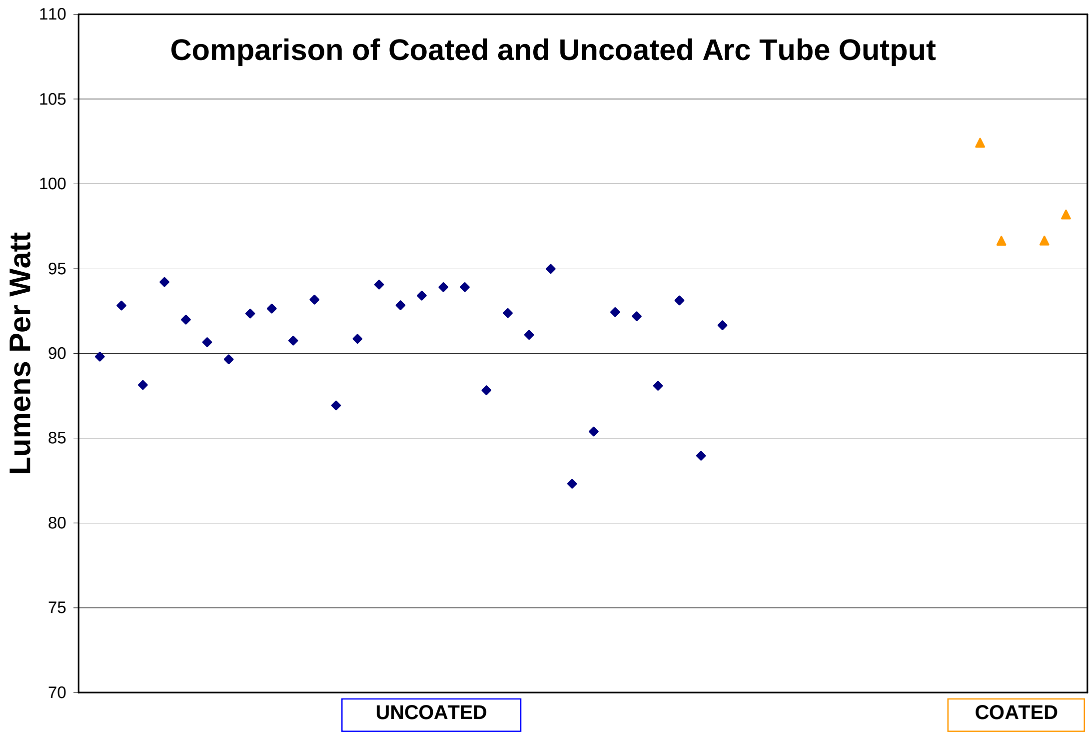


Figure 7: Coated Tube Lumen Improvement

Ballast efficiency improvements
Under HEDLight, Fiberstars made improvements in our ballast technology that were focused on efficiency improvements. Figure 8 shows the history of these improvements. We started with DC ballast systems and then switched to AC systems so that all of our illuminator lines can benefit from the advancements.

These ballasts have high power factor, low harmonic distortion, compact size and scalable (affordable) construction.

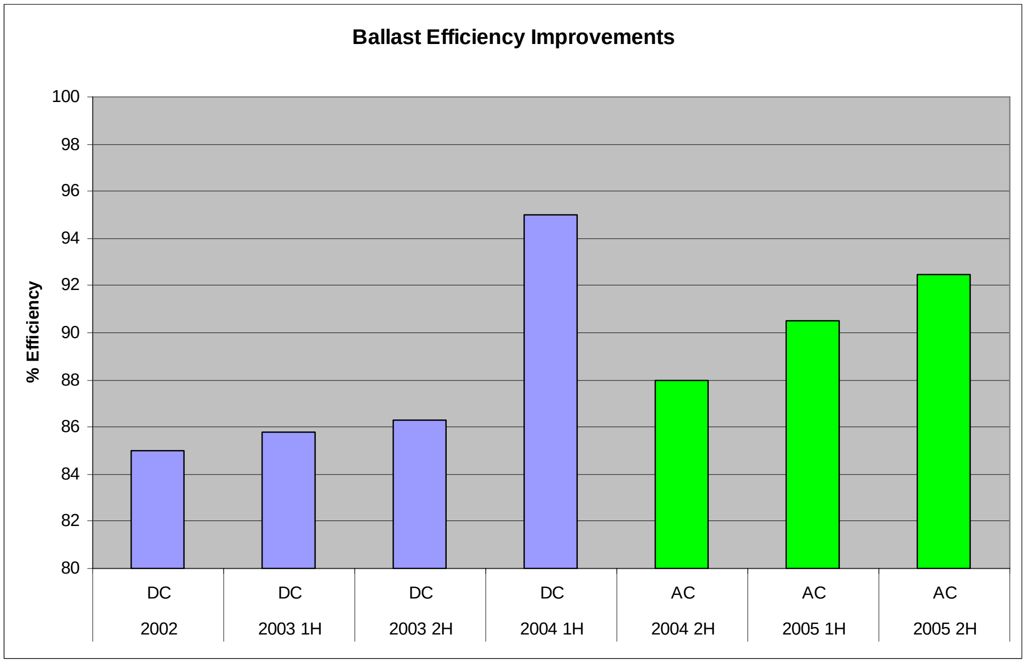


Figure 8: Recent Ballast Efficiency Improvements

Summary and Suggestions for Further Work

It has been shown that external coating of metal halide lamps holds great promise for improving the efficiency and lifetime. Thin film coatings can improve efficiency by recycling IR or UV energy back into the lamp and can improve optical efficiency of coupling and fixtures by including anti-reflective coatings. They can also increase cold spot temperature by absorbing unwanted radiation.

Two coating methods hold particular promise for coating metal halide lamps. Low Pressure Chemical Vapor Deposition (LPCVD) methods can produce coatings with uniform thickness that can coat all surfaces. This method requires relatively little tooling but is a batch process. Microwave plasma assisted sputter deposition requires significant tooling investment, but is potentially a more scalable process than LPCVD.

Fiberstars has developed ways to make electronic ballasts for low wattage lamps more efficient. These improvements have been focused on optimizing the ballast power, starting profile, and size that is important to EFO applications. These improvements could be explored for other wattages and starting profiles.

RECENT DEVELOPMENTS IN DOSE OPTIMIZATION AND DESIGN OF LOW-WATTAGE QUARTZ METAL HALIDE LAMPS

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Abstract

New low-wattage metal halide lamp and ballast systems with outstanding color rendition and luminous efficacy have been developed and are nearing entry into commercial and military installations. These efficient light sources, designed for use in distributed fiber optic lighting systems, approach daylight, "full spectrum" output and contain multi-component metal halide mixtures that are a result of intense dose chemistry and lamp design optimization efforts. Simplex optimization and designed experiment techniques are described for chemical dose and arc tube geometry optimization, and highlights of results to date are given. New photometry metrics, useful for achieving optimum, targeted spectral response, are described in detail. Newly-developed high temperature coating materials for inhibiting oxidation of molybdenum sealing foils and for preventing reaction of metal halide dose materials with quartz arc tube walls are presented. The use of infrared thermal imaging and thermal modeling techniques in maximizing lamp performance and life is discussed. Results of recent work in electrode materials, in fill gas composition and pressure, and in metal halide ballast design and performance are also summarized. Recommendations for future work in high temperature lamp materials and dose chemistry optimization in low-wattage, miniature metal halide light sources are presented.

Background

Today, metal halide (MH) lighting technology finds widespread use in a variety of commercial, industrial and specialty applications. Metal halide technology provides an extremely attractive combination of high luminous efficacy, quality of light, and color rendering capability, especially in comparison to less efficacious sources such as incandescent or halogen lamps, or to sources with poorer color rendering capability such as high pressure sodium (HPS) or high pressure mercury (HPM) lamps. Miniature, low wattage MH lamps, in particular, can provide higher performance and quality of light than compact or conventional linear fluorescent sources in terms of efficacy, color rendering and optical performance.

Current discharge light sources of all types have often been developed for long life and high luminous efficacy, with less importance placed on color rendering and "full spectrum" output. There is evidence today to suggest that sources with "full-spectrum" output can allow the use of lower light levels in many applications, thus lowering the energy costs when compared to sources of similar efficacy but lower color rendering ability.

Low wattage, miniature MH lamps are typically not as efficacious as their high wattage counterparts. This is due in part to fundamental limitations of physics (e.g., unavoidable electrode energy losses and necessarily short arc gaps). However, halide dose chemistry optimization, improvements in the thermal design of arc tubes, new envelope materials and coatings, improved electrode designs and materials, and ballast improvements are all areas where significant improvements are yet to be made. This paper will highlight some of the recent work that we have performed in these areas.

Existing Technology

One of the main deficiencies of metal halide technology is poor lumens maintenance. Low wattage lamps are no exception. Typically, in many commercial MH products, lumens maintenance may decline to 75% to 85% (or lower) at rated life. This situation has not changed significantly in the 30+ years that the technology has been on the market.

As noted above, current discharge light sources of all types have often been developed for long life and high luminous efficacy, with less importance placed on color rendering. In the US, most commercial medium to high wattage MH lamps employ $NaI\text{-}ScI_3$ dose chemistry, often with additional metal halide components. While providing good luminous efficacy, these low CCT sources (~3500-4000K) provide only mediocre color rendering (CRI (R_a) ~70). In European and Asian markets, products typically have higher CCT (> 4000K) with higher CRI (R_a) values (> 80). These lamp types are usually based on rare earth (*i.e.*, lanthanide) halide doses such as DyI_3, TmI_3, etc., in combination with other components such as TlI, NaI and CsI. These dose chemistry systems are well-established and most have been in use by manufacturers worldwide for 20 to 30+ years.

While fundamental chemistry, physics and spectral analysis provide guidance, most lamp dose chemistry has been optimized experimentally with the aid of statistical design tools, as reported in the literature [DO1-DO5]. There are no available *ab initio* simulation tools for accurately predicting spectra of metal halide discharge lamps from the metal halide chemical dose components. The high cost and lengthy development times of previous empirical approaches usually dictates that most lamp designs fall short of their potential optimum performance.

Numerous enhancements to the MH lamp technology have occurred since its introduction, mostly in the last 10-15 years. These include:

- New dose chemistry systems and lamp designs (as noted above).
- Pulse start operation and elimination of starter probe electrodes in QMH lamps [BA1].
- Tipless construction in QMH lamps which improves arc tube geometry and temperature uniformity.
- Ceramic lamp envelope materials, enabling higher wall temperatures, high efficacy, good color rendering, more precise geometry and reduced color variation from lamp to lamp.
- Miniaturization and precision manufacturing, as embodied in the D2 and D4 automotive MH lamps and the Philips UHP projection light source [LP3].
- Highly efficient non-imaging optics and high efficiency distributed (HED) fiber optic systems such as those being developed by Fiberstars and APL for the DARPA HEDLight program and for

commercial EFO systems, enabled by efficient, full spectrum, compact, low wattage metal halide sources.

All of these innovations are breakthrough technologies in their own right. The leveraging of these breakthroughs presents substantial opportunities for further development of commercial and consumer products and for the worldwide reduction of energy consumption.

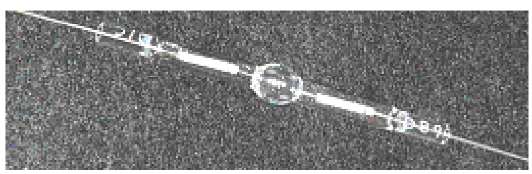
<u>Current Research</u>

Low Wattage Metal Halide Lamp Development

Recent work at APL Engineered Materials involves the development of low-wattage DC and AC quartz metal halide (QMH) light sources and ballasts. Much of this work has been performed as part of the DARPA HEDLight Program. The goals for improved light sources in this program are the development of 68W to 70W DC and AC light sources of high luminous efficacy (>80 LPW), high color temperature (CCT of 5000 to 6500 K) with a good spectral match to daylight reference spectra (D5000 to D6500). Our work in this area involves the optimization of both the arc tube and ballast components of the system, with a focus on the dose chemistry; arc tube design, and new materials which can enhance performance.

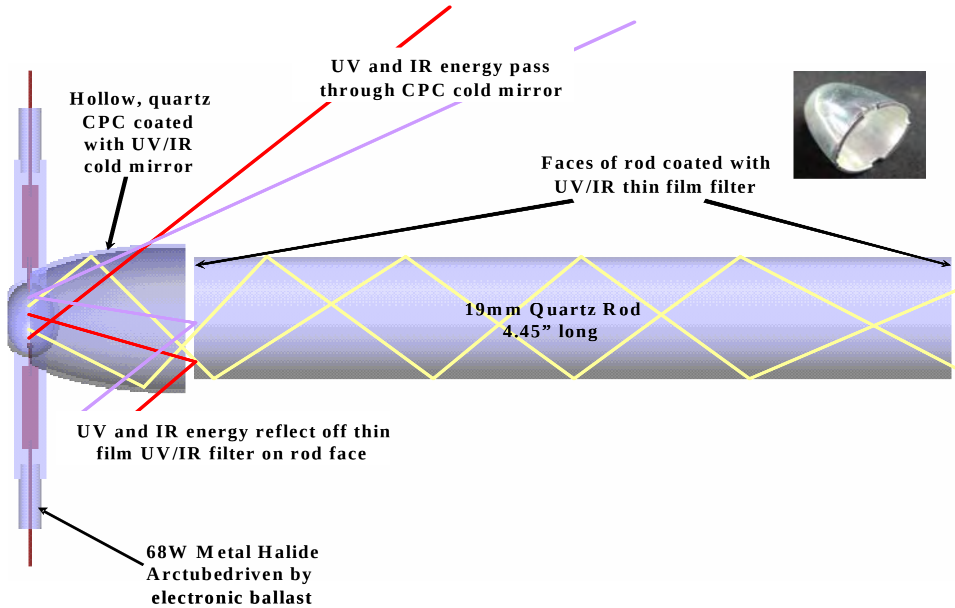
Illustrated below are typical QMH arc tubes containing rare earth halide based doses which we have developed:

10.8 mm bowl length arc tube design, 3 x 5 mm legs.



9 mm bowl length arc tube design, 2 x 4 mm legs

These QMH light sources are integrated into a High Efficiency Distributed (HED) fiber optic lighting system using non-imaging reflectors (compound parabolic collectors, CPC's), quartz rod thermal isolation components and large core polymer fiber optic components. The arc tube and optical components of the system are illustrated schematically below.



(Diagram courtesy Fiberstars, Inc, Solon. OH)

While the focus of our current work is on low-wattage QMH light sources for HED fiber optic systems, the remainder of this paper will treat issues and opportunities for improvements in MH light source performance in general.

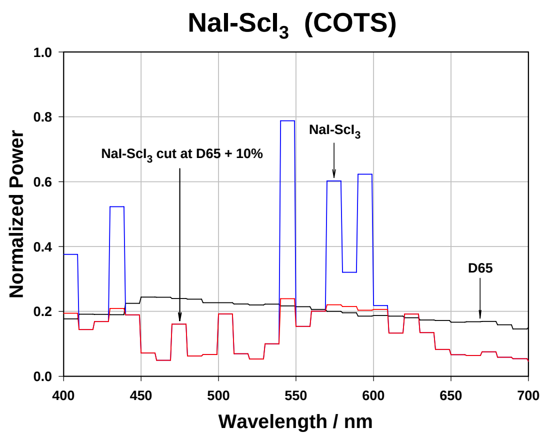
New Metrics for Lamp Photometric Performance

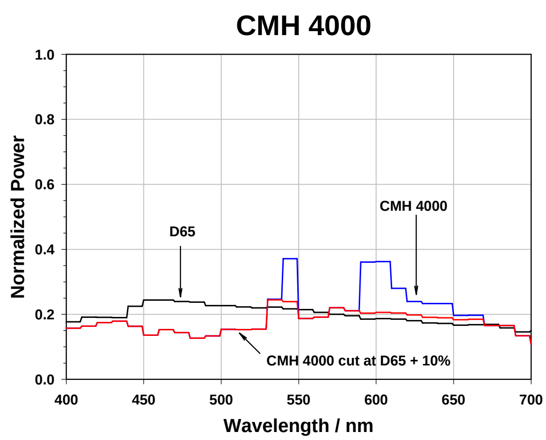
In our DARPA HEDLight work, two significant new metrics of lamp photometric performance have been implemented to facilitate the characterization of light sources with high luminous efficacy and "full spectrum" output:

- Modified Lumens (or alternatively Modified LPW)
- χ' (chi prime) (a measure of the match to spectral target, typically attainment of daylight spectral response (e.g., D5000 to D6500)

The first of these metrics (Modified Lumens) is essentially the result of applying a filter (actual or simulated) to the lamp spectrum to remove peaks that are more than 110% of the desired target spectrum (e.g. D6500). The lamp spectral response and the target spectrum are first binned in 10 nm increments. The target spectrum is then normalized to have lumens equal to the lamp spectrum. Spectral power in peaks falling above 110% of the normalized target spectrum are then removed from the lamp spectrum, resulting in a "filtered" spectrum. The net effect in the Modified Lumens metric is thus to penalize lamps having sharp spectral peaks above the 110% limit. The percentage of lumens remaining after this operation is multiplied by the actual lumens to yield the Modified Lumens metric. A Modified CCT value can also be computed for the "filtered" spectrum.

This is illustrated in the two figures below for a tipped 68W DC lamp containing a $NaI\text{-}ScI_3$ COTS (commercial off-the shelf) system used as a starting point in the HEDLight program and for a commercial 4000K 70W AC ceramic metal halide lamp. A target D6500 daylight spectrum is used as the target reference spectrum. The spectral power shown in the blue peaks above 110% of the target is not counted towards the Modified Lumens value. When %Efficiency is defined as the ratio of Modified lumens to actual lumens, the $NaI\text{-}ScI_3$ lamp has a %Efficiency of 57% and the CMH 4000 lamp, 84%.





The second of these metrics, χ', is a measure of the match to the spectral target. It is calculated from the sum of the squares of the deviations of the lamp spectrum from the normalized target spectrum in the range of 400-700 nm. A perfect spectral match thus yields a χ' value of zero. The χ' metric is similar to the Full Spectral Index metric recently proposed by the Lighting Research Center at Rensselaer Polytechnic Institute [LP4], except that it is general for any arbitrary target spectral response.

We also routinely tabulate the number of spectral “holes” where the lamp spectrum falls below a selected threshold (typically 50%) of the normalized target spectrum in a given 10 nm wavelength range. This provides yet another measure of the match to the target spectrum. The computational details of these performance metrics are explained in further detail in Appendix A below.

These new metrics, in combination with conventional photometric parameters such as CCT, and x- and y-chromaticity have been employed as figures of merit in the dose chemistry and lamp design optimization work described in the next section. The χ' metric, rather than CRI, was used in the optimization work.

Metal Halide Lamp Dose, Loading and Geometry Optimization

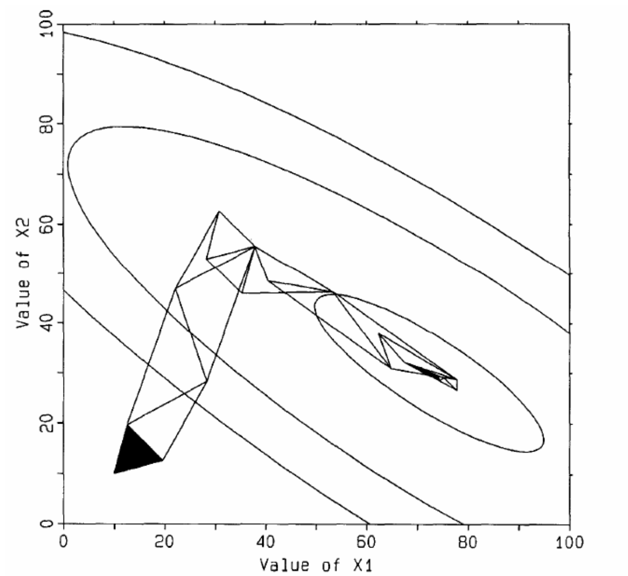
The realization of metal halide light sources with desired spectral output and high luminous efficacy cannot generally be achieved by designing from first principles. There are no *ab initio* simulation tools for accurately predicting spectra of metal halide discharge lamps. In our recent work we have used the following approaches to optimize dose chemistry and lamp design:

- Modification and extension of known, existing lamp doses and arc tube designs.
- Mathematical and experimental optimization of dose composition and arc tube design using the mathematical/statistical tools of Simplex Optimization (SO) and Design of Experiments (DOE).
- Improved performance through increased wall loading and wall temperature (*i.e.*, resulting in increased MH vapor pressure). Note that wall temperature increases will generally shorten lamp life for a given arc tube material (e.g., quartz glass). Approaches to enabling higher wall temperatures while maintaining life are improved thermal design of the arc tube and the use of internal chemical barrier coatings.
- Arc tube dimensions/shape. Increased performance can be achieved through improved temperature uniformity of the arc tube wall through optimization of arc tube dimensions and shape. The use of tipless arc tubes has been shown to increase performance by improving wall temperature uniformity, and can provide better optical performance in imaging and non-imaging optical applications. A tipless design is a requirement for practical internal barrier [BC1-BC9] or external filter or radiation-absorbing coatings [BC10-BC12].

The Simplex Optimization (SO) [SO1] technique involves simultaneous variation of the control variables (factors or inputs) to find levels that achieve the best possible outcome (responses or outputs). The simultaneous variation of multiple control variables is far more efficient than "trial-and-error" approaches or methods where a large number of experimental measurements are required in advance to define the multivariate response surface. Since its introduction in 1962 [SO1] the simplex method has been improved with numerous modifications [SO2-SO7].

The SO procedure is, by nature, a sequential process: the next experimental trial is determined by the results of the previous measurements. In the optimization of MH lamp dose composition and design parameters many factors and trials are required. In addition, one is confronted with the optimization of many desirable but interdependent responses (e.g., LPW, CCT, χ') which must be optimized simultaneously. A combined figure of merit which gives appropriate weight to each response must be established.

The figure below illustrates the progress of a simplex optimization for a simple case of 2 control variables, X1 and X2. The experimental trials are represented by the vertices of the triangles, and the optimization procedure calculates the next trial (vertex) based on the response function of the previously measured trials (vertices). The net result is a progression of expanding or contracting triangles (starting from the first 3 trials at the vertices of the black shaded triangle) that approach the optimum of the response surface (at the center of the small oval).

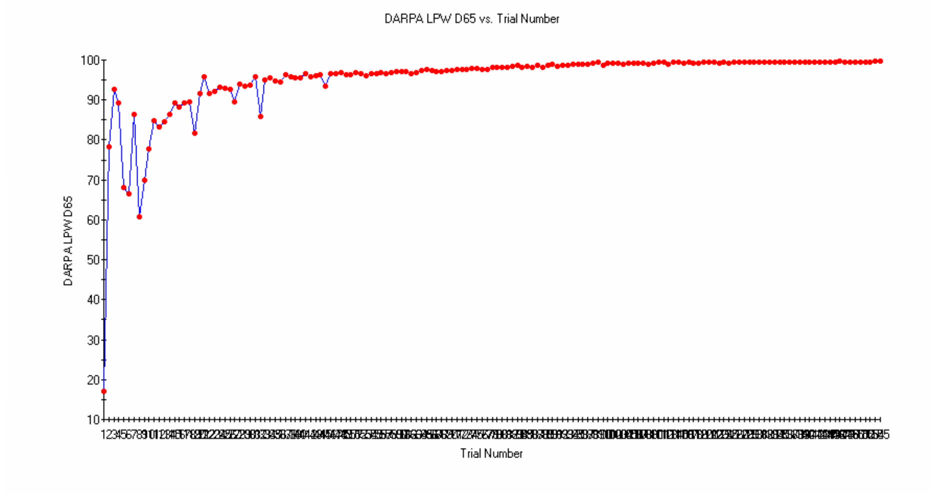


The use of the SO technique can be illustrated in the following simulated example of an eight component MH dose optimization using the Multisimplex software package. [SO6,SO7]. A simulated response function: Response = $100 - \Sigma\,(a_i\text{-}c_i)^2$, where a_i is the trial Simplex component value, and c_i is the optimum value, was defined. For each of the 8 components an optimum concentration in weight percent was assumed:

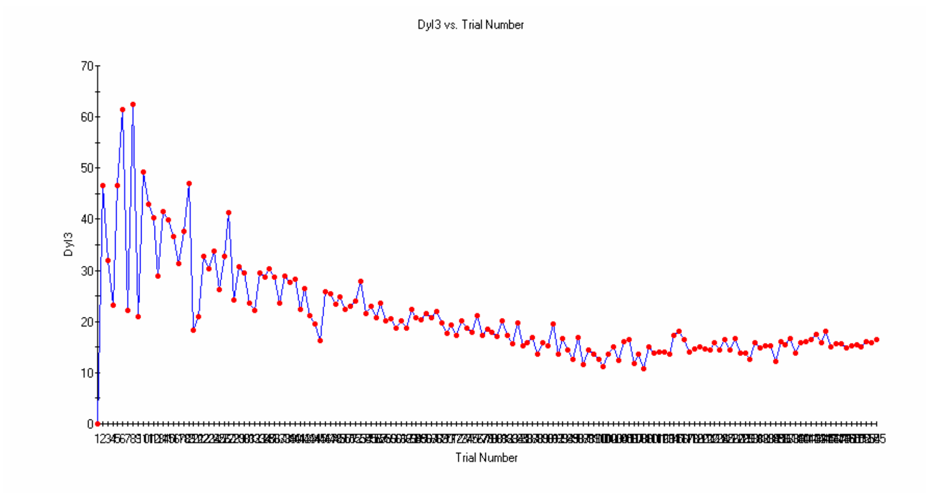
Component	Optimum Value (wt %)
NaI	5
CsI	15
DyI_3	15
HoI_3	22
TmI_3	18
NdI_3	15
TlI	5
ScI_3	5

The initial trials were started far from the assumed optimum, and the SO algorithm used variable step size contraction and expansion factors of 0.5 and 2.0. The mixture constraint was imposed which forces the sum of the component percentages to be 100%. The algorithm was set up to maximize the modified efficacy (Modified LPW) response function. The approach to the optimum value of 100 LPW as all 8 component percentages were varied simultaneously is shown below as a function of trial number.

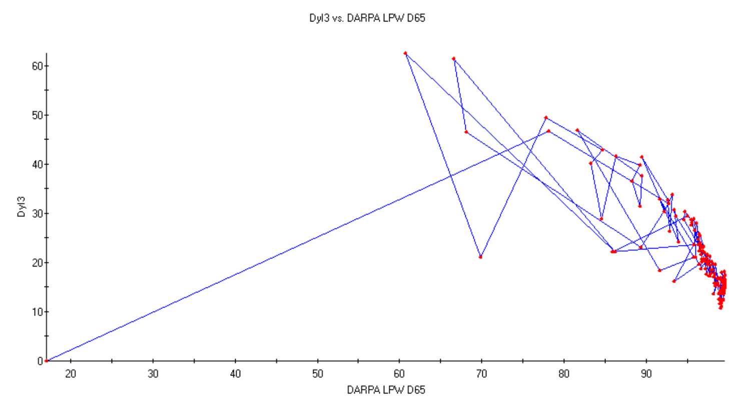
The procedure attained >95% of the optimum after 33 steps, and >99% after 94 steps.



The adjacent figure shows the approach of one of the components (% DyI_3) to the optimum as a function of trial number:



This approach to the optimum weight percent DyI_3 component is also shown here as a function of the response variable:

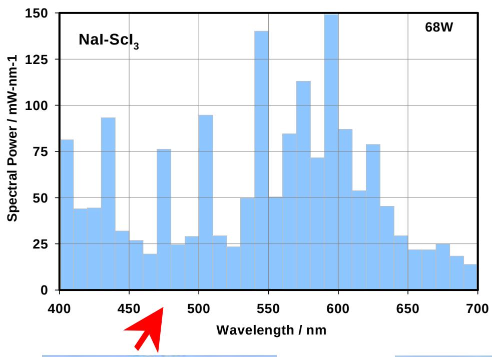


In our recent work we have applied the simplex algorithm to a number of experimental dose composition optimizations of up to 8 components in low wattage DC and AC MH lamps. The algorithm performs well, and has resulted in significant improvements in efficiacy and spectral match to daylight reference spectra in experimental trials with as few as 20 iterations. The results of these optimzations are illustrated further in the examples below.

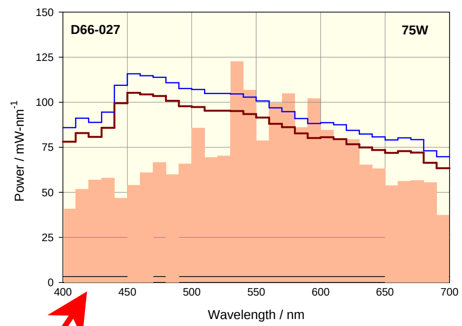
We have found that optimization of physical and geometric parameters of the lamp design are usually best treated by a Design of Experiments (DOE) approach [DO6]. The DOE technique is a well-established and powerful statistical tool, and it has been applied to numerous dose chemistry and lamp design problems in the past [DO1-DO5]. We have used DOE to study and to optimize design parameters such as:

- Electrode dimensions and geometry
- Arc tube shape and geometry
- Electrode position within the arc tube
- Minimization of wall temperature hot spots and wall temperature gradients
- Fine tuning of dose composition to optimize color coordinates.

The figure below shows some highlights of the optimization of lamp design and dose chemistry by SO and DOE techniques achieved in our recent HEDLight and commercial development work. A combined figure of merit which maximizes Modified LPW, minimizes both χ' and the number of 50% spectral holes, and targets a value of CCT (typically 4500-6500K) is employed in these trials.



Evolution of Dose Chemistry and Lamp Design

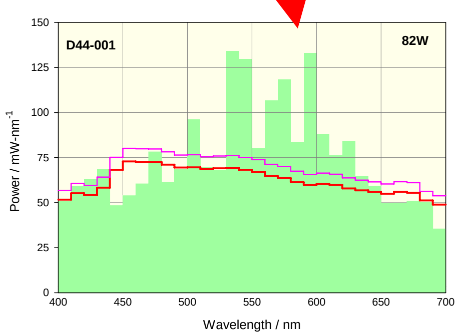


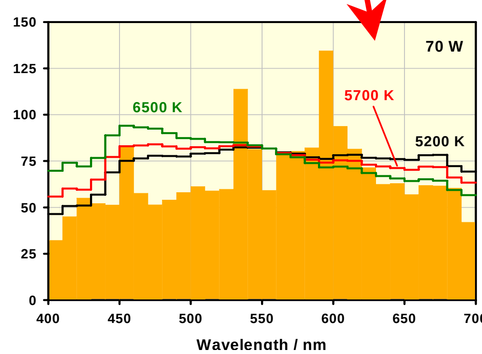
NaI-ScI3	
Lumens 5777	Mod. Lumens 4632
LPW 84.9	Mod. LPW 68.1
CCT 3640	Mod. CCT 4250
x Chrom. 0.398	y Chrom. 0.385
10% Holes 0	50% Holes 13
% Efficiency 80.2%	CRI 70

D-44	
Lumens 5525	Mod. Lumens 4877
LPW 81.2	Mod. LPW 71.7
CCT 5106	Mod. CCT 5261
x Chrom. 0.345	y Chrom. 0.389
10% Holes 0	50% Holes 5
% Efficiency 88.3%	CRI 73

D-66	
Lumens 5745	Mod. Lumens 5325
LPW 84.5	Mod. LPW 78.3
CCT 4956	Mod. CCT 5007
x Chrom. 0.350	y Chrom. 0.390
10% Holes 0	50% Holes 1
% Efficiency 92.7%	CRI 81

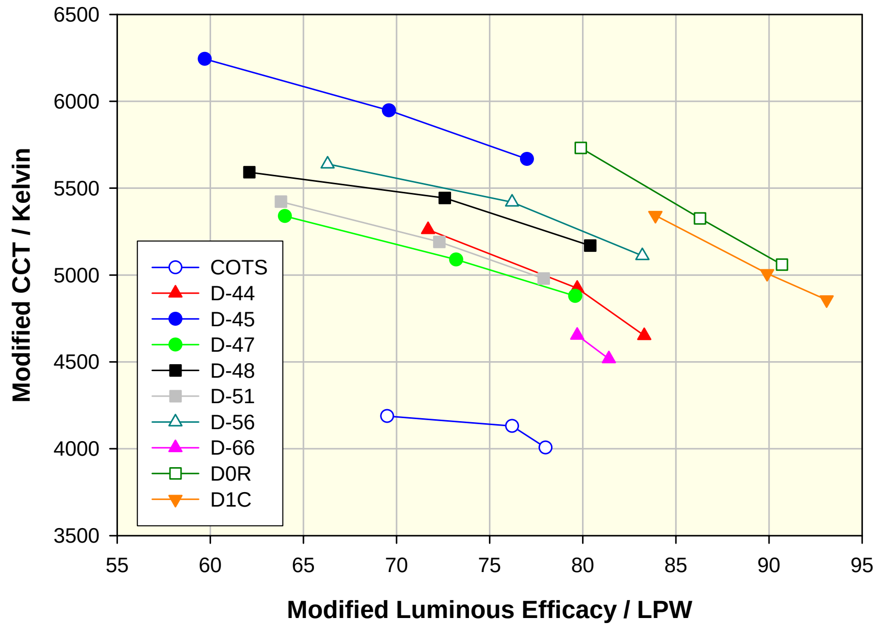
D1P	
Lumens 5785	Mod. Lumens 5325
LPW 82.6	Mod. LPW 76.1
CCT 4267	Mod. CCT 4656
x Chrom. 0.369	y Chrom. 0.366
10% Holes 0	50% Holes 1
% Efficiency 92.0%	CRI 90





Of particular note in these trials is the significant improvement in modified LPW, increases in % Efficiency from 80% to over 92%, increases in CRI (R_a) from 70 to 90, reduction of 50% spectral holes from 13 to 1, and attainment of good matches to high color temperature target spectra in the D4500 to D5500 range (as measured by decreases in χ', not shown).

The progress of the optimization trials can also be illustrated in a plot of Modified CCT versus Modified LPW.

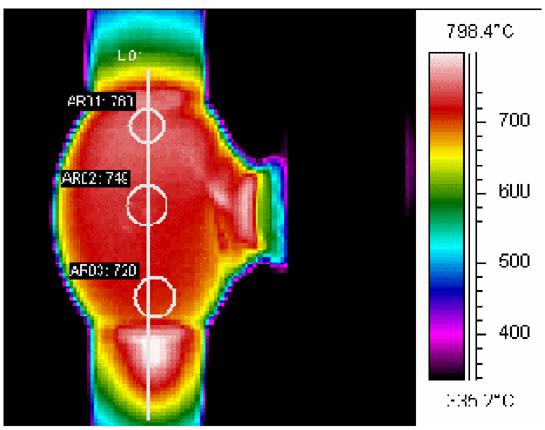


The figure above shows lamp trial data for a number of dose chemistry and design variations at 2 to 3 operating power levels in 68-70W metal halide lamps. Simultaneous attainment of the design goals of both high CCT and high efficacy (LPW) is a difficult and conflicting design goal. The techniques applied have resulted in significant improvements in both of these quantities, as can be seen in the D0R and D1C trials.

Thermal Imaging and Modeling

The thermal operating conditions of the inner and outer surfaces of the arc tube envelope are vitally important to HID lamp performance and life. Optimum luminous efficacy and spectral performance are generally improved with higher envelope wall temperatures. However, high temperature chemical reactions of the dose with the arc tube in both QMH and CMH lamps, and devitrification of silica wall materials in QMH lamps are primary life limiting factors.

Infrared (IR) imaging camera technology is essential in the experimental determination of outside wall temperature distributions. Experimental data can then be coupled with accurate thermal models which simulate radiation, conduction and convection phenomena inside and outside of the arc tube.



In our recent work we have employed both IR imaging and thermal modeling techniques to identify and eliminate hot spot temperatures and to reduce temperature gradients in the development of optimum lamp designs. The accompanying figure shows a thermal image of an early, unoptimized tipped DC lamp design. Thermal camera images identify the problematic hot spots at the bottom anode and the cold spots at the tip-off of the arc tube, both of which can degrade lamp performance and life. Thermal modeling approaches allow the designer to compare model with experiment and to optimize the design for efficacy, spectral output and lamp life.

Inner Wall Barrier Coatings

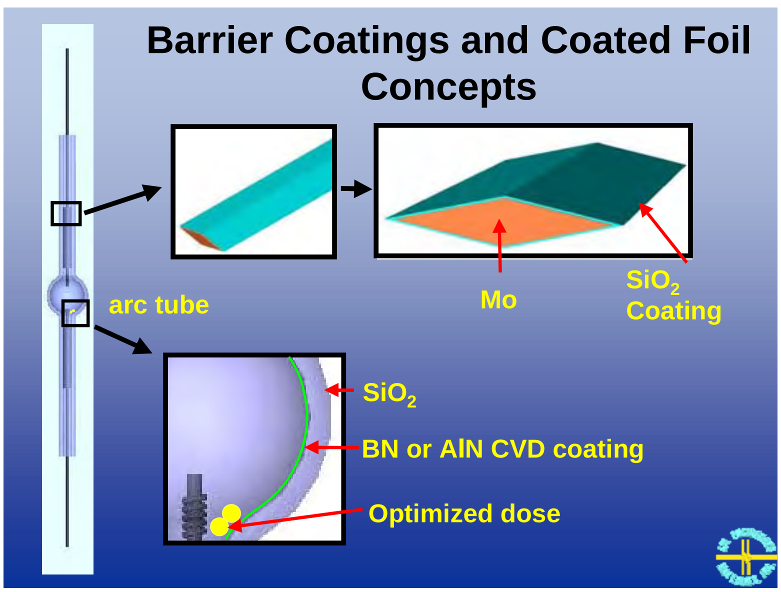
High temperature chemical reactions of metal halide salt dose components (especially Sc and rare earth halides) with the SiO_2 and PCA walls of arc tubes are primary factors in lumens loss and in reduced lamp life. In QMH lamps consumption of metal halide dose, release of excess halogen, and degradation of W electrodes occur according to the following reactions [BC1-BC3,LP2]:

$$4ScI_3(\text{dose}) + 7\,SiO_2\,(\text{wall}) \rightarrow 3SiI_{4(g)} + 2\,Sc_2Si_2O_{7\,(s)}$$

$$2SiI_{4(g)} + W_{(s)}\,(\text{electrode}) \rightarrow WSi_{2(s)} + 4I_{2(g)}$$

Similar reactions can occur with other rare earth halides and SiO_2. Corrosion reactions between rare earth halides and PCA envelope materials also occur in ceramic metal halide lamps [LP2].

Barrier layers have the potential to reduce or eliminate the salt–wall reactions. This can enable increases in wall loading, higher wall temperatures, increased metal halide vapor pressure, longer life and improved lumens maintenance over life. The ability to increase wall loading enables reduction of arc tube dimensions and increased photometric and optical performance.



Although several patents have been issued [BC4-BC9] discussing the concept of inner wall barrier coatings of several compositions on fused silica arc tubes, we are not aware of any current commercial use of inner wall barrier coating technology.

In our work at APL, barrier layer materials such as AlN or BN have been shown to provide good chemical resistance to metal halide salts [BC4]. These materials can absorb UV radiation as well, and their use may minimize the need for additional UV absorption coatings or filters outside of the arc tube. Since the thermal conductivity of these nitride coatings is high, it may help to improve uniformity of the wall temperature [BC9], although the magnitude of this effect may not be significant unless the coatings are highly conductive or quite thick.

APL has conducted a large number of tests on both BN and AlN coatings prepared by conventional CVD and by PECVD techniques. Adherence of these materials to the inner silica wall has been a significant problem to date. It is likely that the mismatch of thermal expansion coefficients of the coating and substrate and the large temperature swings that occur with hundreds or thousands of lamp on-off cycles are responsible for poor adherence. Intermediate layers of other materials which provide a gradient of thermal expansion coefficients is one approach which may address this problem. Adherence remains a significant challenge to a successful implementation of internal chemical barrier coatings.

There are also a number of practical manufacturing challenges in the application of inner barrier coatings. In coating tipless arc tubes, current technologies are often limited by the difficulty of coating the inside walls of the arc tubes without adversely affecting the leg portions of the arc tube where the glass to Mo foil pinch seal is made. Other challenges and issues include the adaptation of CVD or PECVD techniques to miniature arc tubes, and minimizing the cost of added manufacturing steps to apply the coatings.

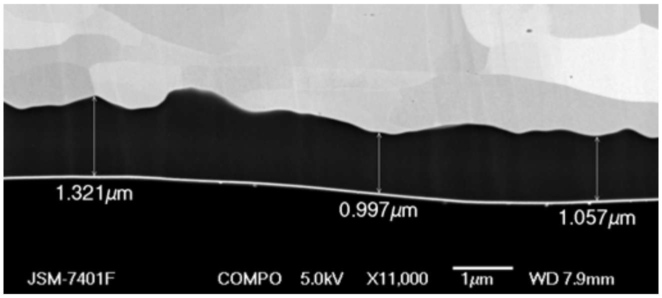
Outer Lead Oxidation Protection in QMH Lamps

In QMH lamps, thin molybdenum foil with tapered edges is the material of choice for making the gas tight metal-to-glass seals. An inner electrode (tungsten) and an outer lead (Mo wire) are spot-welded to a short piece of Mo foil, onto which the quartz envelope is pinch-sealed or shrink-sealed. For arc tubes burned in air, or for lamps with air-filled outer jackets, the oxidation and premature failure of the outer leads and lead-foil welds becomes a problem. This problem can be more severe as the arc tube loading (W/cm^2) is increased.

For QMH lamps, a number of methods for protecting molybdenum foil from oxidation have been described [OX1-OX3]. These methods involve coating the foil with chromium metal [OX1], molybdenum phosphide [OX2] or molybdenum silicide, by elaborate gas phase procedures. Other approaches, long used in halogen lamps, include covering the exposed Mo foil/lead with a low melting glass such as antimony borate.

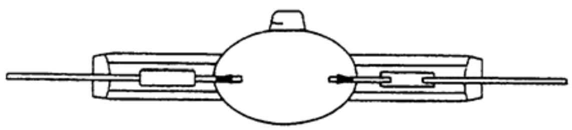
As part of our work on light sources for HED systems, we have developed a new SiO_2-coated Mo foil material which provides oxidation resistance superior to previous approaches. The SiO_2 coating is fused onto the surface of the Mo foil, and is compatible with all quartz glass sealing operations. The reader is referred to the figure on Barrier Coatings and Coated Foil Concepts above, and to reference [OX3] for details on the material and the fabrication process.

The SEM micrograph below shows the cross section of a typical coated foil where the surface of the fused silica film is made visible by the edge of a thin gold film sputtered onto the fused silica coating surface. Typical fused silica film thickness is on the order of 1 μm.

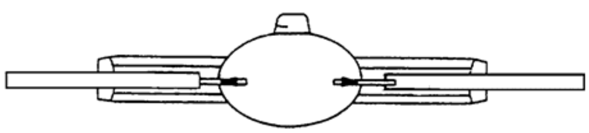


Backscattered SEM image of SiO_2-coated 6 mm foil. The thin white line in the image is the gold layer deposited onto the silica surface. Courtesy of JEOL.

The diagrams below compare a conventional QMH lamp design to a typical QMH design of the type being developed for HED low wattage MH light sources. In these new designs the coated foil emerges from the pinch without welds susceptible to oxidation at high temperatures. The electrical connections (crimps or welds) can then be made at a position further from the arc tube leg where temperatures are lower.



Conventional Design:



With Oxidation Resistant SiO_2-coated Mo Foils:

Because the coated foils are thin and flexible, a different approach to mounting and supporting the arc tube is required. This is a design and manufacturing challenge that should be readily accomplished.

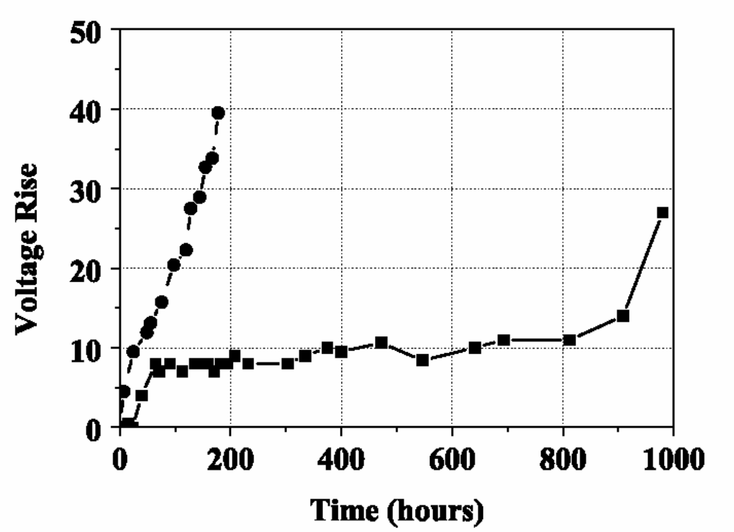
There are a number of advantages to the use of silica-coated Mo foils in QMH lamps:

- For QMH lamps which normally burn in air (e.g., high wattage sports and graphic arts types, and low wattage HED and projection types operating in CPC's or reflectors), the primary advantage is elimination of a common failure mechanism and greatly increased lamp life. This results in reduced replacement and logistics costs.
- For QMH lamps designed to burn in nitrogen or inert gas filled outer jackets the coated foil can allow replacement of the inert gas fill with air or a small percentage of oxygen. The potential advantages are two-fold:

- Elimination of outer jacket exhaust process entirely -- the outer jacket can be filled with air and need not be hermetically sealed.
- Elimination of outer jacket getters for H_2 (such as Zr-Al and BaO_2 types). The air or O_2 fill itself can serve as a getter for H_2 (forming H_2O at a small but sufficient rate). Elimination of getter components reduces materials and manufacturing costs.
- Reduction in Na loss in QMH lamps containing NaI or NaBr doses. The presence of air or O_2 in the outer jacket should be effective in reacting with hydrocarbon contamination which contributes to Na loss [LP1].

Electrode Materials, Fill Gas and Ballast Considerations

A recent paper [BA2] from our laboratories describes the influence of electrode composition, buffer gas fill pressure and control gear on the performance of metal halide lamps. It is shown that pure tungsten electrodes improve lumen maintenance and reduce voltage rise over lamp life in medium wattage QMH lamps, as shown in the figure below.



Voltage rise comparison for 350W pulse start lamps with charged frames and vacuum outer jackets operated on (—■—) 100 kHz electronic ballast and (--•--) 60 Hz magnetic ballasts.

The results of this study also indicate that that there is an optimum fill gas pressure (between 50-150 Torr) which minimizes lumen depreciation over life in conventional medium to high-wattage QMH lamps. In this range of fill pressures, a compromise between the deleterious effects of multiple starts and continuous operation appears to apply. The results are similar for argon and xenon buffer gases. There is evidence that the buffer gas to mercury density ratio plays a major role in lamp lumen maintenance in continuous operation. Lamps using pure tungsten electrodes show better lumen maintenance and less voltage rise than lamps using thoriated tungsten electrodes. There is evidence that ThI_4 increase in lamps with thoriated electrodes is caused by ScI_3 reaction with ThO_2 in the electrodes and results in higher lamp operating voltages, leading to poor lumens maintenance and shortened lamp life. The use of electronic control gear is shown to improve the performance in these lamps. Further investigation into the influence of electrode material and lamp ballast system interaction on the performance of metal halide lamps of all types and wattages is needed.

Potential Future Enhancements

Recommendations for future work in the areas of research described above are summarized in the table below. In this table we address the applicability of each approach as it relates to:

- Efficacy improvements
- Wattage and lamp size reduction
- Performance enhancements (i.e., life, color, or lumens maintenance)
- Applicability to lighting technology (low-, medium-, or high-wattage; MH, QMH, all HID or all lamps)
- Lamp and system cost reduction (via manufacturing or replacement/maintenance cost reductions)

A check mark is indicated where each approach is deemed applicable, and an assessment of the priority of the approach is also indicated.

Potential Future Enhancements and Future Work

	Priority	Enables Efficacy Improvements	Enables Wattage/ Lamp Size Reduction	Results in Performance Enhancements	Applic-able to Lamp Type	Enables Lamp and System Cost Reduction
New metrics for full spectrum performance	**Med**				**All Lamps**	
Provide equivalent quality light with less energy						
Dose chemistry optimization	**High - Med**	√	√	√	**All MH, esp. low-watt**	
Effects efficacy and all performance measures						
Thermal design of arc tubes	**High**	√	√	√	**All HID, esp. low-watt**	
Essential for life and miniaturization						
Internal chemical barrier coatings	**Med - Low**	√	√	√	**All QMH, esp. low-watt**	
Difficult, but potential high payoff						
Oxidation resistant Mo foils	**High**		√	√	**All QMH**	√
Applicable to all QMH types						
Electrode materials	**Med**			√	**All MH**	
Important for life and maintenance						
Ballast design and performance	**Med-High**	√		√	**All HID, esp. low-watt**	√

The following potential projects follow and expand upon the approaches which we have described above and would have significant benefits to MH technology and reduction of energy consumption:

- Dose chemistry and lamp design: Apply simplex optimization and DOE techniques to optimize the following types of low-wattage MH lamps with the following goals: %Efficiency >90, CRI >90 and χ' (chi prime) < 20 for CCT of 3000 K to 3400 K, while improving luminous efficacy by >10% over existing designs. Apply the same tools to other low, medium and high wattage QMH and CMH lamps to achieve similar levels of performance with high color temperature CCT goals of 4500 to 6500 K.

- Oxidation resistant Mo foil: Develop new mounting and supporting technology to enable application of silica coated Mo foils in low, medium and high wattage QMH lamps. Prove and test concepts of air-filled outer jackets and elimination of hydrogen getters for reduction of Na loss and for reducing manufacturing and lamp costs.

- Photometry Metrics: Define new color quality metrics such as the χ' (chi prime) and spectral “holes” concepts and apply to modern and historical lamps. Publish software to allow critique of the metrics by members of industry. Refine appropriately and facilitate creation of industry standards.

- Ballast design and performance: Continue studies of lamp-ballast system interactions and the role of electrode materials and fill gas pressure and composition to achieve extended performance and life. This will apply to a wide range of MH lamp types from low to high wattages.

Acknowledgments

This work was supported in part under DARPA Contract Number DAAH01-03-9-R002. The author expresses his thanks to S.C. Hansen, T. Emilsson, R.L. Steward and D.L. Miller of APL Engineered Materials, Inc., Urbana, IL, for their assistance in preparing this manuscript, and to R. Buelow of Fiberstars, Inc., Solon, OH, for data and support.

Public Release

Abbreviations

AC	Alternating Current
ADLT	Advanced Lighting Technologies, Inc., Solon, OH
APL	APL Engineered Materials, Inc., Urbana, IL
BN	Boron Nitride
CCT	Correlated Color Temperature
CMH	Ceramic Metal Halide
COTS	Commercial-Off-The-Shelf
CPC	Compound Parabolic Concentrator
CRI	Color Rendering Index (defined as R_a = average of R1-R8 targets)
CVD	Chemical Vapor Deposition
DC	Direct Current
DOE	Design of Experiments
HED	High Efficiency Distributed
HID	High Intensity Discharge
HPM	High Pressure Mercury
HPS	High Pressure Sodium
IR	Infrared
LPW	Lumens Per Watt
MH	Metal Halide
PECVD	Plasma Enhanced Chemical Vapor Deposition
QMH	Quartz Metal Halide
SEM	Scanning Electron Microscopy
SO	Simplex Optimization
UHP	Ultra High Performance (High Pressure)
UV	Ultraviolet
VLI	Venture Lighting International, Inc., Solon, OH

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Appendix A

Calculation of Metrics for Lamp Photometric Performance

Quantitative figures of merit for the spectral distribution of test lamps have been developed to calculate the Lumens Modifier and goodness-of-fit parameters χ and χ'. The Lumens Modifier specifies the fraction of the lamp lumens falling under the appropriately scaled daylight reference spectrum.

$$\text{\% Efficiency} = 100 \times \text{Lumens Modifier} = \frac{\vec{L} \cdot \vec{M}\left(\vec{S}, 1.1 \times \frac{\vec{L} \cdot \vec{S}}{\vec{L} \cdot \vec{R}} \times \vec{R}\right)}{\vec{L} \cdot \vec{S}}$$

$\vec{R}$ = Reference Spectrum (typically D5500 - D6500)
$\vec{L}$ = Photopic luminosity efficiency distribution
$\vec{S}$ = Sample spectrum of test lamp
$\vec{\mathrm{M}}(\vec{A}, \vec{B})$ = Minimum of $[A_i, B_i]$ for each i in $\vec{A}$ and $\vec{B}$

In the above expression $\vec{R}$ is scaled to 10% greater lumens than $\vec{S}$. The luminous efficacy of $\vec{S}$ ″clipped″ by scaled $\vec{R}$ is then divided by the luminous efficacy of $\vec{S}$. In compliance with the stated requirements, each element in $\vec{R}$, $\vec{L}$, and $\vec{S}$ is the integral of the continuous spectrum over 10 nm increments, i.e.,

$$R_{\lambda=500} = \int_{\lambda=495}^{\lambda=505} \vec{R}$$

The goodness-of-fit parameters are determined by the degree to which the sample spectrum matches the daylight reference spectrum. For the calculation of χ, the absolute value of the difference between each segment of the sample and reference spectra is normalized and averaged. For χ', the normalized difference is squared and the square root is taken of the average.

$$\chi = \frac{\sum \frac{\left|\vec{S}_i - \vec{R}_i\right|}{\vec{R}_i}}{n}$$

$$\chi' = \sqrt{\frac{\sum \left(\frac{\vec{S}_i - \vec{R}_i}{\vec{R}_i}\right)^2}{n}}$$

Both χ and χ' approach zero as the sample spectral distribution more closely matches the daylight reference spectral distribution.

Calculation of the Lumens Modifier allows the tabulation of the number of 10 nm wavelength blocks which are more than 10% and 50% below the corresponding blocks in the target daylight reference spectrum. Those deficient wavelength blocks are denoted as spectrum "holes" and serve as a qualitative means of discriminating unfavorable spectral distributions from the favorable spectral distributions (with the fewest holes.)

APPENDIX D

HID Lighting Technology Workshop Registrant List

HID Lighting Technology Workshop Registrant List

Registrant's Name	Title	Company
Norman Boling	VP R&D	Deposition Sciences, Inc.
James Brodrick	DOE Lighting Program Manager	U.S. Department of Energy
Timothy Brumleve	Vice President - Technology	APL Engineered Materials, Inc.
Roger Buelow	Chief Technology Officer	Fiberstars, Inc.
William Busch	Senior Product Manager	Day-Brite Lighting
Joel Chaddock		National Energy Technology Laboratory
Nancy Chen	Staff Scientist	Osram Sylvania
Jim Cirillo	Sr. Project Manager	Fiberstars
Holger Claus	Vice President	USHIO America
John Curry	Physicist	NIST
Gary Eden	Professor	University of Illinois
Cheryl English		Lithonia Lighting
Scott Graves	Project Manager	ICF Consulting
Meghan Hoye	Associate	ICF Consulting
David Hrubowchak		Osram Sylvania
Jerzy Janczak	Engineering Manager, Electronic HID	Philips Lighting Company
Walter Lapatovich	Staff Scientist	Osram Sylvania
Sheri Lausin	Senior Associate	ICF Consulting
Michael Litvinovich	Sr. Design Engineer	Universal Lighting Technologies
Karen Marchese	Senior Writer/Project Manager	Akoya
Peter Ness	Manager of Technology and Product Development	EYE Lighting International of North America, Inc.
Bob Nigrello		Osram Sylvania
Jeffrey Popielarczyk	Business Development	General Electric
Mohamed Rahmane	Lighting Physicist	General Electric
Victor Roberts	President	Roberts Research & Consulting, Inc.
Ronald Runkles	Program Manager	NEMA
Bill Ryan		ICF Consulting
Craig Sansonetti	Physicist	NIST
Hans Schellen	Director, R&D HID Lamps	Philips Lighting Company
Jack Strok	Systems Manager	General Electric
Nikolaus Voggenauer	Sr. Engineer	APL
Paul Vrabel	Project Manager	ICF Consulting
Paul Walitsky		ICF Consulting
Dale Work	Government Relations	Philips Electronics