ILLUMINATING THE CHALLENGES

SOLID STATE LIGHTING PROGRAM PLANNING WORKSHOP REPORT

November 13-14, 2003
Crystal City, Virginia

Lighting Research and Development
Building Technologies Program
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy

Prepared by Navigant Consulting, Inc.
February 2004

DISCLAIMER

COPIES OF THIS REPORT

Electronic (PDF) copies of this report are available to the public from:

U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Building Technologies Program
Solid State Lighting Research and Development Portfolio
http://www.netl.doe.gov/ssl

ACKNOWLEDGEMENTS

The Department of Energy would like to acknowledge and thank all the participants for their valuable input and guidance provided during this two-day workshop. The Department would also like to thank all the direct contributors, and especially the speakers who presented at the conference, raising the quality of the content and discussion:

Charles Becker, Next Generation Lighting Industry Alliance / GelCore
Arpad Bergh, Optoelectronic Industry Development Association
James R. Brodrick, U.S. Department of Energy
C. Edward Christy, National Energy Technology Laboratory
David K. Garman, U.S. Department of Energy
Michael Hack, Universal Display Corporation
Douglas Kirkpatrick, Advanced Technology Office, DARPA
Michael Krames, Lumileds
Harriet Kung, Office of Basic Energy Sciences, U.S. Department of Energy
Edward D. Petrow, Lincoln Technical Services
M.R. Pinnel, U.S. Display Consortium
Michael Schen, National Institute of Standards and Technology
Vasundara Varadan, National Science Foundation

COMMENTS

The Department of Energy is interested in receiving any feedback or comments on the material presented in this workshop report. Please write directly to James Brodrick, Lighting R&D Program Manager:

James R. Brodrick, Ph.D.
Program Manager, Lighting R&D
EE-2J / **Forrestal Building**
U.S. Department of Energy
1000 Independence Avenue SW
Washington D.C. 20585-0121

TABLE OF CONTENTS

1. INTRODUCTION 1

1.1. SSL OPERATIONAL PLAN 2
1.2. CONES OF LIGHT 3
1.3. ACTIVITIES PRESENTLY FUNDED 5

2. WORKSHOP PRESENTATIONS 7

2.1. GOVERNMENT SUPPORT OF SSL R&D 8
2.1.1. Dr. Harriet Kung, Office of Basic Energy Sciences (BES) 8
2.1.2. Dr. Vasundara Varadan, National Science Foundation 9
2.1.3. Dr. Michael Schen, National Institute of Standards and Technology 9
2.1.4. Dr. Douglas Kirkpatrick, Advanced Technology Office, DARPA 10
2.2. TRADE ASSOCIATION SUPPORT 10
2.2.1. Dr. Charles Becker, Next Generation Lighting Industry Alliance / GELCore 10
2.2.2. Dr. M.R. Pinnel, U.S. Display Consortium 11
2.2.3. Arpad Bergh, Optoelectronic Industry Development Association 11
2.3. TECHNICAL PERSPECTIVES 12
2.3.1. Dr. Michael Krames, Lumileds 12
2.3.2. Dr. Michael Hack, Universal Display Corporation 12
2.4. OVERVIEW OF PROJECTS, AND ORGANIZATION OF THE SSL PORTFOLIO 13
2.4.1. Dr. James Brodrick, Department of Energy 13
2.4.2. C. Edward Christy, National Energy Technology Laboratory 14
2.4.3. Graphical Representation of Proceedings 15

3. DAY TWO – BREAKOUT GROUP DISCUSSIONS 15

3.1. LIGHT EMITTING DIODES (LEDS) 16
Topical Area 1: LED Applied Research 16
Topical Area 2: LED Product Development and Systems Integration 22
3.2. ORGANIC LIGHT EMITTING DIODES (OLEDS) 25
Topical Area 1: OLED Applied Research 25
Topical Area 2: OLED Product Development And Systems Integration 31

4. LIST OF APPENDICES 33

APPENDIX A. WORKSHOP REGISTRANTS LIST
APPENDIX B. WEB-SITES AND OTHER RESOURCES RELATED TO SSL
APPENDIX C. GRAPHICAL IMAGES CAPTURING DISCUSSION FROM THE WORKSHOP
APPENDIX D. ORIGINAL LIST OF RESEARCH AREAS DISCUSSED
APPENDIX E. RESULTS OF HOMEWORK ASSIGNMENT
APPENDIX F. C. EDDIE CHRISTY, NETL PRESENTATION

ABBREVIATIONS

AEO	Annual Energy Outlook
CRI	Color Rendering Index
DOC	Department of Commerce
DOE	Department of Energy
EELA	Energy Efficient Lighting Association
EIA	Energy Information Administration (DOE)
HID	High Intensity Discharge
kWh	Kilo-watt Hour
LBNL	Lawrence Berkeley National Laboratory
LED	Light Emitting Diode
MOCVD	Metal Organic Chemical Vapor Deposition
NAICS	North American Industry Classification System
NEMA	National Electrical Manufacturers Association
NEMS	National Energy Modeling System
OIDA	Optoelectronics Industry Development Association
OLED	Organic Light Emitting Diode
R&D	Research and Development
SECA	Solid State Energy Conversion Alliance
SSL	Solid State Lighting
US	United States

1. Introduction

On November 13th and 14th, 2003, the Department of Energy (DOE) held a workshop to shape and prioritize its solid state lighting (SSL) research activities. The workshop included over 160 technology leaders from industry, universities, trade associations, research institutions, and national laboratories. These participants reviewed and discussed more than 40 research topics, to clarify technological research needs and objectives, and to prioritize tasks that will form the basis of future DOE solicitations.

This workshop represented the first annual meeting of DOE's newly established initiative to accelerate advances in SSL technology. The DOE is working with industry to accelerate the development of high efficiency, general illumination semiconductor technologies. The Department is targeting a product system efficiency of 50 percent with lighting that accurately reproduces the full spectrum of sunlight. The research challenges to achieve this mission are significant, but the potential benefits are tremendous. No other single lighting technology offers so much potential to conserve energy and, at the same time, improve the quality of our building environments.

A recent study found that if white-light SSL devices achieve the projected price and performance characteristics anticipated under an accelerated development scenario, 3.5 quadrillion BTUs of energy could be saved by 2025[1]. If realized, this market transformation would have the following impacts:

1) By 2025, SSL would displace light sources such as incandescent and fluorescent lamps, decreasing national energy consumption for lighting by 29 percent.

2) The cumulative energy savings from 2005 – 2025 would result in more than $125 billion dollars of savings to consumer electricity bills.

3) More than forty 1000 MW power plants would be deferred, contributing to a cleaner environment and a more reliable electrical transmission and distribution system.

4) The SSL market revenues in 2025 are projected to be as much as $10 billion/year nationally.

LEDs and OLEDs have made tremendous strides in recent decades improving performance and lowering costs. These advances have resulted in the development of niche and emerging applications for SSL technology, such as exit signs, traffic signals and runway edge-lights.[2] Just as this technology has evolved to supplant lighting technologies such as incandescent and fluorescent in colored light applications, SSL technology is now poised to spear-head a

[1] The energy savings potential of white-light SSL devices is estimated in the Department's recent publication, *Energy Savings Potential of Solid State Lighting in General Illumination Applications*, available on the SSL website in the publications section: http://www.netl.doe.gov/ssl/publications.html
[2] LED niche applications, and their energy potential savings, are detailed in the Department's recent publication *Energy Savings Estimates of Light Emitting Diodes in Niche Lighting Applications*, also available on the SSL website publications section.

revolution in the general illumination market. Government support of long-term, high-risk R&D to improve SSL performance and lower its cost will make it more competitive in this market.

1.1. SSL Operational Plan

The Department proposed a SSL operational plan that centers around two concurrent, interactive thrusts – (1) core technology research, involving academia, national laboratories, and research institutions, and (2) product development, involving manufacturers and allies that are individually or collaboratively capable of producing and marketing SSL products. Figure 1-2 illustrates this structure, and demonstrates the symbiotic relationship between the two pillars of the proposed operational plan. The core technology research (on the right) works to incubate, develop and advance SSL technology. The industry group (on the left) partners with members of the core technology group, bringing market and commercialization expertise, to develop SSL products for the market. Details of the operational plan were presented at the workshop by Eddie Christie from NETL, who's complete presentation appears in Appendix F of this report.

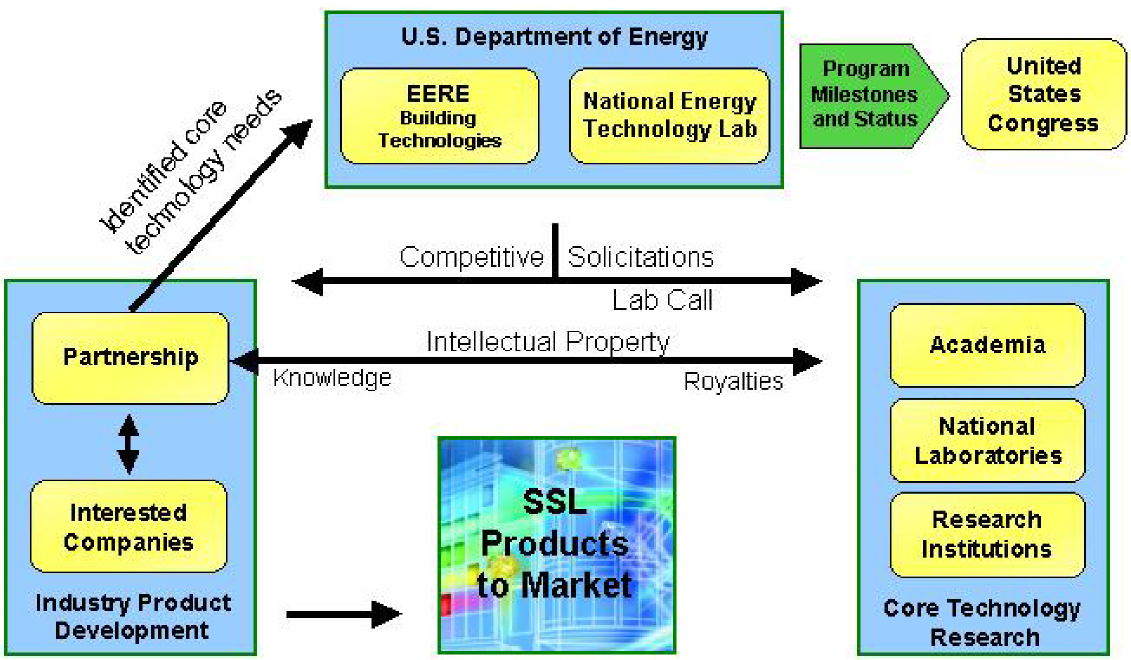


Figure 1-1. Structure of DOE SSL Operational Plan

The industry group's SSL Partnership will also provide input that shapes the Core Technology Research group's priorities, as well as be a ready recipient for intellectual property licensing. As SSL technologies develop, any R&D gaps identified will be addressed by the Core Technology Research group, enabling the SSL Partnership companies to continue their development process, while breakthrough technologies are developed concurrently.

The Partnership members will confer among themselves and recommend R&D needs to DOE program managers, who will, in turn, transfer these needs to the Core Technology Research group. In addition, DOE expects to solicit proposals from interested companies (or teams of companies) for product development, demonstrations, and market conditioning. DOE expects these proposals will include comprehensive work plans to develop a specific SSL product or product family. Since the ultimate goal is to manufacture energy efficient, high performance SSL products, each work plan should address the abilities of each participant or manufacturer throughout the development process. These offerors must not only have all the technical requirements to develop the desired SSL technology, but also must have reasonable access to manufacturing capabilities and targeted markets to move their SSL product from the industry laboratory to the marketplace.

The Core Technology Research group will provide the focused applied research necessary to advance SSL technology—research that is typically longer-term in nature and not the focus of sustained industry R&D investment. DOE will fund these research efforts at universities, national laboratories, and other research institutions through competitive solicitations. The Core Technology Research group will support the SSL Partnership by utilizing applied, problem-solving research to overcome identified technology barriers. The Department intends that work conducted by the Core Technology Research group would be widely-applicable and technology-gap solving, and will be offered to all Partnership members under a non-exclusive license. Core Technology Research projects will be peer-reviewed by government personnel, independent organizations, and the SSL Partnership.

1.2. Cones of Light

The common research goal of all the projects is to develop full spectrum, energy-efficient, white-light SSL sources for use in general illumination applications. Through its R&D initiatives in SSL, the Department is working to develop promising technologies, to capture significant energy savings for all lighting users. If the price and performance objectives are achieved, SSL technology will supplant conventional lighting technologies, including incandescent and fluorescent.

For the overall initiative to be successful in achieving the performance goals necessary for general illumination in the next decade, DOE will support R&D activities with a range of R&D partners in six key technical areas: quantum efficiency, packaging, lifetime, infrastructure, stability and control, and cost reduction. These six technical areas are illustrated in Figure 1.2.

Figure 1-2. The Department's Six Key Technical Areas

Each of these six key technical areas of research are briefly described below:

> Quantum Efficiency – the ability of solid state light sources to convert electrons into photons is governed by the material system and its associated internal quantum efficiency and external quantum efficiency. The internal quantum efficiency assesses a material's ability to convert electron-hole pairs into photon emissions. The external quantum efficiency measures the amount of light that leaves the semiconductor device and is available for collection and use.
>
> Longevity – research into materials and fabrication methods that guarantee performance in excess of 20,000 hours are sought. Research here focuses on advancing scientific understanding of the role of impurities, defects, crystal structure and other factors closely related to materials systems choices.
>
> Stability and Control – as time passes, the quality of the white-light emission may not remain stable. Basic material properties and semiconductor physics directly impact the evolution of photon wavelength, emission bandwidth and ultimately, color. For the future, emission spectrum approaching the spectral power distribution of natural sunlight is desired.
>
> Packaging – research focuses on SSL device packages that seal out moisture and oxygen, manage heat transfer, and protect optical material from UV degradation. These devices are then assembled into an optimized light delivery system.

Infrastructure – the installation, maintenance and supporting systems (power conversion) for the SSL products. Includes health and safety issues, information dissemination and training.

Cost Reduction – activities will concentrate on materials, methods and techniques to reduce production costs through aggressive development of suitable manufacturing technologies and technical elements of production.

1.3. Activities Presently Funded

At the workshop, the Department published a portfolio of projects that are currently funded through the SSL R&D portfolio[3]. In total, there are twenty-nine projects listed, totaling more than $31 million in cumulative government and industry investment. Figure 1-3 presents these twenty-nine projects, grouped in different disciplines within the first level of the pyramid, Applied Research. As projects are completed, technology gaps are overcome and efficacy improves with other performance attributes. Projects then will appear at higher levels of the pyramid (Product Development, Demonstration and Market Conditioning).

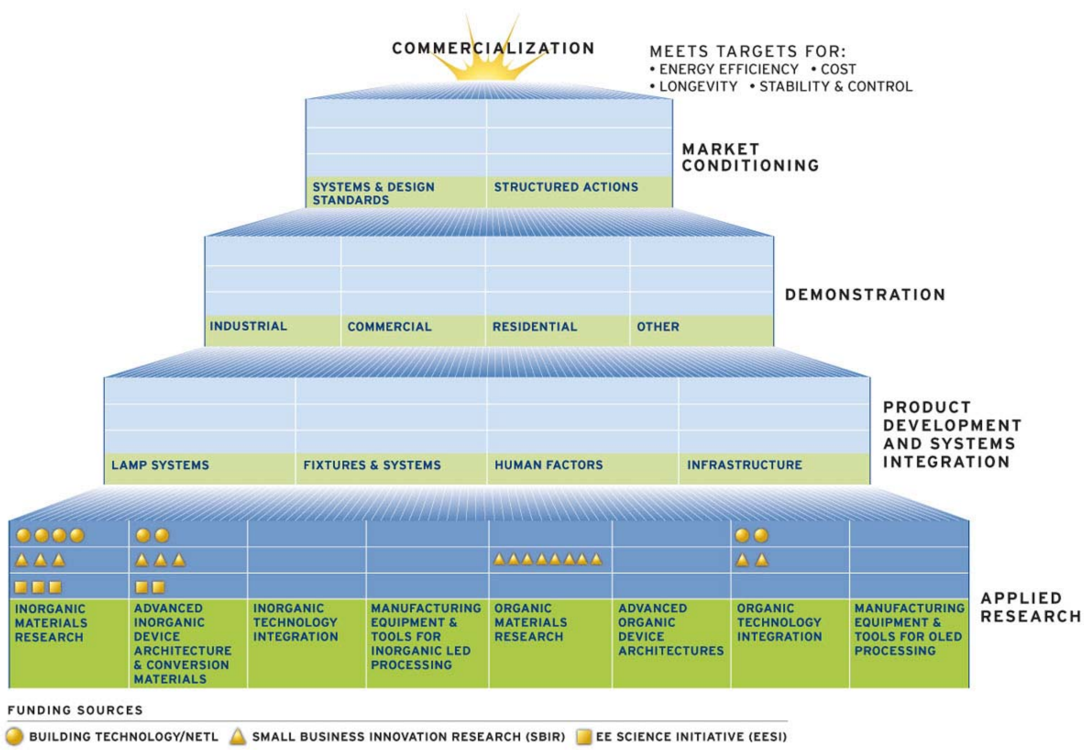


Figure 1-3. Pyramid of Technology Development (Applied Research Focus in 2004)

[3] The report, *Project Portfolio: Solid State Lighting*, is available on the Department's SSL web site: http://www.netl.doe.gov/ssl/PDFs/SSL_Portfolio.pdf

This level of investment associated with these twenty-nine projects shown in Figure 1-3 is only a fraction of the investment necessary for SSL to achieve its projected price and performance attributes, saving energy and retaining the technical leadership of the United States.

At the workshop, the Department presented a very detailed, comprehensive, item-by-item GANTT chart (not in this report), dissecting the major topics of the research agenda into more than 300 elements. This multi-year plan is currently being revised, based on input received from workshop participants during the November 2003 meeting. According to this plan, over a ten year period, approximately $500 million of government investment, matched with $500 million of private sector investment, is necessary to realize the price and performance objectives. This estimate of the total research investment has been collaborated by two independent estimates performed by private industry sources.

As stated earlier, the cumulative level of effort starting in 2000 and extending through all contracts listed in the Project Portfolio report is $31 million, of which approximately $25 million are contributed by the DOE. Looking across the projected $500 million of government investment, this represents 5% of the estimated investment necessary to achieve the price and performance objectives that will save energy and improve lighting quality. Further, since this is Applied Research, the present portfolio of projects may not be successful in completely solving the technology gaps identified in these tasks. Thus, tasks that are funded are not necessarily completed.

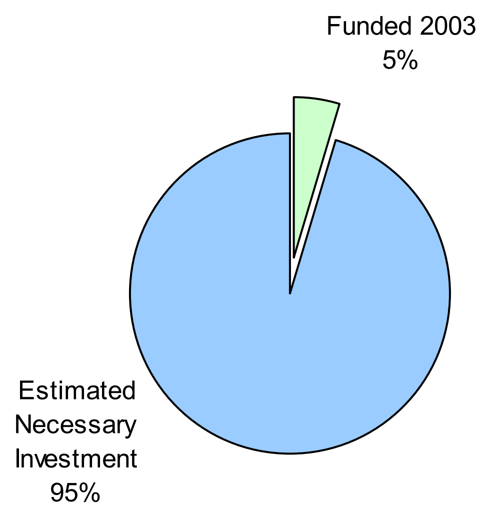


Figure 1-4. Cumulative SSL R&D Funding in 2003 as % of Total Estimated Necessary Investment

2. Workshop Presentations

The workshop had four primary goals: to educate the R&D community on DOE's vision for SSL technology; to update the R&D community on broad-based government funding opportunities related to SSL; to communicate current successes and challenges for SSL from an industry perspective; and to prioritize the SSL R&D topics to insure a focused, quality research agenda. All the presentations given at the workshop are available on the Department's SSL website: http://www.netl.doe.gov/ssl/materials.html

David Garman, Assistant Secretary for Energy Efficiency and Renewable Energy, launched the workshop with a keynote address highlighting the importance of SSL technology. Mr. Garman discussed creating a focused partnership between government and industry, to accelerate SSL technology with the potential to reduce energy consumption, to create affordable long-lasting general illumination technology, to strengthen U.S. leadership in this critical technology area, and to provide the necessary infrastructure (people and policy) to accelerate market adoption. Indicators of success would be two quads of energy per year displaced, a market price of $3 per kilolumen, and the creation of new forms of lighting systems that improve our quality of life.

Mr. Garman released two studies, and outlined the reasons why the United States needs a national research initiative in SSL:

- To maintain its leadership position in SSL, it must compete with other countries' government funding efforts.
- White-light sources present a higher risk R&D investment that industry is unlikely to fund in the near term.
- The projected energy savings potential for U.S. consumers is significant.

Mr. Garman also provided the workshop participants with the goal of the DOE's SSL R&D portfolio:

> *By 2015, develop advanced solid state lighting technologies that, compared to conventional lighting technologies, are much more energy efficient, longer-lasting, and cost-competitive by targeting a product system efficiency of 50 percent with lighting that accurately reproduces sunlight spectrum.*

Jim Brodrick, also from the Department of Energy, supported these remarks, and presented the Department's mission statement for the SSL R&D portfolio:

> *Guided by a government-industry partnership, the mission is to create a new market for high-efficiency, general illumination products through the advancement of semiconductor technologies, to save energy and enhance the quality of the lighted environment.*

Together, the portfolio goal and mission statement clearly enunciate the Department's motivation behind its support of research in SSL technology. Figure 2-1 illustrates the funding sources

(Offices and solicitations) which are available at the DOE to support this research. The level of technical maturity and the particular actions proposed by the researcher place a proposal on the chart shown below.

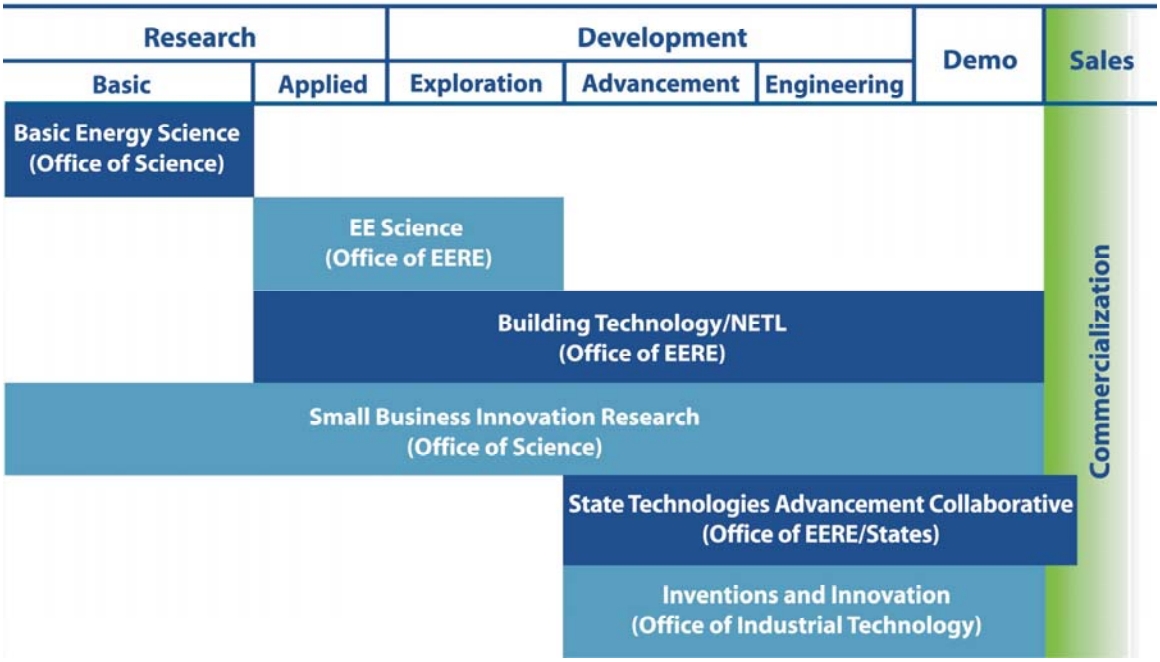


Figure 2-1. Stages of Product Development Mapped to DOE Funded R&D Programs

These Offices' solicitations are typically conducted on an annual basis. Representatives from some of these Offices and industry spoke on their involvement or relationship to DOE's overall SSL R&D portfolio. Summaries of these presentations follow, and web-links to these programs are included in Appendix B of this report.

2.1. Government Support of SSL R&D

Representatives from Basic Energy Sciences (BES) of DOE, the National Science Foundation (NSF), the National Institute of Standards Technology (NIST) Advanced Technology Program (ATP), and the Defense Advanced Research Project Agency (DARPA) outlined their investments in SSL and related materials and device technologies. Each of these agencies provides significant funding to SSL R&D or related topics. A brief summary of each of the presentations is provided below. Complete copies of all of the presentations given at the workshop can be found on the Department's SSL website: http://www.netl.doe.gov/ssl/

2.1.1. Dr. Harriet Kung, Office of Basic Energy Sciences (BES)

The Office of Science- BES program is one of the Nation's largest sponsors of basic research in materials sciences, chemistry, geosciences, and aspects of biosciences related to energy resources, production, conversion, efficiency, and use. Dr. Kung explained that BES supports research in more than 150 academic institutions and 13 DOE laboratories, as well as several world-class scientific user facilities. Based on a BES advisory committee study summarizing the status of energy supply and use, BES has identified SSL as a proposed research direction. The complete report can be found at: http://www.science.doe.gov/bes/BESAC/reports.html BES research in SSL has the following objective: To obtain a fundamental understanding of basic physics and chemistry of new materials, both organic and inorganic, which could be used for solid-state lighting and related applications. In line with this SSL objective, Dr. Kung discussed the four major areas of current research currently underway:

1) Structures, properties, and defect physics of wide bandgap semiconductors (AlGaInN Blue and UV LED materials)
2) Quantum wires and dots (nanoscale technology)
3) Theory and modeling of doping on electronic structures
4) Electroluminescent organic materials and devices

A complete outline of BES programs can be found at http://www.science.doe.gov/bes

2.1.2. Dr. Vasundara Varadan, National Science Foundation

The NSF's mission is "enabling the nation's future through discovery, learning, and innovation." Dr. Varadan stated that the main entity within NSF supporting LED and OLED research is the Electrical and Communication Systems (ECS) division. A core program within ECS is the Electronics, Photonics, and Device Technologies (EPDT) effort. The EPDT funds a broad range of materials and device R&D focused on the fundamental science of LED and OLEDs devices. More information can be found by contacting-

Dr. Filbert Bartoli, Program Director
Optoelectronics, Photonics
Electronic, Photonics, and Device Technologies

or,

Dr. Usha Varshney, Program Director
Photovoltaics, Organic Electronics, Power Electronics
Electronic, Photonics, and Device Technologies

2.1.3. Dr. Michael Schen, National Institute of Standards and Technology

Dr. Schen, Group Leader, Electronics and Photonics in the Information Technology and Electronics Office at NIST discussed the Advanced Technology Program (ATP) at NIST. The ATP program is designed to accelerate the development of innovative technologies for broad national benefit through partnerships with the private sector; bridging the gap between the laboratory and the marketplace. Dr. Schen explained that ATP has funded over seven hundred programs for a total of US$2.1 billion in technology areas including biotechnology (20%), manufacturing (discrete) (11%), information technology (23%), electronics/photonics (25%), and advanced materials and chemistry (21%). ATP is currently supporting several projects directly related to SSL technologies:

Roll-to-Roll Processing to Enable Organic-Electronics Revolution
Lead Institution: General Electric Company, Global Research

Manufacturable Solid-State Lighting
Lead Institution: Cree Lighting Company

Bulk GaN and Homoepitaxial Device Manufacturing
Lead Institution: General Electric Company, Global Research

Dr. Schen explained that there are two ways to apply to the ATP program: as an independent company (plus subcontractors), or as a consortium (formal alliances of companies, academia, with subcontractors). And, to ensure marketable product focus, industry shares half or more of the costs of the project. Project evaluation criteria are weighted 50:50 between scientific & technological merit, and the potential for broad-based national economic benefits. Further information can be found at www.atp.nist.gov

2.1.4. Dr. Douglas Kirkpatrick, Advanced Technology Office, DARPA

Dr. Douglas Kirkpatrick, from the Advanced Technology Office at DARPA, broadened the perspective on SSL. He described the history of lighting, emphasizing that solid state lighting should learn important lessons from the development of other revolutionary general illumination white-light sources, including incandescent, fluorescent, high-intensity discharge, and ceramic metal halide lights. Dr. Kirkpatrick noted that the existing lighting technologies are not standing still – either in price or performance - and have the advantage of large amounts of supporting infrastructure behind them.

Dr. Kirkpatrick challenged the notion of a rapid adoption of SSL, and proposed a longer horizon (2030) for widespread adoption as a general illumination source. In addition, he outlines a less “device-centric” approach, focusing more on near-term market entry with the following key challenges:

- Fixture integrated thermal designs
- “Socket compatible” power supplies
- Multi-chip modules integrating lamp systems and controllers

Regarding light quality, the key to this market share, Dr. Kirkpatrick discussed the use of the CRI index (with 8 measurement wavelengths) and indicated that this measure did not work well for DARPA as a good measure of broad band lighting quality. Instead, he proposed a “percentage deviation from daylight” measure as an alternative. He also thought that the unit of a lumen, while a precise measurement at 555 nm, does not reflect broader band human perception; equally perceived brightness does not equal equally perceived lumens.

2.2. Trade Association Support

2.2.1. Dr. Charles Becker, Next Generation Lighting Industry Alliance / GELCore

Dr. Charles Becker introduced the Next Generation Lighting Industry Alliance (NGLIA), which at the time of workshop was comprised of Cree, Inc., Corning, Inc., Eastman Kodak Company, General Electric Company, GELcore, LLC, Lumileds Lighting, LLC, Osram Opto

Semiconductors, and Philips Electronics North America Corporation. The primary mission of the NGLIA is to accelerate SSL development and commercialization through government-industry partnerships. This includes supporting inorganic and organic based SSL research through:

- Public advocacy for SSL and the Next Generation Lighting Initiative (draft Energy Bill)
- Promotion and support of DOE's ongoing assessment of SSL potential, the state of SSL technology, and DOE's SSL R&D Portfolio
- Facilitation of communication between NGLIA members and other parties with a substantial interest in SSL and the Next Generation Lighting Initiative

The NGLIA is separate from, but allied with the NEMA SSL section (NGLIA does not require NEMA membership). All members have one voting member on Board of Directors, which annually appoints a Chair and Vice Chair. Companies interested in NGLIA should contact Mr. Kyle Pitsor at kyl_pitsor@nema.org

2.2.2. Dr. M.R. Pinnel, U.S. Display Consortium

The USDC is an industry consortium focused on flat panel display manufacturing and infrastructure. The consortium is comprised of 17 member companies and is supported by the US Army Research Laboratory. Dr. Pinnel indicated that projects supported by USDC serve to enhance manufacturing capability for microdisplays, projection systems, OLEDs and flexible substrate technology. The 2003 USDC technical programs support 35 projects at $30.2 million with more than 50% industry match. In addition to funding research, the USDC also:

- Identify and address supply chain gaps by funding R&D projects.
- Promote members in technical and financial forums.
- Provide valuable information, such as technology roadmaps, technical trends and market information
- Foster international cooperation among display consumers, display makers and tools and materials suppliers.

Finally, Dr. Pinnel highlighted many of the technical differences between flat panel displays and general illumination that OLED technology will need to address. Specifically, he divided display and SSL lighting research into three categories: (1) parameters unique to displays - including fine patterning, contrast, pixel switching, and color saturation (NTSC standard); (2) parameters unique to SSL – specifically white light with high CRI, and uniformity over a very large area; and (3) parameters in common – including cost, efficacy, stability, lifetime, and materials.

2.2.3. Arpad Bergh, Optoelectronic Industry Development Association

Arpad Bergh offered a brief tutorial on LED light sources, discussing the major challenges, introducing a variety of niche applications, and estimating the energy savings potential. The major challenges to SSL from OIDA's perspective were discussed: (1) develop low cost, variable color RGB LED lamps; (2) achieve a 120 lm/W green LED; and (3) the need for different "socket" infrastructure to support power delivery and heat management. Arpad Bergh also anticipates that compact fluorescent lamps (CFLs) will replace incandescent bulbs first in the marketplace, which will then be replaced by SSL – raising the performance bar necessary for market penetration in these applications. Arpad Bergh expressed reservations that the previous OIDA roadmap efficiency and cost targets were achievable, given current technology and likely breakthroughs. In particular, other foreign research consortiums have set less aggressive efficacy goals (100-150 lumens per watt versus 180-250 lumens per watt).

2.3. Technical Perspectives

2.3.1. Dr. Michael Krames, Lumileds

Dr. Krames offered a comprehensive overview of the current status and recent progress of LED technology including efficiencies, phosphor conversion, fabrication, light extraction, power packages, and lifetimes. Challenges for LED-based SSL are highlighted by comparison with current manufacturing and R&D performance. The current state-of-the-art in LED external quantum efficiencies are UV (405nm, 43%), blue (460nm, 35%), green (540nm, 5%), amber (590nm, 10%), and red (630nm, 50%). The major challenges for LED-based SSL identified by this presentation are:

- Cost ($/klm)
- Green LED internal quantum efficiency
- Link between the chip/level-1 package and existing sockets
- Improved manufacturing technology (epitaxial reactors and in-situ tools)

Overall, the industry is meeting its efficacy goals, compared to the 2002 OIDA roadmap goals, but needs to reduce costs dramatically. The roadmap goals also dictate an increase in input power density. However, some prototypes constructed which have a higher power density led to a decrease in efficacy, indicating a tradeoff between cost and efficacy.

Dr. Krames highlighted a key driver for cost reduction as material improvements (epitaxial, phosphors, substrates), leading to the ability to drive the LEDs harder and extracting more lumens per square millimeter.

2.3.2. Dr. Michael Hack, Universal Display Corporation

Dr. Hack offered the participants an overview of the current status and recent progress of OLED technology including efficiencies, fabrication, out-coupling, and lifetimes. With regards to SSL technologies, OLEDs offer several potential advantages – transparency, flexibility, and low-cost manufacturing. The discovery of phosphorescent OLEDs in 1997 is highlighted as a key accelerator for OLED technology into the flat panel display market, and forms the basis for OLED-based general illumination. Dr. Hack highlighted the different OLED performance characteristics between general illumination and flat panel display technologies. General illumination is driven by efficiency, whereas as flat panel displays are more strongly dependent on contrast, pixel switching and color saturation.

Key challenges identified by Dr. Hack for the use of OLEDs in general illumination are:

- High-efficiency (~100% internal quantum efficiency) RGB phosphorescent materials
- Improved out-coupling efficiency from 20% to 50%
- Reduced drive voltages (improved transport and interface layers)
- Increased lifetimes

2.4. Overview of Projects, and Organization of the SSL Portfolio

After lunch, Douglas Brookman, the workshop facilitator, asked the participants to create a vision of the future of solid state lighting in 2015. After much discussion and feedback, six primary vision elements were distilled from the group:

- Develop entirely new products based on SSL's unique attributes
- Reduce per capita energy consumption thru efficient lighting
- Create affordable, high quality, long lasting technology for general illumination, e.g. 50% market penetration
- Strengthen U.S. leadership in SSL—materials, products, & markets
- Promote sustainability & environmental improvement thru SSL
- Provide necessary infrastructure to support SSL adoption & use

DOE's solid state lighting portfolio is working toward these visions.

2.4.1. Dr. James Brodrick, Department of Energy

Dr. Brodrick is the lead manager for the SSL R&D portfolio within the Building Technologies Program at DOE. Dr. Brodrick's talk provided an overview of the SSL lighting portfolio at DOE, and potential impact of SSL on energy consumption. At the present time, lighting uses 8.2 quads (42% incandescent, 41% fluorescent, and 17% HID) of primary energy. The first-costs for today's principal light sources indicate the degree of the challenge facing SSL in the marketplace:

Incandescent	0.60 $/klm (klm is an abbreviation for kilolumens - 1000 lumens)
Fluorescent	0.73 $/klm
HID	1.27 $/klm
LED	350.00 $/klm

Dr. Brodrick presented to the group an estimate of one to three quads of primary energy savings potential, depending on the price and performance improvements achieved in white-light, general illumination SSL devices. From the Department's perspective, the principal benefits of SSL are:

- Energy savings
- Improved service and features

- United States employment
- Durability
- Use of less hazardous materials

Dr. Brodrick also introduced the Department's Pyramid of Technology Development (see figure 1-3). This represents DOE's vision for the evolution of funding priorities over time, based on four distinct steps: applied research, product development and systems integration, demonstration projects, and market conditioning. The current SSL R&D portfolio is focused on funding for applied research, but Dr. Brodrick discussed that it will evolve overtime as technical hurdles are overcome and SSL devices become ready for commercialization. Finally, Dr. Brodrick also gave brief project summaries of the SSL R&D activities currently supported by the Department.

2.4.2. C. Edward Christy, National Energy Technology Laboratory

C. Edward Christy from the National Energy Technology Laboratory presented a talk on the proposed SSL portfolio organization. For convenience, this presentation is included in this report as Appendix F.

Mr. Christy focused on a description of the details of the structure of the proposed operational plan for the Department's SSL R&D portfolio. He outlined the proposed operational plan including the following key ingredients, based roughly on the Solid State Energy Conversion Alliance (SECA) model:

Emphasis on competition for research funds
Cost (and risk) sharing between Government and research partners
Partners involved in planning and funding
Targeted research for a focused need
Innovative Intellectual Property (IP) provisions
Open information and process
Success determined by milestones met, and products developed

Congress appropriates funding through the DOE, which in turn works with NETL to manage the program and solicitations. Research or national lab institutions compete for solicitation funds based on research priorities set at this workshop, with or without cost sharing. Interested companies compete for funding with a cost-shared proposal focused on developing a marketable product.

The Department is interested in developing an active industry / government SSL partnership to (1) prioritize research needs, (2) provide technical reviews of projects, and (3) organize an annual SSL research planning workshop. Addressing the issue of intellectual property, Mr. Christy indicated that the Department intends to file a request for an 'exceptional circumstances determination' under the Bayh-Dole (Patent and Trademark Law Amendments Act) to accelerate SSL development. This determination would allow core developers easier access to manufacturers, and give manufacturers the opportunity to negotiate non-exclusive, first year licensing.

2.4.3. Graphical Representation of Proceedings

At the proceedings of the first day of the workshop, a visual artist captured key phrases, concepts and ideas, and developed those into large colorful murals representing what was discussed. These five illustrations are included in Appendix C of this report.

3. Day Two – Breakout Group Discussions

The balance of the workshop focused on establishing priorities and defining the individual R&D program tasks. Participants were split into two groups – LEDs (~80 participants), and OLEDs (~40 participants). Each group was asked to evaluate and prioritize their respective research tasks and subtasks. In the morning, the topic was "Applied Research" – critical materials, device, and system research that would, in time, enable creation of products that meet the SSL R&D goals. In the afternoon, the topic shifted toward "Product Development and Systems Integration" – the development work that would enable prototypes of complete products and systems to be realized.

The Department's approach for engaging participants in the planning process for these topic areas, tasks and subtasks at the workshop proceeded as follows:

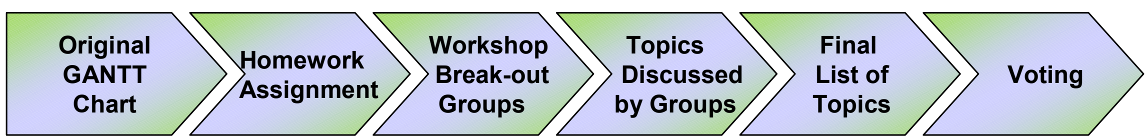


Figure 3-1. Linear Representation of SSL R&D Topics Discussion and Voting

An initial list of research topics, tasks and subtasks was distributed, based on previous road-mapping activities (see Appendix D for original list distributed). This list was discussed, by repeatedly asking the group the following questions:

- Which tasks or subtasks should be a focus of R&D efforts over the next ten years?
- Are these tasks and subtasks well-described? Would you change any language describing an task or sub-task?

Through this process, much of the original language changed, tasks and subtasks were re-shuffled, dropped or amended. A key theme regarding language was to make it broad enough that new approaches or ideas would not be excluded from funding because of terminology.

Finally, the group was asked to force-rank and prioritize the task and subtasks agreed upon by a show of hands. After extensive discussion of each task and sub-task, where viewpoints on the prioritization were discussed, the prioritization was done within the following parameters:

- High ranking tasks should be a high priority in the near term – two to three years. Thus a low rank does not mean that a task is not or will not eventually be critical, only that it does not need to be immediately funded.
- Research that is occurring under other auspices (for example, display or semiconductor technology) should be ranked as a low priority, to conserve DOE resources
- A high rank should indicate a participant's view of the importance or criticality of the task or sub-task relative to the SSL R&D goals.

There was some discussion of conflicting goals – for instance, which is more important – reliability, spectrum, cost (manufacturability), or efficacy? This issue was not directly resolved, but the underlying trend seemed to be that there are a few attributes that SSL must have in order to be considered in the lighting market (for instance, reliability) and other attributes that determine whether it will be competitive against conventional technologies (for instance, cost).

In general, for both LEDs and OLEDs, the materials related tasks dominated the priority ranking, followed by device architectures, packaging, and manufacturing. The following pages have a finalized task description and ranking from the LED and OLED breakout sessions.

3.1. Light Emitting Diodes (LEDs)

For the two topic areas – applied research and product development and systems integration – a summary chart identifies the highest ranked options for each topic (where the break-out groups performed the ranking). Within each topic area, a table shows the force-rank voting of the break-out group prioritization. Following that table, each research task and sub-task is described in detail to expand on the language and meaning.

Topical Area 1: LED Applied Research

Table 3-1 provides a summary of the voting on tasks and subtasks by the approximately 80 participants in the LED breakout session. This is the final list that was agreed to, and the relative ranking of the tasks and subtasks. Note that task level ranking is relative to each other, but sub-task levels are only relative within a given task.

Table 3-1. Group Prioritization of R&D Tasks and Subtasks: LED Topic Area 1

Task and Subtask	Rank*
Task 1.1 Inorganic Materials Research	**High**
1.1.1 Novel substrates, buffer layers, and wafer engineering	Medium
1.1.2 High efficiency visible and near UV semiconductor materials for LED based general illumination technology	High
1.1.3 Reliability and defect physics for improved LED lifetime	Low
Task 1.2 Advanced Inorganic Device Architecture and Conversion Materials	**High**
1.2.1 Advanced architectures and high power conversion efficiency emitters	High
1.2.2 High temperature, efficient, long-life phosphors, luminescent materials for wavelength conversion and encapsulants	High
Task 1.3 Inorganic Technology Integration	**Medium**
1.3.1 Innovative, high-flux reliable packages and packaging materials for point source and distributed LED source building block technology	High
1.3.2 Physical, chemical, and optical models for the epitaxial process and the LED device	Low
Task 1.4 Manufacturing Equipment and Tools for Low-Cost High-Yield Inorganic LED Processing	**Low**
1.4.1 In-situ diagnostic tools for the epitaxial process	High
1.4.2 Low maintenance, low-cost, high-efficiency reactor designs for efficient source utilization	Medium
1.4.3 Die separation, chip shaping, and wafer bonding equipment	Medium

* Task rankings are relative to each other. Subtask rankings are within a task.

Task 1.1 Inorganic Materials Research

The greatest potential for efficiency improvement exists in materials research. For example, there is still significant opportunity in the internal quantum efficiency (IQE) of inorganic devices that emit in the green region.

Table 3-2. Group Prioritization of Inorganic Materials Research

Task 1.1 Inorganic Materials Research	High	Med	Low
1.1.1 Novel substrates, buffer layers, and wafer engineering • Large area, low defect density bulk substrates • Low defect density buffer layers	15	25	15
1.1.2 High efficiency visible and near UV semiconductor materials for LED based general illumination technology • Efficient, yellow-green emitters • Efficient UV emitters • P-doping and structures • High purity process materials	40	13	1
1.1.3 Reliability and defect physics for improved LED lifetime • Device and dopant interactions with defects • Characterization of defects and dopants • Device, package level reliability	0	19	37

For subtask 1.1.1, novel substrates, buffer layers, and wafer engineering, the focus is on substrates that would lead to more efficient LED devices. Current nitride and phosphide material quality has been determined insufficient to achieve improved efficiency and cost reduction goals. Basic materials research is necessary, and substrate and buffer research are treated independently.

For subtask 1.1.2, high efficiency visible and near UV (>380nm) semiconductor materials for LED based general illumination technology, the focus is on devices with emission in the near UV (>380nm). Research can include raw source (epimaterials) materials and growth. Innovations in green (520-560 nm) and yellow (560-600 nm) emitter materials may well be necessary to achieve white light efficiencies greater than 100 lumen/watt. State-of-the-art green and yellow emitters have external quantum efficiencies of only 5-10%.

For subtask 1.1.3, reliability and defect physics for improved LED lifetime, the focus for this subtask is on research at the device level resulting in high efficiency LEDs. Novel low defect-density substrates or buffer layers are needed for high-drive current LEDs to maximum the number of lumens generated per square millimeter, as well as enable high efficiency directional emitters like laser diodes. Furthermore, white light general illumination applications impose stringent lifetime requirements on brightness uniformity, color rendering consistency, and color temperature stability. The current generation of white LEDs are not able to meet these requirements due limitations in materials and packaging, as well as the basic understanding of how material quality effects device performance. In addition to novel substrate, buffer layers and wafer engineering (above in subtask 1.1.1), new analytical and modeling approaches are needed to advance the understanding of these efficiency-reducing impacts.

Task 1.2 Advanced Inorganic Device Architecture and Conversion Materials

Advanced device architectures that optimize both transport and optical properties will be needed to achieve longer-term efficiency goals in excess of 150 lumens/watt and meaningful energy savings. Traditional LED designs will rely on novel fabrication methods, including chip-shaping, texturing, laser liftoff, etching, and novel metallization for improved efficiency. More advanced light emitting designs will include micro cavities, photonic lattices, quantum dots, edge-emitting and vertical-cavity laser structures.

Table 3-3. Group Prioritization of Advanced Inorganic Device Architecture and Conversion Materials

Task 1.2 Advanced Inorganic Device Architecture and Conversion Materials	High	Low
1.2.1 Advanced architectures and high power conversion efficiency emitters • Chip scaling • Multi-color chip • Lasers and directional emitters • Contacts	20	29
1.2.2 High temperature, efficient, long-life phosphors, luminescent materials for wavelength conversion and encapsulants • Efficient phosphors / luminescent materials • Novel phosphor / luminescent material synthesis and blends • Encapsulants, mounting materials	29	20

Generally, break-out group participants agreed that both these subtasks are equally important and should be developed concurrently.

For subtask 1.2.1, advanced architectures and high power conversion efficiency emitters, research will focus on the discrete LED itself, at the chip level, with no bias to a particular scheme or method to achieve white light. Research here is generally higher risk and assumes that other advances already occurred. The group deleted the terms “sub-threshold” and “integrated” as descriptors for this subtask.

For subtask 1.2.2, high temperature, efficient, long-life phosphors, luminescent materials for wavelength conversion and encapsulants, this subtask focuses on all technology that down-convert to the visible spectrum, including quantum dots for LEDs. Within down-conversion approaches to white light generation, more efficient (>95%), stable (100,000 hrs), high-temperature (>150 degrees C), environmentally friendly phosphors with no dissipative optical absorption or scattering will need to be developed. Novel approaches are also needed in the synthesis and processing of novel conversion materials, including, but not limited to nanocrystalline semiconductors, photonic lattices, quantum dots, organic coordination-compound phosphors, phosphor blends or slurries, and coated phosphors.

High-drive, high-lumen output LED devices place demanding performance characteristics on encapsulation materials. Future encapsulation materials for high-power general illumination "lamps" will need to have an index > 1.6, high transmission (>80%) through thick layers throughout the visible spectrum (440-650 nm), UV filtering and resistance, low H_2O permeability for up to 100,000 hours, and withstand high processing and operation temperatures (100-150 C).

Task 1.3 Inorganic Technology Integration

Present day, high-volume, low-cost LED packaging was designed for low current (<20 mA) and power (<5 mW) applications. Until eventual and significant improvements in efficacy are achieved, near-term general illumination LED technology will need to accommodate up to 1000 Watt/cm^2 and maintain chip and phosphor temperatures of no more than about 200ºC. New low-cost packaging architectures are needed with low chip-lamp thermal resistances (<25ºC/W), able to handle input powers >10 W, and allow integration with novel light extraction approaches.

Table 3-4. Group Prioritization of Inorganic Technology Integration

Task 1.3 Inorganic Technology Integration	High	Low
1.3.1 Innovative, high-flux reliable packages and packaging materials for point source and distributed LED source building block technology • High flux single emitter packages • High flux multiple emitter packages • New packaging architectures	42	11
1.3.2 Physical, chemical, and optical models for the epitaxial process and the LED device • Optoelectronic simulation, analysis, and validation • High flux multiple emitter packages	11	42

For subtask 1.3.1, innovative, high-flux reliable packages and packaging materials for point source and distributed LED source building block technology, the focus is on existing form factors (i.e., point and linear sources). Research areas include novel materials such as carbon nanotubes to achieve thermal transfer. Since packaging is 50% to 80% of the final device cost, this subtask area is critical in achieving significant cost reductions in manufacturing.

For subtask 1.3.2, physical, chemical, and optical models for the epitaxial process and the LED device, the subtask focuses on theoretical models and tools to help increase knowledge and understanding of the LED device. This includes reactor simulations and chemical modeling. Participants generally gave this task a low ranked priority.

Task 1.4 Manufacturing Equipment and Tools for Low-cost, High-Yield Inorganic LED Processing

Even with major advances in materials, device and packaging technologies on the immediate horizon, the cost to manufacture high brightness, good quality white LEDs is more than several orders of magnitude too high. An ordinary one kilolumen incandescent lamp costs less than \$0.25 to produce, whereas an equivalent white-light LED lamp is several hundred dollars. To overcome this major hurdle to widespread market penetration, innovative high-volume, high-yield manufacturing equipment and tools are needed.

Table 3-5. Group Prioritization of Manufacturing Equipment and Tools

Task 1.4 Manufacturing Equipment and Tools for Low-Cost High-Yield Inorganic LED Processing	High	Med	Low
1.4.1 In-situ diagnostic tools for the epitaxial process • E.g., growth rate, temperature monitor • Film stress monitors • Dopant, composition monitors	27	10	7
1.4.2 Low maintenance, low-cost, high-efficiency reactor designs for efficient source utilization • E.g., vertical, horizontal designs • Novel designs	8	18	17
1.4.3 Die separation, chip shaping, and wafer bonding equipment • Separation tools • Chip shaping tools • Wafer bonding tools • Lift-off process tools	8	17	20

The group elected to delete one subtask from task 1.4 - Etching, Metallization, and Passivation Equipment. It was agreed that standard wafer level processing equipment and tools already exist, and therefore the subtask did not need to be listed.

For all three of the remaining subtasks, the participants agreed that the material was self-explanatory, and required no further explanation. However, it was noted that for subtask 1.4.3, die separation, chip shaping, and wafer bonding equipment, the group believed that die separation technology was the most critical aspect of this subtask.

The most demanding and costly manufacturing process steps are all related to the epitaxial growth of the LEDs using MOCVD reactors. In general, the yield from today's reactors are relatively low (~60%) in comparison with the silicon-chip industry. For more demanding white light applications in the future, where specifications on color rendering index and color temperature may narrow, improvements in reactors and associated manufacturing processes will be necessary. A concerted effort between epitaxial growth scientists, equipment manufacturers, chemical source suppliers, and modeling and simulation specialist is needed. In addition, in-situ diagnostic tools able to accurately measure growth rates, wafer temperature, strain evolution, surface morphology, alloy and doping concentrations will be extremely valuable in reducing manufacturing costs.

Topical Area 2: LED Product Development and Systems Integration

Table 3-6 provides a summary of the voting on tasks and subtasks for the product development and systems integration topical area.

Table 3-6. Group Prioritization of R&D Tasks and Subtasks: LED Topic Area 2

Task and Subtask	Rank*
Task 2.1 Inorganic Lighting Systems	**High**
2.1.1 Luminaire design, materials	High
2.1.2 Secondary optics	Medium
2.1.3 Hybrid LED and OLED systems	Low
2.1.4 High efficiency, reliable, intelligent electronics	High
Task 2.3 Human Factors	**Medium**
2.3.1 Human comfort and workplace productivity	Low
2.3.2 Human factors metrics / definitions	High
Task 2.4 Infrastructure	**Low**
2.3.1 Socket compatibility and other	High
2.3.2 Building intelligence	Low

* Task rankings are relative to each other. Subtask rankings are within a task.

The group unanimously voted to delete task 2.2 Inorganic Fixtures and Systems from the activities under product development and system integration. This task contained two subtasks - subtask 2.2.1 high-reliability, programmable power supplies and drive electronics, and subtask 2.2.2 low thermal impedance, smart high-flux solid-state luminaires. Subtask 2.2.1 was incorporated into subtask 2.1.4. Subtask 2.2.2 was deleted.

Task 2.1 Inorganic Lighting Systems

The following table provides the break-out group's ranking of these four subtasks within the Inorganic Lighting Systems task.

Table 3-7. Group Prioritization of Manufacturing Equipment and Tools

Task 2.1 Inorganic Lighting Systems	High	Med	Low
2.1.1 Luminaire design, materials	38	3	0
2.1.2 Secondary optics	1	12	0
2.1.3 Hybrid LED and OLED systems	0	4	43
2.1.4 High efficiency, reliable, intelligent electronics	5	18	1

For subtask 2.1.1, luminaire design, materials (including thermal management), the group ranked this as a high priority. Participants recognize that thermal management of LEDs is critical to its performance. There will always be a heat sink issue because the heat produced by an LED is conductive. Therefore, this subtasks involves design of the luminaire including design for thermal management.

For subtask 2.1.2, secondary optics, the focus is on the optical issues at the system, or luminaire, level. Optical issues at the chip level are addressed elsewhere.

For subtask 2.1.3, hybrid LED and OLED systems, the group did not support making this activity a priority at this time. Activities in this area are more applied for now, and encompasses all possible solutions, including both discrete and non-discrete designs.

For subtask 2.1.4, high efficiency, reliable, intelligent electronics, participants noted that there are already several companies doing this. However, this subtask was given a medium importance, as it may provide a short-term "band-aid" fix for technical challenges. Participants voted to add subtask 2.2.1, high-reliability, programmable power supplies and drive electronics, which was deleted from task 2.2, to this subtask.

Task 2.3 Human Factors

The following table provides the break-out group's votes on the two subtasks contained within the Human Factors task.

Table 3-8. Group Prioritization of Human Factors Subtasks

Task 2.3 Human Factors	High	Low
2.3.1 Human comfort and workplace productivity	11	26
2.3.2 Human factors metrics / definitions	26	11

For subtask 2.3.1, human comfort and workplace productivity, activities include how to use SSL to improve productivity. Although no definitive study exists on SSL's impact on productivity, the group agreed that the industrial sector would likely adopt this first because they are concerned with productivity.

For subtask 2.3.2, human factors metrics / definitions (standards for CRI, lumen measurement), the group believed that current metrics for lighting are not adequate to address the needs of SSL. Therefore, this subtask promotes the development of new standards for SSL (and lighting in general). Research areas for this subtask include color rendering, light output, perception sensitivity. Some in the group argued that organizations such as the CIE and IESNA are better equipped to perform this research and therefore should not be a part of this SSL initiative.

Task 2.4 Infrastructure

The following table provides the break-out group's votes on the two subtasks contained within the Infrastructure task.

Table 3-9. Group Prioritization of Infrastructure Subtasks

Task 2.4 Infrastructure	High	Low
2.4.1 Socket compatibility and other	34	3
2.4.2 Building intelligence	3	34

For subtask 2.4.1, socket compatible and others, the group raised a few questions - should new infrastructure be created, or should a direct replacement be pursued? Is socket compatibility important to achieve goals? Identifying this subtask as a high priority, the group noted that users can relate to the "Edison" sockets, and if SSL devices were made that could fit into these sockets, it would accelerate near-term market adoption.

For subtask 2.4.2, building intelligence, the group strongly recommended that resources could be better used elsewhere. This subtask, it was explained, involves the creation of an entirely new infrastructure, such as intelligent homes.

3.2. Organic Light Emitting Diodes (OLEDs)

Each research task and subtask is described to expand on the language and meaning of the tasks; at the introduction of each task, a chart showing the force-rank voting clearly delineates how the break-out group prioritized each task. For the applied research topic area, a summary chart identifies the ranking of each task and subtask. For the systems integration topic area, the OLED group developed a series of questions that need further discussion before the tasks and subtasks are prioritized.

Topical Area 1: OLED Applied Research

Table 3-10 provides a summary of the voting on tasks and subtasks by the approximately 30 participants in the OLED breakout session.

Table 3-10. Group Prioritization of R&D Tasks and Subtasks: OLED Topic Area 1

Task / Subtask Descriptions	Ranking*
Task 1.5 Electro-Active Organic Materials Research	**High**
Subtask 1.5.1 High efficiency, low-voltage, stable materials for OLED-based general illumination technology (hosts, dopants, and transport layers)	High
Subtask 1.5.2 Functional electro-active materials for low cost manufacturing	Low
Task 1.6 Advanced Organic Device Architectures	**Medium**
Subtask 1.6.1 Strategies for improved light extraction and manipulation	High
Subtask 1.6.2 Novel device structures for improved performance and low cost	Medium
Subtask 1.6.3 Encapsulation and packaging materials for high reliability	Medium
Subtask 1.6.4 Novel approaches to achieve white light	Low
Subtask 1.6.5 Materials for low-cost, large area electrodes and interconnects	Low
Task 1.7 OLED Module Integration	**Low**
Subtask 1.7.1 Reliable packages for lighting applications	High
Subtask 1.7.2 Physics, chemistry, and optical design models from OLED molecules to modules	High
Subtask 1.7.3 Characterization tools for device, module and process optimization and manufacturing	Low
Task 1.8 Manufacturing Equipment and Tools for OLED Lighting	**Medium**
Subtask 1.8.1 Large area low cost substrates	High
Subtask 1.8.2 Low cost fabrication technologies	High
Subtask 1.8.3 Large area patterning technology	Low

* Task rankings are relative to each other. Subtask rankings are within a task. The OLED group used a somewhat different ranking than the LED group. OLED group used High, High2, and Low; where High2 means high priority, but not as strong as a high ranking. For consistency with the LED group, High2 has been given a medium ranking in this table. Also, note that the group agreed that there are some subtasks in lower priority tasks that should still be considered as a high priority.

Task 1.5 Electroactive Organic Materials Research

This task was identified as "high" priority by seventeen participants. Two participants identified the task as "medium" and no participants said it was low priority. Thus, OLED material research has been identified as a high priority task.

Electroactive materials were defined as the material(s) that emits light in response to application of a voltage, the critical active part of an OLED device. Use of the word "organic" was meant to include purely organic (carbon-based) materials, and/or hybrids of organic material used in conjunction with inorganic materials.

Table 3-11. Group Prioritization of Electroactive Organic Materials Research

Task 1.5 Electroactive Organic Materials Research	High	Med	Low
1.5.1 High Efficiency, Low-Voltage, Stable Materials for OLED-Based General Illumination Technology (Hosts, Dopants and Transport Layers)	21	8	0
1.5.2 Functional Electroactive Materials for Low Cost Manufacturing	1	8	0

For subtask 1.5.1, high efficiency, low-voltage, stable materials for OLED-based general illumination, the group discussed the fact that current materials are low efficiency, driven by too high voltages (which is one loss factor leading to low efficiency), and unstable (low lifetime). All of these factors need to be addressed to meet the needs of the general illumination market, through new host materials, dopants, and transport layers.

For subtask 1.5.2, functional electroactive materials for low cost manufacturing, the group discussed the fact that current OLED active display materials are expensive on a $\$/m^2$ basis, particularly when compared to general illumination market requirements (e.g., fluorescent lighting). Estimates of lifetime and efficiencies necessary for OLED based general illumination are roughly 50,000 hours and 100 lumens/Watt, respectively. Lifetimes and efficiency of state-of-the-art white OLEDs (at 850 cd/m^2) are about 500 hours and 5 lumens/Watt respectively. Research into less expensive electroactive wide-area materials is needed to enable OLEDs to develop cost-competitive, energy efficient lighting technologies

To realize the full potential of OLED technology, new materials and systems are needed that offer the promise of vastly improved efficiency and stability in the active regions of the OLED device- cathode and anode layers, electron and hole transport and injection layers, emission layers, and carrier blocking layers. New phosphorescent OLED systems with nearly 100% internal quantum efficiency (triplet state emission and singlet to triplet energy transfer) at high current densities are required in the red, green, and blue spectral regions. Single molecules that produce a broadband emission and that harvest triplet energies otherwise lost as heat are also needed. Innovative device structures and materials are needed to reduce high-luminance (~1000 cd/m^2) drive voltages from 10-20V to 4-5V. Compatibility with practical methods of current distribution and controls must be assured.

Task 1.6 Advanced Organic Device Architectures

This task addresses the challenge of developing the special manufacturing tools and equipment necessary for cost effective and large-sale manufacture of practical OLED products. Today, OLEDs are made either by vapor deposition or by spin coating in relatively low volumes. Although manufacturing costs are reasonable for the display and specialty applications they are designed for, their cost is more than several orders of magnitude higher than what is required for competitive general illumination products.

The device architecture includes not only new device structures, but also materials research on other ingredients necessary for a functional device (electrodes, light extractors, etc.) that were not included in task 1.5. As in task 1.5, use of the word "organic" is not intended to eliminate organic/ inorganic hybrid approaches.

Table 3-12. Group Prioritization of Advanced Organic Device Architectures

Task 1.6 Advanced Organic Device Architectures	High	Med	Low
1.6.1 Strategies for Improved Light Extraction and Manipulation	15	6	1
1.6.2 Novel Device Structures for Improved Performance and Low Cost	6	10	0
1.6.3 Encapsulation and Packaging Materials for High Reliability	4	7	0
1.6.4 Novel Approaches to Achieve White Light	0	0	16
1.6.5 Materials for Low-Cost, Large Area Electrodes and Interconnects	0	2	5

For subtask 1.6.1, strategies for improved light extraction and manipulation, participants discussed that light extraction from OLED devices is low affecting device efficiency. As the internal efficiency and stability of new OLED materials improves, OLED researchers will need to focus their attention on novel device architectures, light extraction and manipulation designs, encapsulation and packaging concepts for high reliability and robustness. Current light out-coupling efficiencies are on the order of 20%. Innovative approaches utilizing surface texturing, gratings, periodic nanostructures, integrated lens or device shaping are necessary to increase the out-coupling efficiency to the desired level of >50%. Research funded under this subtask would address light extraction and manipulation strategies that apply to OLED devices only (avoid duplication with LED research).

For subtask 1.6.2, novel device structures for improved performance and low cost, participants discussed that OLED device performance is defined by color spectrum, efficiency, and reliability (lifetime, and color spectrum aging stability). There is controversy surrounding the definition of color spectrum performance, but the trend for general lighting applications (and the majority of the savings potential) appears to be centered on replacing the incandescent lamp. This implies that the output color spectrum must be broad, and the human eye should respond positively to it. OLED and LED white light technologies may also allow the ability to adjust color spectrum output, changing it relative to biorhythms or personal preference.

For subtask 1.6.3, encapsulation and packaging materials for high reliability, participants discussed the fact that to obtain reasonable lifetimes, current OLED materials are extremely sensitive to humidity, CO_2, and oxygen. Operational lifetimes are severely affected by ambient (oxygen, water, carbon dioxide) permeability into the active layers of the OLED devices. Novel barrier or encapsulation materials will be needed to increase operation and shelf lifetime, as well as limit materials degradation due to short-wavelength (blue-UV) excitations, low levels of thermal cycling and/or damp heat stress associated with operating an OLED device.

For subtask 1.6.4 , novel approaches to achieve white light, participants discussed the fact that current LED approaches to create a white light device center on three approaches: (a) blue LED with phosphor(s), (b) UV LED with phosphor(s), or (c) three or more LEDs of different colors mounted closely together in the same package. New ideas are needed in the area of white OLEDs to improve the color stability over time and operating conditions. Concepts including RGB blends, monomer-excimer complexes, separate RGB emissive layers, and pixilation need to be explored to determine the optimal approach to OLED-based white light generation.

For subtask 1.6.5, materials for low-cost, large area electrodes and interconnects, participants discussed the problems associated with current materials for electrodes/interconnects being too reactive, difficult to deposit (cathodes), and too resistive, brittle, or difficult to deposit (ITO anodes). New materials are required that are able to be processed at high-speed, with low base material cost, are needed to meet OLED cost targets for general illumination lighting.

Task 1.7 OLED Module Integration

As suitable OLED molecules and systems are developed and their performance potential is demonstrated, more applied work will be needed to integrate these advanced materials into practical structures that are both functional and reliable for use in general illumination applications. Many of the challenges anticipated in this area are associated with package design in general with a special emphasis on optical design that will allow the identified systems to function as intended when integrated into a device, yet allow the light to be efficiently delivered to where it is needed.

Task 1.7 is concerned with all levels of an OLED system or module, integrating an OLED device with its environment (voltage source & plug, lamp packaging if different from the device, etc.) In addition, two research tasks that apply to all levels-- active layer, device, and system – have been included in the module integration task. These are (a) modeling and (b) characterization tools. The participants voted task 1.7 to be a “low” priority, with 18 votes for low. There were two participants who voted for medium priority, and no votes for high priority. However, two of the subtasks within task 1.7 were given high priority.

Table 3-13. Group Prioritization of OLED Module Integration

Task 1.7 OLED Module Integration	High	Med	Low
1.7.1 Reliable Packages for Lighting Applications	13	0	2
1.7.2 Physics, Chemistry, and Optical Design Models from OLED Molecules to Modules	13	0	1
1.7.3 Characterization Tools for Device, Module and Process Optimization and Manufacturing	0	0	23

Receiving a "high" priority from participants, subtask 1.7.1, reliable packages for lighting applications, moves beyond the encapsulation and packaging materials of the device detailed in subtask 1.6.3. This subtask focuses on the issue of packaging and reliability for the entire OLED system or module, including system reliability issues. Many experts believe that as OLED devices are developed, completely new fixture designs and lighting design approaches will be required. Other experts believe that present lighting form factors must be preserved to allow the replacement lighting technology (i.e., OLEDs) plug compatibility with existing lamps (e.g., linear fluorescents). This implies that in order to achieve significant market penetration and attendant lighting energy conservation, OLED designs must be developed that allow for the direct replacement of commonplace linear fluorescent lamps. This significant design and engineering challenge will have to be supported by the more basic development of OLED modules under this task.

For subtask 1.7.2, physics, chemistry, and optical design models from OLED molecules to modules, participants discussed the physics, chemistry, and optics of OLEDs, from the active layer to device to system, can be characterized through design modeling (and accompanying implied theory). This subtask is focused on increasing our understanding of OLED devices at all levels, to more quickly optimize structures and devices, and to be predictive of new material system properties and behavior. This subtask received a "high" priority from participants.

For subtask 1.7.3, characterization tools for device, module and process optimization and manufacturing, participants highlighted the importance of being able to accurately measure material, device, and module properties of OLEDs. This task is focused on OLED-specific (as opposed to LED or other semiconductor) characterization tools that will need to be developed at the material, device, and module level as OLED devices move toward commercialization. In the later stages of commercialization this would include a focus on in-line manufacturing characterization tools.

Task 1.8 Manufacturing Equipment and Tools for OLED Lighting

While many believe that flexible substrates are the key to meeting this manufacturing challenge, this opinion is not universally held. Plastic or glass, either one will have to be available in very high purity, uniformity and in large areas at very low cost. Low cost, high-speed, efficient fabrication technologies will have to be explored that certainly may include roll-to-roll processing but other candidate methods must be considered also. Likewise, should any OLED multifunctionality be desired (combined illumination and display or photovoltaic or electrochromic) or should current distributing patterning be required, the technology necessary to apply this in a practical manufacturing environment will have to be developed.

The following table presents the group voting results on the three subtasks associated with task 1.8, OLED manufacturing equipment and tools, which received a medium ranking.

Table 3-14. Group Prioritization of Manufacturing Equipment and Tools for OLEDs

Task 1.8 Manufacturing Equipment and Tools for OLED Lighting	High	Med	Low
1.8.1 Large Area Low Cost Substrates	23		1
1.8.2 Low Cost Fabrication Technologies	5		2
1.8.3 Large Area Patterning Technology	1		22

For subtask 1.8.1, large area low cost substrates, participants discussed the fact that current substrates have defects, or do not allow high temperature deposition (biaxially oriented PET). This task is focused on finding large area low cost substrates. Flexibility is desired, but not required.

For subtask 1.8.2, low cost fabrication technologies, current deposition technologies typically have speed vs. material quality tradeoffs. To meet OLED cost goals, high speed, wide area (or large batch) deposition techniques are required. Other key attributes are deposition uniformity (thickness and area).

For subtask 1.8.3, large area patterning technology, one approach to large area current spreading includes dividing a larger area into cells, which requires patterning of materials. RGB approaches to white light generation also require patterning, and it is anticipated that low cost large area patterning technology will be need for OLEDs. Leveraging the knowledge of the display, printing and semiconductor industries and applying it to OLED devices is the focus of this research task.

Topical Area 2: OLED Product Development And Systems Integration

The OLED working group felt that because OLED technology is a nascent and developing technology for general illumination applications, it is premature to force-rank prioritize product development and systems integration research tasks. Therefore the task list was divided into broader categories, without subtasks, in anticipation of sub-task breakdowns being created at some later date. These tasks are key initial product development issues that active material, device, and module designers must keep in mind during the early stages of development of the technology.

Task 2.5 Novel Form Factors
What are the desirable form factors for OLED lighting? Should OLED lighting be task lighting, or wide area? What shape should the module be? Is flexibility required?

Task 2.6 Human Factors
What are the human acceptability factors for OLED lighting (optimal spectrum, novel forms, diffuse vs. point source, source uniformity, flicker)?

Task 2.7 Systems Architecture
How do you design and integrate OLEDs into spaces?

Task 2.8 Identifying and Overcoming Barriers
What are the early barriers to commercialization and acceptance?

Task 2.9 System Engineering
How do you optimize thermal, mechanical, and electrical design aspects from modules to applications (buildings, autos, etc.)? This task includes power supplies, drive electronics, thermal management, socket compatibility, controls integration, etc. One issue identified is how the heat generated by a high intensity OLED point source can be effectively dissipated in a typical light socket.

Task 2.10 Field Testing and Optimization
How to define criteria for testing and optimization (power efficiency, reliability, ease of installation/replacement, etc.)?

4. List of Appendices

Appendix A.	Workshop Registrants List Name, title and company of the 155 people who registered for the two-day workshop.
Appendix B.	Web-sites and other resources related to SSL WWW sites on funding, R&D activities and other programs relating to SSL.
Appendix C.	Graphical Images Capturing Discussion From the Workshop Illustrations of key points in the discussion at the workshop
Appendix D.	Original List of Research Areas Discussed The original list of research topic and subtopic areas discussed on Day 2.
Appendix E.	Results of Homework Assignment Results of the workshop participants who submitted initial prioritization scoring on the research topics and subtopics. These tables were used to guide the discussion in the breakout groups.
Appendix F.	C. Eddie Christy, NETL Presentation The complete presentation of Eddie Christy's focusing on the proposed structure of the SSL R&D portfolio.

APPENDIX A

Workshop Registrants List

Table A.1 Complete List of Workshop Registrants

Registrant's Name	Title	Company
Srinath Aanegola	Program Manager	GELcore LLC.
Homer Antoniadis	Product Development Manager	Osram Semiconductors
Diana Arsenian	Graphic Facilitator	
Stephen Arthur	Physicist	GE Global Research
Bruce Baretz	President	Keen Materials & Devices Ltd.
Fil Bartoli	Program Director	NSF
Suresh Baskaran	Manager	Pacific Northwest National Laboratory
Charles Becker	Manager ELectronic Materials and Manufacturing Lab	General Electric Global Research
Arpad Bergh	President	OIDA
Kris Bertness	Dr.	NIST
Dietrich Bertram	New business creation manager	Philips Ligthing
Robert Biefeld	Technical Manager	Sandia National Laboratories
George Brandes	Director - GaN Products	ATMI
James Brodrick	Solid State Lighting R&D	U. S. Department of Energy
Doug Brookman	Public Solutions	
Darren Burgess	Head of Sales & Product Management	AIXTRON Inc
Kevin Burnett		Naval Research Laboratory
Paul Burrows	Research Scientist	Pacific Northwest National Laboratory
Wendy Butler-Burt		US DOE
Elizabeth Cecchetti	Consultant	Pacific Northwest National Laboratory
David Chernin	Vice President	SAIC
Babu Chalamala		
Makarand Chipalkatti	Director	Lamp Modules North America
Eddie Christy		DOE/NETL
Jim Cirillo		Unison
Jim Cirillo	Senior Program Manager	Fiberstars
Jeff Cites	Senior Research Scientist	Corning, Inc.
Kathryn Conway	Principal	LED Consulting
M George Craford	CTO	Lumileds
Brian Crone		Los Alamos National Laboratory
John Curran	VP Engineering	Wheelock, Inc.
Lynn Davis	Senior Research Associate	RTI International
Steven DenBaars	Research Professor	UCSB
Dan Donahoe	Assistant Research Scientist	University of Maryland
Kevin Dowling	VP Strategy & Technology	Color Kinetics

Table A.1 Complete List of Workshop Registrants (continued)

Registrant's Name	Title	Company
Anil Duggal	Advanced Technology Leader	GE Global Research
Paul Eckels	CFO	H.E. Williams, Inc.
Arthur Epstein	Distinguished University Professor	The Ohio State University
Jonathan Epstein	Staff	Senator Bingaman's Office
Alfred Felder	Director of OLED Technology	Osram Semiconductors
Ian Ferguson	Professor	Georgia Institute of Technology
John Ferraris	Professor of Chemistry	University of Texas at Dallas
Mark Fink	Director Of Engineering	Breault Research Organization
Jeffrey Flynn	Manager - GaN Epitaxy	ATMI
Michael Frate	Engineering Services Business Coordinator	Breault Research Organization, Inc.
Kenneth Frederick	VP Corporate Development	Symmorphix
Doug Freitag	Mr.	Dow Corning Corporation
Jim Gaines	Dr.	Philips
Bobi Garrett	Associate Director	National Renewable Energy Laboratory
Ken Gertz	Assistant Vice President	Rensselaer Polytechnic Institute
Maria Gherasimora	Professor	Yale University, Dept of Elec Eng
Todd Graves	Consumer Products Business Program Manager	GE Global Research
Kevin Gray	Techno-Marketing	Saint-Gobain High Performance Materials
Yi Gu	Associate Research Scientist	Columbia University
Louis Guido	Professor	Virginia Tech
Brad Gustafson	Utility Program Manager	DOE
Douglas Gyorke	Project Manager	USDOE/NETL
Michael Hack	VP Strategic Product Development	Universal Display Corporation
Douglas Hamilton	Director of Technology	Norlux
Norbert Hiller	LED Research	Cree, Inc.
Orin Holland	Professor	University of North Texa
Denise Holliday	Contracts Manager	Cree, Inc.
Eugene Hong	Consultant	Navigant Consulting, Inc.
Eli Hopson		House Science Committee
William Houck	Mr.	Virginia Tech
James Ibbetson	Manager, LED Process Development	Cree
Ghassan Jabbour	Professor	University of Arizona
Raymond Jarr	General Counsel NETL	Dept of Energy
Hongxing Jiang	Professor	Kansas State University
Steve Johnson	Group Leader for Lighting Research	LBNL

Table A.1 Complete List of Workshop Registrants (continued)

Registrant's Name	Title	Company
Tina Kaarsberg	Staff	House Science Committee
Zakya Kafafi	Dr., OLED Research	NRL
Shawn Keeney	Engineer	Wheelock, Inc.
Bernd Keller	VP, LED Research	Cree
Douglas Kirkpatrick	Program Manager	DARPA
Michael Krames	Advanced Labs Manager	Lumileds Lighting
Sarah Kurtz	Principal Scientist	NREL
Sandy Kushner	Contract Development Manager	Air Products
Marc Ledbetter	Program Manager	Pacific Northwest National Laboratory
Kevin Linthicum	Vice President	Nitronex Corporation
Guo-Quan Lu	Professor	Virginia Tech
George Malliaras	Assistant Professor	Cornell University
Karen Marchese	Senior Writer/Project Manager	Akoya
James Maslar	Research Chemist	NIST
Michael McGehee	Regional Sales Manager	Control Technologies
Raymond McGowan	Energy Consultant	D&R International
Udi Meirav	CEO	Luminus Devices
john midgley	CEO	ultradots
Ley Mitchell	Government Relations	Cree, Inc.
Richard Moorer	Deputy Assistant Secretary EERE	US DOE
Nadarajah Narendran	Director of Research	Rensselaer Polytechnic Institute
Jeff Nause	President	Cermet, Inc.
Jeffrey Nelson	Consultant	MLS
Harry Niedecken	West Coast Sales & Account Manager	AIXTRON Inc
Barney O'Meara	Vice President	The Fox Group Inc
Qibing Pei	Sr. Research Engineer	SRI International
Edward Petrow	Engineer	Lincoln Technical Services, Inc.
Robert Pinnel	CTO	U.S. Display Consortium
Kyle Pitsor	Industry Director	NEMA
Jeff Popielarczyk	Business Development Manager	General Electric
Johnathan Raab	Raab Associates	
Ramachandran Radhakrishnan	Manager-Technology Development	Materials Modification, Inc.
Emil Radkov	Dr.	GELcore, LLC
David Ramer	Senior Scientist	SAIC

Table A.1 Complete List of Workshop Registrants (continued)

Registrant's Name	Title	Company
James Rannels		US DOE
Spilios Riyopoulos	PhD	SAIC
Mehmet Rona	Director, Applied Physics and Modeling	TIAX LLC
George Ryals	Manager of Compound Semiconductor Materials R&D	Air Products and Chemicals
Bernard Saffell	Buildings Account Manager	Pacific Northwest National Laboratory
David Salzman	President	LightSpin Technologies, Inc.
Michael Schen	Group Leader	NIST/ATP
Elliott Schlam	President	Elliott Schlam Associates
Michael Scholand	Senior Consultant	Navigant Consulting, Inc.
Fred Schubert	Professor	Rensselaer Polytechnic Institute
Sean Shaheen	Scientist	NREL
Jianmin Shi	Research Scientist	US Army Research Lab
Joseph Shiang	Staff Scientist	General Electric
Joseph Shinar	Professor	Ames Lab Iowa State Univ
Jerry Simmons	Manager	Sandia National Laboratories
Dave Simon	Principal - Product Innovation	Altair Engineering, Inc.
Anant Singh	Senior Scientist	TIAX LLC
Darryl Smith	Laboratory Fellow	Los Alamos National Laboratory
Richard Smith	Program Manager	Oak Ridge National Laboratory
Franky So	Research	Osram Semiconductors
Christof Sommerhalter	Sales & Product Manager	AIXTRON Inc
Lee Spangler	Director of Special Programs	Vice President of Research
Ruediger Sprengard	Dr.	Schott Spezialglas GmbH
Graham Stevens	Senior Consultant	Navigant Consulting
Ed Stokes	Professor, ECE Dept	Univ of North Carolina Charlotte
Milan Stolka	Dr., Consultant	Consultant
David Strip	Senior Technical Associate	Eastman Kodak
Christopher John Summers	Professor	Materials Science & Engineering
Dorota Temple	Principal Scientist	MCNC RDI
Paul Thurk	Venture Associate	ARCH Venture Partners
John Tozzi	Vice President	Syntek Technologies, Inc.
Jeff Tsao	Principal Member of Technical Staff	Sandia National Laboratories
Tim Valentine	Staff	Senator Alexander's Office
Jud Virden	Director EE Programs	PNNL

Table A.1 Complete List of Workshop Registrants (continued)

Registrant's Name	Title	Company
Paul Vrabel	Project Manager	ICF Consulting
Brent Wagner	Senior Research Scientist	GA Technology Research Institute
Stanton Weaver	LED Project Leader	GE Global Research
Warren Weeks	Business Development	Nitronex Corporation
Christian Wetzel	President	Nitride Consulting
Tim Whitaker	Editor	Compound Semiconductor Magazine
Mark Williams	Director of Wafering	Kyma Technologies
George Woodbury	President	LightSmart Energy
Dale Work	Technology Policy and Industry Affairs	Philips Lighting
Chenchun Wu		University of Utah
A. Brent York	Chief Technology Officer	TIR Systems Ltd.
Ohno Yoshi	Acting Group Leader	NIST
Steffen Zahn	Senior Research Associate	Air Products and Chemicals,Inc.
Anvar ZakHidov	Professor of Physics	University of Texas
Brad Zinke	Business Development	3M

APPENDIX B

Web-Sites and Other Resources Related to SSL

SSL Research and Development Funding Sources and Resource Websites

Department of Energy

http://www.netl.doe.gov/ssl (Building Technology Programs)
http://www.naseo.org/stac/ (State Technologies Advancement Collaborative)
http://www.oit.doe.gov/inventions/solicitations.shtml (Inventions and Innovation)
http://sbir.er.doe.gov/sbir (Small Business Innovation Research)
http://www.science.doe.gov/bes (Office of Basic Energy Sciences)
http://www.science.doe.gov/bes/dms/DMSE.htm (Division of Materials Science & Engineering)
http://www.science.doe.gov/grants/ (sponsored research details)
http://www.energy.gov/scitech/index.html (Science & Technology across DOE)
http://www.sc.doe.gov/bes/BESfacilities.htm
http://www.science.doe.gov/bes/User_Facilities/dsuf/DSUF.htm

Department of Commerce

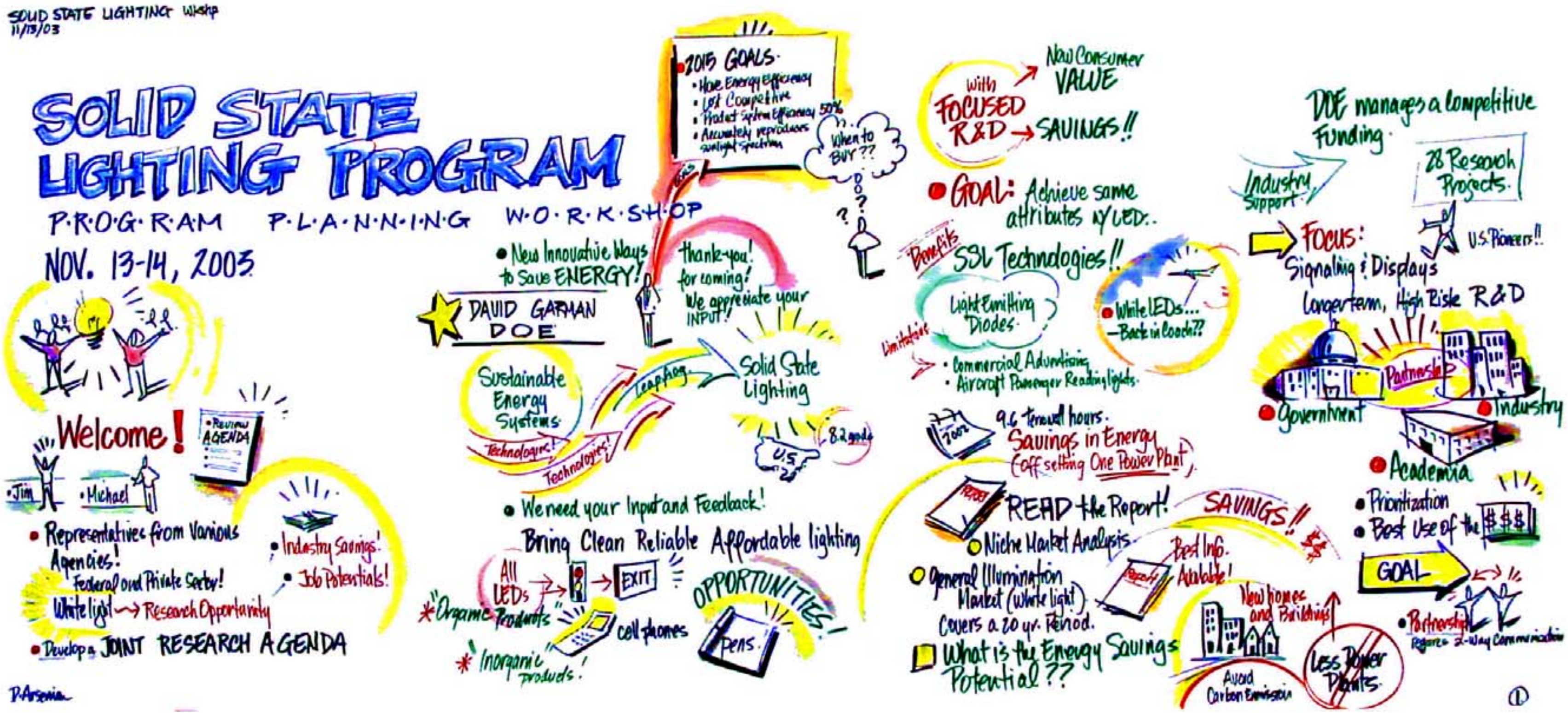
http://www.atp.nist.gov (Advanced Technology Program)
http://www.nist.gov

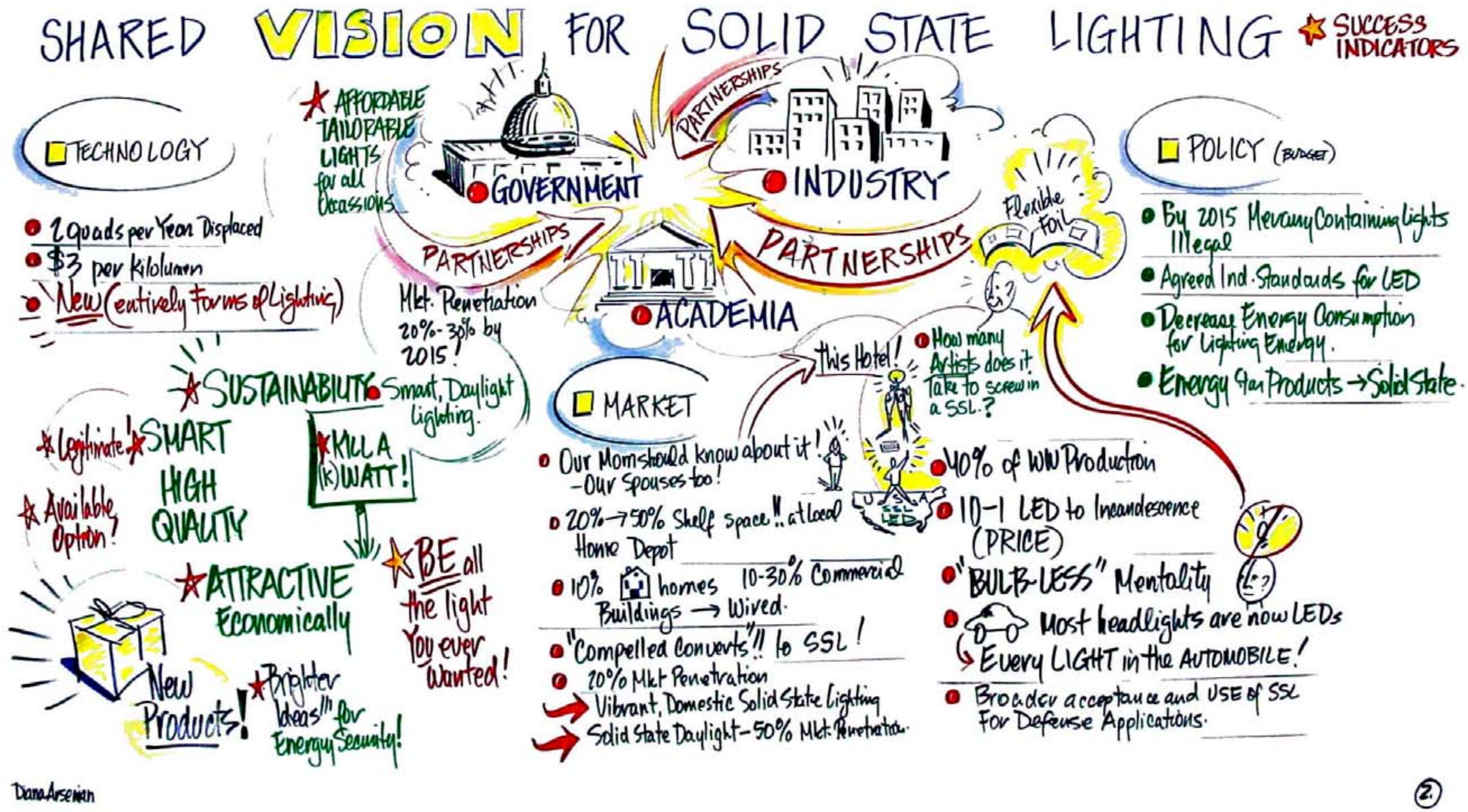
Department of Defense

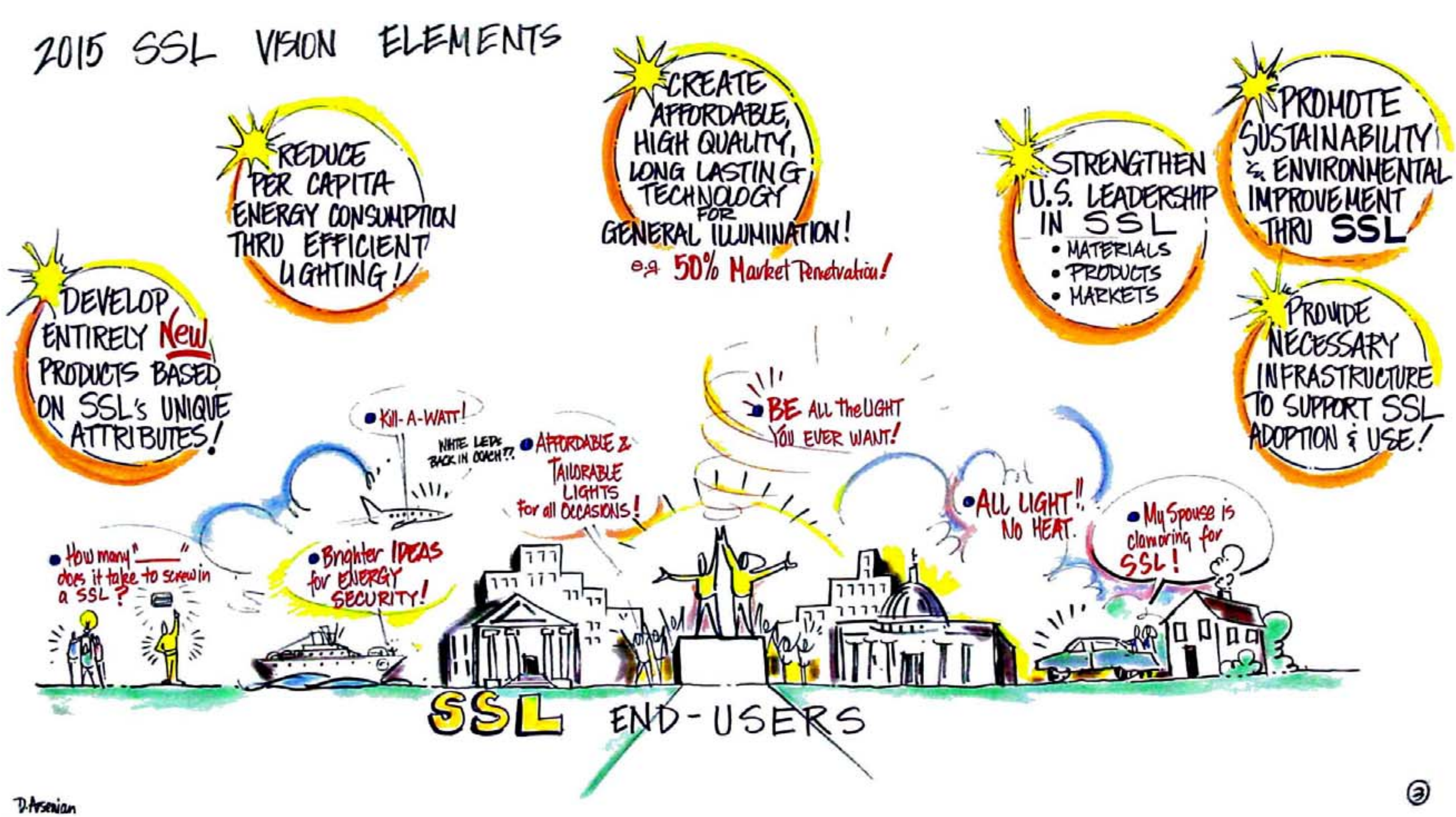
http://www.darpa.mil/mto/ (DARPA Microsystems Technology Office)

APPENDIX C

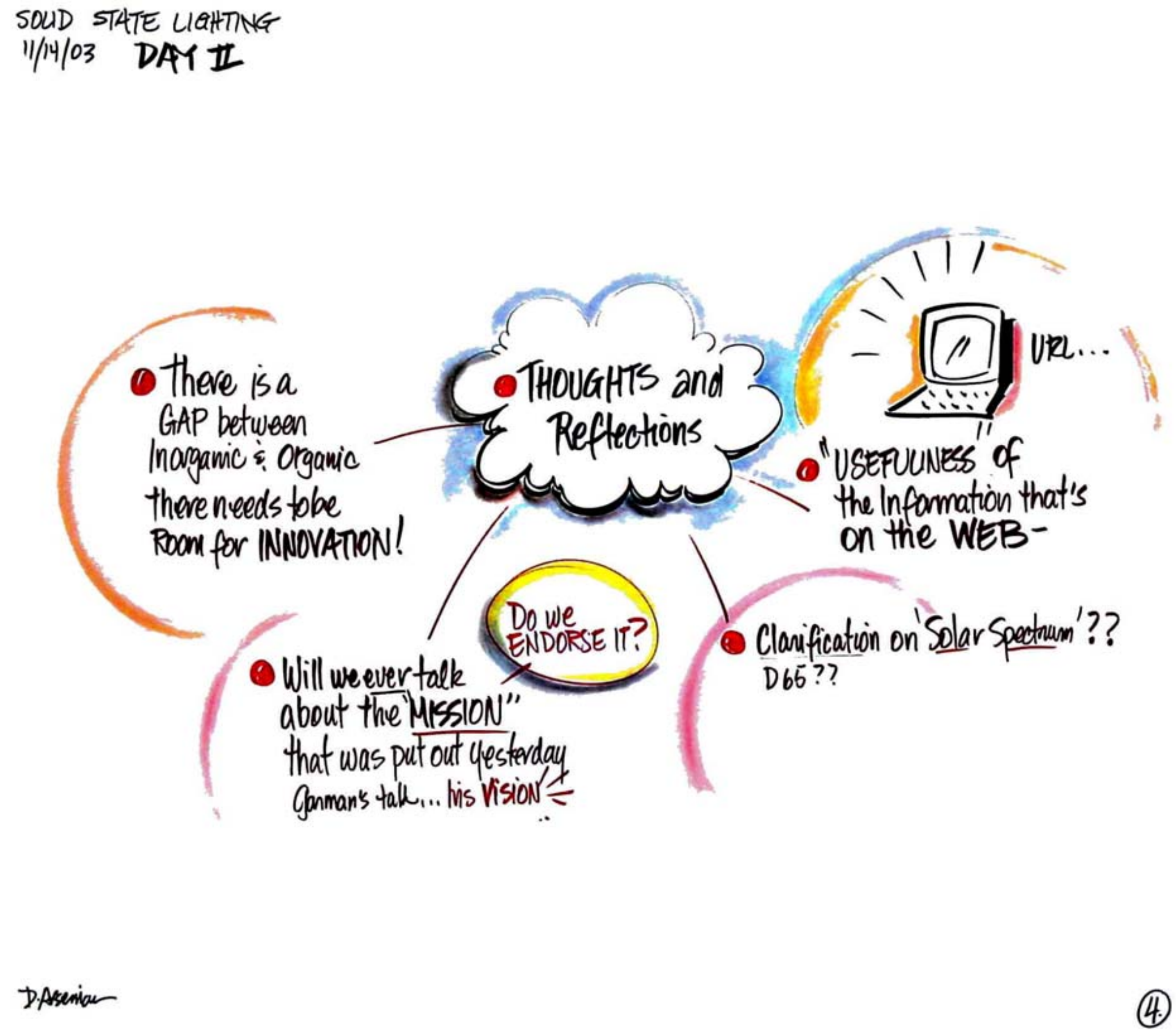
Graphical Images Capturing Discussion from the Workshop


SOLID STATE LIGHTING Wkshp
11/13/03
SOLID STATE LIGHTING PROGRAM
PROGRAM PLANNING WORKSHOP
NOV. 13-14, 2003
Welcome!
Review AGENDA
Jim
Michael
Representatives from Various Agencies!
Federal and Private Sector!
White light → Research Opportunity
Industry Savings!
Job Potentials!
Develop a JOINT RESEARCH AGENDA
D. Arsenia
New Innovative Ways to Save ENERGY!
DAVID GARMAN DOE
Sustainable Energy Systems
Technologies!
Technologies!
Leapfrog
Solid State Lighting
Thank-you! for coming!
We appreciate your INPUT!
2015 GOALS
Have Energy Efficiency
Lost Competitive
Product System Efficiency 50%
Accurately reproduces sunlight spectrum
When to BUY??
U.S.
We need your Input and Feedback!
Bring Clean Reliable Affordable lighting
All LEDs
EXIT
Organic Products
cell phones
Inorganic products
OPPORTUNITIES!
Pens
with FOCUSED R&D → SAVINGS!!
New Consumer VALUE
GOAL: Achieve same attributes w/ LED
Benefits
SSL Technologies!!
Light Emitting Diodes
White LEDs... —Back in Coach??
Limitations
Commercial Advertising
Aircraft Passenger Reading lights
2007
Savings in Energy (offsetting One Power Plant)
READ the Report!
Niche Market Analysis
Best Info. Available!
Report
General Illumination Market (white light)
Covers a 20 yr. Period.
What is the Energy Savings Potential??
SAVINGS!!
New homes and Buildings
Avoid Carbon Emissions
Less Power Plants
DOE manages a competitive Funding
Industry Support
28 Research Projects
U.S. Pioneers!!
FOCUS: Signaling & Displays
Longer term, High Risk R&D
Partnership
Government
Industry
Academia
Prioritization
Best Use of the $$$
GOAL
Partnership
Requires 2-Way Communication
1


SHARED VISION FOR SOLID STATE LIGHTING
SUCCESS INDICATORS
TECHNOLOGY
2 quads per Year Displaced
$3 per kilolumen
New (entirely forms of Lighting)
AFFORDABLE TAILORABLE LIGHTS for all Occassions
GOVERNMENT
INDUSTRY
ACADEMIA
PARTNERSHIPS
PARTNERSHIPS
PARTNERSHIPS
Mkt. Penetration 20%-30% by 2015!
SUSTAINABILITY
Smart, Daylight lighting.
Legitimate!
SMART
HIGH QUALITY
Available Option?
KILL A (K)WATT!
ATTRACTIVE Economically
BE all the light You ever Wanted!
New Products!
Brighter Ideas!!! for Energy Security!
Flexible Foil
This Hotel!
How many Artists does it take to screw in a SSL.?
MARKET
Our Mom should know about it! -Our Spouses too!
20%→50% Shelf space!! at local Home Depot
10% homes 10-30% Commercial Buildings → Wired.
"Compelled Converts"!! to SSL!
20% Mkt Penetration
Vibrant, Domestic Solid State Lighting
Solid State Daylight-50% Mkt. Penetration.
40% of WW Production
10-1 LED to Incandescence (PRICE)
"BULB-LESS" Mentality
Most headlights are now LEDs
Every LIGHT in the AUTOMOBILE!
Broader acceptance and USE of SSL For Defense Applications.
POLICY (BUDGET)
By 2015 Mercury Containing lights Illegal
Agreed Ind. Standards for LED
Decrease Energy Consumption for Lighting Energy.
Energy Star Products → Solid State.
Dana Arsenian
2.



2015 SSL VISION ELEMENTS
DEVELOP ENTIRELY New PRODUCTS BASED ON SSL's UNIQUE ATTRIBUTES!
REDUCE PER CAPITA ENERGY CONSUMPTION THRU EFFICIENT LIGHTING!
CREATE AFFORDABLE, HIGH QUALITY, LONG LASTING TECHNOLOGY FOR GENERAL ILLUMINATION!
e.g. 50% Market Penetration!
STRENGTHEN U.S. LEADERSHIP IN SSL
• MATERIALS
• PRODUCTS
• MARKETS
PROMOTE SUSTAINABILITY & ENVIRONMENTAL IMPROVEMENT THRU SSL
PROVIDE NECESSARY INFRASTRUCTURE TO SUPPORT SSL ADOPTION & USE!
• How many "___" does it take to screw in a SSL?
• Kill-A-WATT!
WHITE LEDs BACK IN COACH??
• Brighter IDEAS for ENERGY SECURITY!
• AFFORDABLE & TAILORABLE LIGHTS for all OCCASIONS!
• BE ALL The LIGHT YOU EVER WANT!
• ALL LIGHT!! NO HEAT.
• My Spouse is clamoring for SSL!
SSL END-USERS
D. Arsenian
3


SOLID STATE LIGHTING
11/14/03 DAY II
THOUGHTS and Reflections
There is a GAP between Inorganic & Organic
there needs to be Room for INNOVATION!
"USEFULNESS" of the Information that's on the WEB-
URL...
Will we ever talk about the "MISSION" that was put out yesterday
Do we ENDORSE IT?
Clarification on 'Solar Spectrum'??
D65??
D.Arsenian
4.

SOLID STATE LIGHTING
11/14/03

"ASSUMPTIONS" FOR THE BREAK-OUT SESSIONS

- CONTENT of TYPOLOGY:
  Based 5-10 yr. Period
- PRIORITIZATION based on 2 - (3) yr. Period
- PRIORITIZATION IS FOR DOE's SOLICITATIONS in '04

(5.)

APPENDIX D

Original List of Research Areas Discussed at the Workshop

Original (Pre-Meeting)
Research Topic Areas for LEDs and OLEDs

Topical Area I: Applied Research

Task 1.1 Inorganic Materials Research

Subtask 1.1.1 Novel Substrates, Buffer Layers, and Wafer Engineering for Efficient Optical Light Extraction and Thermal Management

Subtask 1.1.2 High Efficiency Visible and UV Semiconductor Materials for LED-Based General Illumination Technology

Subtask 1.1.3 Reliability and Defect Materials Physics for Improved LED Lifetime

Task 1.2 Advanced Inorganic Device Architectures and Conversion Materials

Subtask 1.2.1 Advanced Architectures for High-Power Conversion Efficiency Emitters

Subtask 1.2.2 High Temperature, Efficient, Long-Life Phosphors and Encapsulants for Wavelength-Conversion and Packaging

Task 1.3 Inorganic Technology Integration

Subtask 1.3.1 High-Flux, Reliable Packages for Incandescent and Fluorescent Building Block Technologies

Subtask 1.3.2 Physics, Chemistry, and Optical Models for Epitaxial Reactor, Device and Process Optimization

Task 1.4 Manufacturing Equipment and Tools for Inorganic

Subtask 1.4.1 In-Situ Diagnostics

Subtask 1.4.2 Low Maintenance, High Efficiency Reactor Designs for High In, Al, and Mg Incorporation

Subtask 1.4.3 Etching, Metallization, and Passivation Equipment

Subtask 1.4.4 Separation, Chip-Shaping, and Wafer-Bonding Equipment
High Purity Raw Materials for Epitaxial Growth and Fabrication

Task 1.5 Organic Materials Research

Subtask 1.5.1 High Efficiency, Stable Organic Emitter Materials for OLED-Based General Illumination Technology

Subtask 1.5.2 Low Voltage, Organic Materials and Structures for High Current Density and Flux Applications

Subtask 1.5.3 Flexible, High-Temperature Substrates for Low-Cost Large Area Manufacturing

Task 1.6 Advanced Organic Device Architectures

Subtask 1.6.1 Structures for Improved Light Extraction and Manipulation

Subtask 1.6.2 Novel Device Structures for Electron, Hole, and Exciton Transport/Confinement

Subtask 1.6.3 Low Permeability Encapsulation and Packaging Materials for High Reliability

Task 1.7 Organic Technology Integration

Subtask 1.7.1 High-Flux, Reliable Packages for Large-Area Incandescent and Fluorescent Building Block Technologies

Subtask 1.7.2 Physics, Chemistry, and Optical Design Models and Analytical Characterization Tools for Device and Process Optimization, and Manufacturing.

Task 1.8 Manufacturing Equipment and Tools for Organic

Subtask 1.8.1 Large Area Plastic Substrates

Subtask 1.8.2 Roll-to-Roll Large Area Coating Technology

Subtask 1.8.3 Low Permeability Encapsulation and Packaging Materials for High Reliability

Subtask 1.8.4 Infrastructure and Device Powering

Topical Area 2: Product Development and Systems Integration

Task 2.1 Inorganic Lamp Systems

Subtask 2.1.1 Environmentally benign, Long-Life Luminaire Materials

Subtask 2.1.2 Efficient, low-cost optics for room and task lighting Apps

Subtask 2.1.3 Novel hybrid systems employing LED and OLED

Task 2.2 Inorganic Fixtures and Systems

Subtask 2.2.1 High-reliability, programmable power supplies and drive electronics

Subtask 2.2.2 Low thermal impedance, smart high-flux solid-state luminaires

Task 2.3 Inorganic Human Factors Issues

Subtask 2.3.1 Advanced building architectures and lighting systems for energy efficiency human comfort and workplace productivity

Subtask 2.3.2 Metrics for human factors benefits

Task 2.4 Inorganic Device Infrastructure

Subtask 2.4.1 Socket compatibility verses other designs

Subtask 2.4.2 Controls Integration

Task 2.5 Organic Lamp Systems

Subtask 2.5.1 Environmentally benign, Long-Life Luminaire Materials

Subtask 2.5.2 Efficient, low-cost optics for room and task lighting Apps

Subtask 2.5.3 Novel hybrid systems employing LED and OLEDs

Task 2.6 Organic Fixtures and Systems

Subtask 2.6.1 High-reliability, programmable power supplies and drive electronics

Subtask 2.6.2 Low thermal impedance, smart high-flux solid-state luminaires

Task 2.7 Organic Human Factors Issues

Subtask 2.7.1 Advanced building architectures and lighting systems for energy efficiency human comfort and workplace productivity

Subtask 2.7.2 Metrics for human factors benefits

Task 2.8 Organic Device Infrastructure

Subtask 2.8.1 Socket compatibility verses other designs

Subtask 2.8.2 Controls Integration

APPENDIX E

Results of the Homework Assignment
Used to Guide Discussion in the Breakout Groups

Table E.1 Participants Scores on the Homework Assignment, Ranking Program Areas

Solid State Lighting Workshop -- Homework Assignment Program Area Description	HOMEWORK RESULTS 0	1	2	3	WEIGHTED AVERAGE
Topical Area I: Applied Research					
Task 1.1 Inorganic Materials Research	15	2	6	30	1.96
Subtask 1.1.1 Novel Substrates, Buffer Layers, and Wafer Engineering for	18	1	11	23	1.74
Efficient Optical Light Extraction and Thermal Management					
Subtask 1.1.2 High Efficiency Visible and UV Semiconductor Materials for LED-	17	0	7	29	1.91
Based General Illumination Technology					
Subtask 1.1.3 Reliability and Defect Materials Physics for Improved LED Lifetime	18	5	13	17	1.55
Task 1.2 Advanced Inorganic Device Architectures and Conversion Materials	16	1	16	20	1.75
Subtask 1.2.1 Advanced Architectures for High-Power Conversion Efficiency Emitters	17	4	17	15	1.57
Subtask 1.2.2 High Temperature, Efficient, Long-Life Phosphors and Encapsulants	16	3	14	20	1.72
for Wavelength-Conversion and Packaging					
Task 1.3 Inorganic Technology Integration	16	4	21	12	1.55
Subtask 1.3.1 High-Flux, Reliable Packages for Incandescent and Fluorescent	17	6	18	12	1.47
Building Block Technologies					
Subtask 1.3.2 Physics, Chemistry, and Optical Models for Epitaxial Reactor, Device	17	11	22	3	1.21
and Process Optimization					
Task 1.4 Manufacturing Equipment and Tools for Inorganic	19	19	13	2	0.96
Subtask 1.4.1 In-Situ Diagnostics	22	16	12	3	0.92
Subtask 1.4.2 Low Maintenance, High Efficiency Reactor Designs for High In, Al,	21	18	8	6	0.98
and Mg Incorporation					
Subtask 1.4.3 Etching, Metallization, and Passivation Equipment	30	15	6	2	0.62
Subtask 1.4.4 Separation, Chip-Shaping, and Wafer-Bonding Equipment	27	14	10	2	0.75
High Purity Raw Materials for Epitaxial Growth and Fabrication					

Table E.1 Participants Scores on the Homework Assignment, Ranking Program Areas (continued)

Solid State Lighting Workshop -- Homework Assignment Program Area Description	HOMEWORK RESULTS 0	1	2	3	WEIGHTED AVERAGE
Task 1.5 Organic Materials Research	21	3	7	22	1.57
Subtask 1.5.1 High Efficiency, Stable Organic Emitter Materials for OLED-Based General Illumination Technology	22	1	8	22	1.57
Subtask 1.5.2 Low Voltage, Organic Materials and Structures for High Current Density and Flux Applications	22	2	12	17	1.45
Subtask 1.5.3 Flexible, High-Temperature Substrates for Low-Cost Large Area Manufacturing	24	6	9	14	1.25
Task 1.6 Advanced Organic Device Architectures	24	3	12	14	1.30
Subtask 1.6.1 Structures for Improved Light Extraction and Manipulation	23	1	16	13	1.36
Subtask 1.6.2 Novel Device Structures for Electron, Hole, and Exciton Transport/Confinement	23	10	8	12	1.17
Subtask 1.6.3 Low Permeability Encapsulation and Packaging Materials for High Reliability	22	6	11	14	1.32
Task 1.7 Organic Technology Integration	23	16	11	3	0.89
Subtask 1.7.1 High-Flux, Reliable Packages for Large-Area Incandescent and Fluorescent Building Block Technologies	24	15	11	3	0.87
Subtask 1.7.2 Physics, Chemistry, and Optical Design Models and Analytical Characterization Tools for Device and Process Optimization, and Manufacturing.	25	12	13	3	0.89
Task 1.8 Manufacturing Equipment and Tools for Organic	22	7	16	8	1.19
Subtask 1.8.1 Large Area Plastic Substrates	24	9	13	7	1.06
Subtask 1.8.2 Roll-to-Roll Large Area Coating Technology	24	7	14	8	1.11
Subtask 1.8.3 Low Permeability Encapsulation and Packaging Materials for High Reliability	24	4	12	13	1.26
Subtask 1.8.4 Infrastructure and Device Powering	28	12	11	2	0.75

Table E.1 Participants Scores on the Homework Assignment, Ranking Program Areas (continued)

Solid State Lighting Workshop -- Homework Assignment Program Area Description	HOMEWORK RESULTS				
	0	1	2	3	WEIGHTED AVERAGE
Topical Area 2: Product Development and Systems Integration					
Task 2.1 Inorganic Lamp Systems	17	7	16	13	1.47
Subtask 2.1.1 Environmentally benign, Long-Life Luminaire Materials	20	16	9	8	1.09
Subtask 2.1.2 Efficient, low-cost optics for room and task lighting Apps	21	8	16	8	1.21
Subtask 2.1.3 Novel hybrid systems employing LED and OLEDs	28	10	8	7	0.89
Task 2.2 Inorganic Fixtures and Systems	19	6	23	5	1.26
Subtask 2.2.1 High-reliability, programmable power supplies and drive electronics	18	16	16	3	1.08
Subtask 2.2.2 Low thermal impedance, smart high-flux solid-state luminaires	17	8	17	11	1.42
Task 2.3 Inorganic Human Factors Issues	20	13	12	8	1.15
Subtask 2.3.1 Advanced building architectures and lighting systems for energy efficiency human comfort and workplace productivity	24	11	13	5	0.98
Subtask 2.3.2 Metrics for human factors benefits	22	10	12	9	1.15
Task 2.4 Inorganic Device Infrastructure	20	8	17	8	1.25
Subtask 2.4.1 Socket compatibility verses other designs	25	6	13	9	1.11
Subtask 2.4.2 Controls Integration	23	9	18	3	1.02
Task 2.5 Organic Lamp Systems	23	18	10	2	0.83
Subtask 2.5.1 Environmentally benign, Long-Life Luminaire Materials	33	9	7	4	0.66
Subtask 2.5.2 Efficient, low-cost optics for room and task lighting Apps	30	15	6	2	0.62
Subtask 2.5.3 Novel hybrid systems employing LED and OLEDs	32	12	7	2	0.60
Task 2.6 Organic Fixtures and Systems	28	15	10	0	0.66
Subtask 2.6.1 High-reliability, programmable power supplies and drive electronics	35	12	5	1	0.47
Subtask 2.6.2 Low thermal impedance, smart high-flux solid-state luminaires	31	14	8	0	0.57

Table E.1 Participants Scores on the Homework Assignment, Ranking Program Areas (continued)

Solid State Lighting Workshop -- Homework Assignment	HOMEWORK RESULTS				
Program Area Description	**0**	**1**	**2**	**3**	**WEIGHTED AVERAGE**
Task 2.7 Organic Human Factors Issues	29	11	12	1	0.72
Subtask 2.7.1 Advanced building architectures and lighting systems for energy efficiency human comfort and workplace productivity	31	9	11	2	0.70
Subtask 2.7.2 Metrics for human factors benefits	30	12	9	2	0.68
Task 2.8 Organic Device Infrastructure	28	15	10	0	0.66
Subtask 2.8.1 Socket compatibility verses other designs	31	14	8	0	0.57
Subtask 2.8.2 Controls Integration	33	13	7	0	0.51

APPENDIX F

C. Eddie Christy, NETL Presentation

National Energy Technology Laboratory

Solid State Lighting Program - "Organization"

C. Edward Christy

November 13, 2003

NETL

Government – SSL Partnership Cooperative R&D Program for SSL

- Emphasize Competition
- Cost (and Risk) Sharing
- Partners Involved in Planning and Funding
- Targeted Research for Focused Need
- Innovative IP Provisions
- Open Information and Process
- Success determined by milestones met and ultimately energy efficient, long-life and cost-competitive products developed

NETL

2

CEC/Adv. Init./11-13-03

Current Structure…

- Disclaimer: The slides that follow are current thinking, November 13, 2003. The DOE values your input to the structure of this innovative government-private sector partnership and encourages you to communicate your thoughts (at the appropriate times, of course). Following this presentation is the "Panel Discussion: Question and Answer Period".

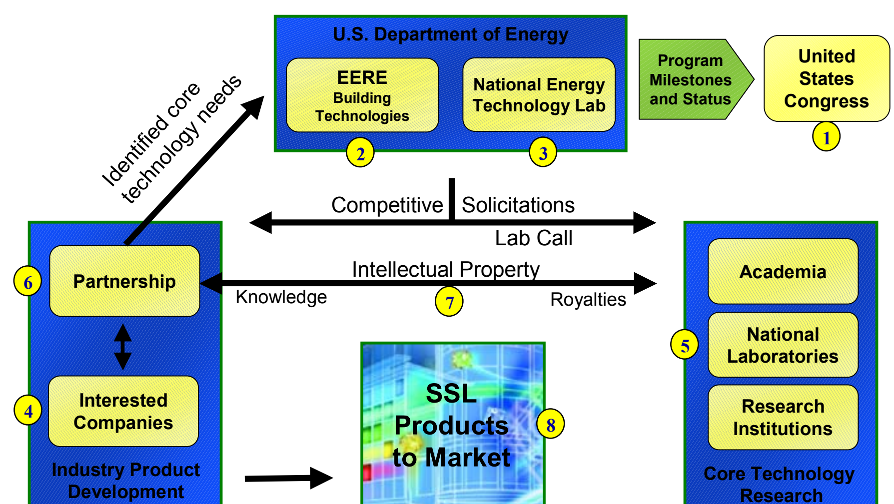
and comment

NETL

3

CEC/Adv. Init./11-13-03

Structure of SSL Operational Plan

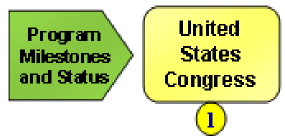


NETL

4

CEC/Adv. Init./11-13-03

United States Congress



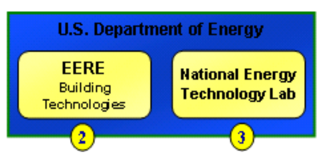
- **Issues Appropriations and Language that "authorizes" the DOE to perform research and development in programs**
  - May issue appropriations
  - May issue language
  - Language may provide detailed guidelines on how to implement the program
- **Requires reporting on program success**
  - Milestones
  - Status

NETL

5

CEC/Adv. Init./11-13-03

Building Technologies and NETL



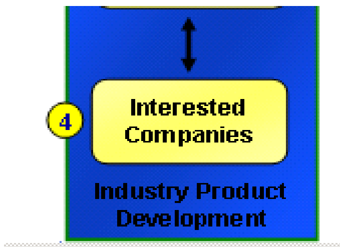
- **EERE Building Technologies**
  - Serve as Program Lead for activities
  - Performs strategic planning
  - Performs program definition
  - Interfaces with Congress
- **National Energy Technology Laboratory**
  - Develops and issues solicitations
  - Performs project management of selected projects
  - Reports on project status to HQ

NETL

6

CEC/Adv. Init./11-13-03

Interested Companies



- Competitive solicitation to industry
- Needs developed by DOE from results of this meeting
- Applications will require cost sharing
- Applications will require plan/SOW through development of a marketable product

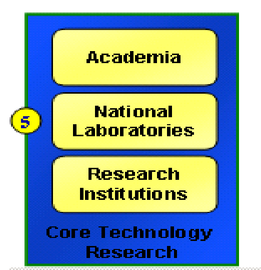
NETL

7

CEC/Adv. Init./11-13-03

Core Technology Program

- Solicitations
  - to National Laboratories (“lab call”)
  - to academia and research institutions
- Earlier stages of development
- May or may not require cost sharing
- Needs developed by DOE with input from Partnership group
- Applications will be for barrier issues that may apply to multiple technical areas, i.e. product development not required



NETL

8

CEC/Adv. Init./11-13-03

SSL Partnership

WHY?

- Provide input to and prioritization of the Core Technology Needs
- Provide technical reviews of Core Technology projects
- Help organize and sponsor yearly SSL conference/workshop
- Congress is requesting (officially or unofficially) more industry involvement

NETL

9

CEC/Adv. Init./11-13-03

SSL Partnership

Selection Priorities:

1. Guarantee all interested, qualified[1] organizations have fair and equal access to participate in the group
2. Maximize the group's self-governing while assuring priority 1

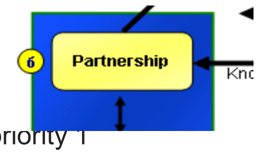
Note 1) It is intended that this group will include organizations that produce SSL products

NETL

10

CEC/Adv. Init./11-13-03

SSL Partnership



Two Possible Methods of Selection

1. **Competitive solicitation to select the "Partnership Group"**
   – Would maximize priority 2 but might limit priority 1
2. **DOE issues a Request for Qualifications to meet certain, DOE defined criteria, i.e. related to production of products.**
   – Would maximize priority 1 but might limit priority 2

- **The chosen method would likely incorporate the positive aspects of both methods to assure both priorities are met.**

Reminder: Priority 1 is related to "fair and equal access" and priority 2 is "self-governing"

NETL

11

CEC/Adv. Init./11-13-03

Intellectual Property

- **DOE plans to request an exceptional circumstances determination to Bayh-Dole (Patent and Trademark Law Amendments Act)**
- **Purpose is to speed the development of improved solid state lighting products**
- **It is envisioned that:**
  – Core developers have easy access to a group of interested manufacturers
  – Non-exclusive licensing (in SSL area within first year after patents issued) will create competition to market products faster

NETL

12

CEC/Adv. Init./11-13-03

SSL Products to Market

SSL Program Goal…

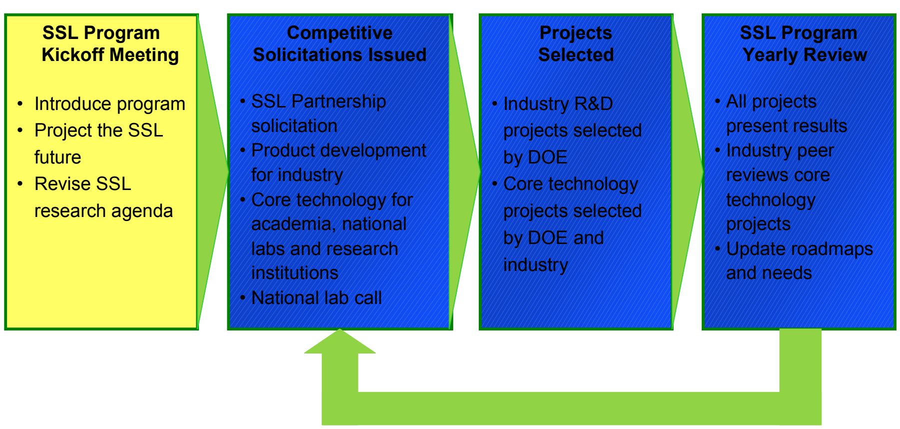
"By 2015, develop advanced solid state lighting technologies that compared to conventional lighting technologies, are much more energy efficient, longer lasting, and cost-competitive by targeting a product system efficiency of 50 percent with lighting that accurately reproduces sunlight spectrum"

NETL

13

CEC/Adv. Init./11-13-03

SSL Operational Plan Process



NETL

14

CEC/Adv. Init./11-13-03

Solicitation Schedule

2Q FY'04	• Lab Call and Solicitation for Applied Research
2Q FY'04	• Industry *et al.*, Solicitation for Product Development
2Q FY'04	• SSL Partnership Solicitation

NETL

15

CEC/Adv. Init./11-13-03

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