

SPECTRALLY ENHANCED CERAMIC INCANDESCENT EMITTER

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Governor

INDEPENDENT ASSESSMENT AND FINAL EISG REPORT

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**ENERGY INNOVATIONS SMALL GRANT
(EISG) PROGRAM**

INDEPENDENT ASSESSMENT REPORT (IAR)

SPECTRALLY ENHANCED CERAMIC INCANDESCENT EMITTER

EISG AWARDEE

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PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable and reliable energy services and products to the marketplace. The PIER Program, managed by the California Energy Commission (Commission), annually awards up to \$62 million of which 5% is allocated to the Energy Innovation Small Grant (EISG) Program. The EISG Program is administered by the San Diego State University Foundation through the California State University, which is under contract to the Commission.

The EISG Program conducts up to four solicitations a year and awards grants for promising proof-of-concept energy research.

PIER funding efforts are focused on the following seven RD&D program areas:

- Residential and Commercial Building End-Use Energy Efficiency
- Energy Innovations Small Grant Program
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally-Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies

The EISG Program Administrator is required by contract to generate and deliver to the Commission an Independent Assessment Report (IAR) on all completed grant projects. The purpose of the IAR is to provide a concise summary and independent assessment of the grant project in order to provide the Commission and the general public with information that would assist in making follow-on funding decisions. The IAR is organized into the following sections:

- Introduction
- Objectives
- Outcomes (relative to objectives)
- Conclusions
- Recommendations
- Benefits to California
- Overall Technology Assessment
- Appendices
 - Appendix A: Final Report (under separate cover)
 - Appendix B: Awardee Rebuttal to Independent Assessment (awardee option)

For more information on the EISG Program or to download a copy of the IAR, please visit the EISG program page on the Commission's Web site at:
<http://www.energy.ca.gov/research/innovations>

or contact the EISG Program Administrator at (619) 594-1049, or email at:
eisgp@energy.state.ca.us.

For more information on the overall PIER Program, please visit the Commission's Web site at
<http://www.energy.ca.gov/research/index.html>.

SPECTRALLY ENHANCED CERAMIC INCANDESCENT EMITTER

EISG Grant # 01-17

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Introduction

Conventional tungsten-filament electric light bulbs are inefficient light sources. They radiate much more power in the infrared part of the spectrum than in the visible. While fluorescent lights are significantly more efficient and longer lived than tungsten lights, their performance has not yet attracted most residential consumers. In addition, fluorescent lights contain significant quantities of mercury, an environmental pollutant. There are other alternative light sources available to the consumer, which are more efficient than tungsten, but they have higher initial costs, and consumers consider them to be a poor spectral match to the solar visible spectrum.

This project proposes a new type of spectrally selective electric light emitter. It is designed to produce more visible light and much less infrared than an equivalent tungsten bulb and without the use of mercury. It would be potentially three times as efficient as tungsten-filament bulbs and significantly longer lived. Lighting accounts for about 19 percent of all U.S. electricity consumption¹ and 9.4% of residential electricity consumption². In 1993 the majority of light bulbs in residential households were incandescent. According to the RECS Survey, 453 million lights out of a total of 523 million used one or more hours per day were incandescent (87 percent)³. California consumers could reduce their electrical consumption proportionally by replacing existing tungsten incandescent bulbs with a more efficient incandescent light. In 1999 discarded fluorescent bulbs contained 17 tons of mercury, of which 71% was deposited in the nation's landfills⁴. While there is no consensus on the importance of mercury in landfills, its increasing concentration in the oceans and commercial fisheries is thought to endanger people's health, particularly the health of pregnant women and their offspring. Thus, California's environment would improve if another, more benign source of light replaced fluorescent lights containing mercury.

The key to the new light bulb is the development of a ceramic, spectrally-selective incandescent emitter that emits strongly in the visible spectrum from its surface when heated. The researcher proposed a millimeter scale emitter as illustrated in Figure 1. The tubular emitter is made of doped zirconia powder, which has the characteristic of being an insulator at low temperatures and a conductor at

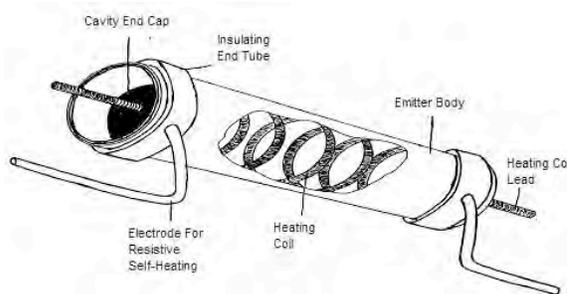


Figure 1. The proposed emitter

¹ [http://www.clasponline.org/download/Energy_Efficiency/2001/142/index.php3]

² [<http://www.eia.doe.gov/emeu/recs/recs4a.html>]

³ [<http://www.eia.doe.gov/emeu/lighting>]

⁴ [<http://www.nema.org/papers/enviimpact.doc>]

high temperatures. This project proposed a new method of heating the emitter. In this method the tube is heated externally up to its conduction temperature using a radiant source. Then a current is passed through the tube causing resistance heating, bringing it to a higher operating temperature. The emitter material suppresses infrared emission from its interior through its microstructure, which is designed to consist of small grains interspersed with small voids. For the light source to succeed, its microstructure must be stable against the usual high-temperature grain growth at its operating temperature of 2,650 K over a lifetime of several thousands of hours.

Objectives

The goal of this project was to determine the feasibility of using a new composite ceramic emitter design in incandescent bulbs to achieve a 300% increase in visible light per watt over standard incandescent bulbs. The researchers established the following project objectives:

1. Utilize a novel heating arrangement to attain a stable emitter temperature of 2,650 K.
2. Optically and physically structure the composite ceramic oxide emitter so that, when heated as designed, it emits three times more of its total radiated power within the visible spectrum than a standard 100 W incandescent bulb does.
3. Generate stability data supporting the long-term goal of achieving an emitter life of greater than 2,100 hours.
4. Obtain updated manufacturing estimates supporting a manufacturing cost goal of approximately \$0.75 per bulb.

Outcomes

The research resulted in the following outcomes:

1. "Utilize a novel heating arrangement to attain a stable emitter temperature of 2650 K."
 - a. Radiant heating routinely achieved emitter turn-on.
 - b. The thermally insulating emitter end tubes and molybdenum electrodes allowed emitter body temperatures of up to 2,653 K.
 - c. The new electro-thermal stability model demonstrated that emitter (temperature) stability is insensitive to emitter dimensions and sensitive to incident radiation intensity.
 - d. There is moderate quantitative agreement between the calculated and the measured minimum coil temperatures needed to prevent thermal runaway, but only qualitative agreement on the operating voltages.
2. "Optically and physically structure the composite ceramic-oxide emitter so that, when heated as designed, it emits three times more of its total radiated power within the visible spectrum than a standard 100 W incandescent bulb does."

Rapid grain growth in the first few minutes at high operating temperatures precluded measurement of spectral selectivity.

3. “Generate stability data supporting the long-term goal of achieving an emitter life of greater than 2,100 hours.”

The researcher did not achieve this objective because rapid grain growth in the first few minutes of operation shortened emitter life. Therefore, no long-term testing was performed.

4. “Obtain updated manufacturing estimates supporting a manufacturing cost goal of approximately \$0.75 per bulb.”

The researcher did not meet this objective because of uncertainty about achieving adequate emitter life.

Conclusions

The PA’s conclusions from this project are:

1. Radiant heating can achieve emitter turn-on as a necessary step, though its outcome was not much in doubt, given the earlier experiments with heating by torch.
2. The molybdenum electrodes work as expected, a significant step since this new substance introduced a potential materials compatibility issue.
3. The new electro-thermal stability model validation does increase understanding of the method. However, the time spent on model development could possibly have been put to better use on more important unsolved issues of material stability.
4. The lack of quantitative agreement with the model is not a serious concern at this time.
5. Rapid grain growth at operating temperature is a serious concern.
6. Emitter lifetime of greater than 2,100 hours has not been demonstrated.
7. The manufacturing goal of \$0.75 per bulb is uncertain at this time, due to the lack of a working design.

The goal of this project, to achieve a 300% increase in visible light per watt over standard incandescent bulbs through a new composite ceramic emitter design, remains unfulfilled. Although the project appears to have been well structured, in retrospect more emphasis could have been placed on issues of materials stability.

Recommendations

The researcher should examine the materials question of grain growth and lay out a plan, based on one or more new experimental results, before additional funding is considered. The PA suggests a program stressing more microstructural analysis of heated specimens and spectral measurements of them at high temperatures. Additional model development seems to be of secondary importance at this stage.

The PA also recommends some analysis of phase diagrams of the constituent pseudo-binary, ternary, quaternary oxide systems and carbon. A specific question in particular is whether initial heating may possibly cause transient liquid phases. If so, that could greatly increase grain growth, since diffusion constants in liquids can be orders of magnitude faster than in solids. If the *final* equilibrated composition does not contain liquid, then *transient* liquid phases might be avoided by optimization of initial time-temperature heating protocols.

Finally, thoria is thought to inhibit grain growth in tungsten and might prove valuable here (with suitable precautions of course). Industry has used it for many years, and its weak radioactivity might not be an environmental impediment. If thoria adequately inhibits grain growth, that result would at least demonstrate the feasibility of the program.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is a reduction in environmental impacts of the California electricity supply or transmission or distribution system. If this research were successful, it would lead to an incandescent light bulb that is three times more efficient than standard tungsten bulbs. Since 87% of the total of 523 million light bulbs used nationally one or more hours per day in residential households are incandescent, replacing them with a design three times more efficient would produce large savings.

The annual, national, average residential electricity consumption for lighting in 1993 was 940 kWh per household. In the Western census region, the average household consumed 856 kWh of electricity for lighting at a yearly cost of \$76 per household (1993 dollars)⁵. While these data are older than desired, and there is significant variation in the per unit cost of electricity within the Western census region, it is clear that California consumers could reduce their electrical consumption and expenditures significantly by replacing existing tungsten bulbs with a more efficient incandescent bulb.

⁵ [<http://www.eia.doe.gov/emeu/lighting/chap2.html#begin>]

Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researcher's overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researcher has not submitted a preliminary business plan at this time. The PA understands that an industrial or commercial company has expressed interest in helping take this technology to market, but only after further development.

Engineering/Technical

This project has not yet met key goals. In particular it is necessary find a way to reduce grain growth at operating temperature

Legal/Contractual

The researcher has secured a patent on this technology and appears to have applied for another one. No contractual agreements have been made.

Environmental, Safety, Risk Assessments/ Quality Plans

The main concern is the technical issue of arresting grain growth rather than environmental/safety/quality issues. There are, however, no obvious impediments to the program of an environmental nature.

Production Readiness/Commercialization

No commercial partner has been explicitly identified.

Appendix A: Final Report (under separate cover)

Appendix B: Awardee Rebuttal to Independent Assessment (none submitted)

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EISG FINAL REPORT

SPECTRALLY ENHANCED CERAMIC INCANDESCENT EMITTER

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Inquires related to this final report should be directed to the Awardee (see contact information on cover page) or the EISG Program Administrator at (619) 594-1049 or email eisgp@energy.state.ca.us.

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Abstract

In general, in the published R&D undertaken by various researchers and inventors, the major impediments to developing considerably more efficient general purpose incandescent lighting include one or both of the following: (1) deficiencies in phase stability at high temperatures, (2) deficiencies in spectral selectivity of emitter materials, (3) operational shortcomings in the various means used to heat the emitter. Prior work at Sonsight Inc. with scattering enhanced selective emitters demonstrated that significant spectral selectivity can be attained in optically thick incandescent emitters by combining large optical scattering coefficients with absorption coefficients within the VIS that are much larger than that within the NIR. However the heating mechanism of those emitters limited operating temperatures to roughly 2000 K. The work reported here investigated the possibility of achieving similar spectral selectivities out to 2650 K, and thereby attaining almost three times the energy efficiency of standard incandescent bulbs. However, it was found that grain growth at high temperatures yields significantly decreased optical scattering, resulting in substantially decreased spectral selectivity. Direct electrical heating of the ceramic selective emitter body to 2650 K via molybdenum electrodes in vacuum was demonstrated. For the zirconia based ceramic, a negative thermal coefficient of electrical resistance normally results in thermal instability during resistance heating. This leads to thermal runaway and requires the use of resistive ballast. However the current work demonstrates that with the addition of radiant heating ballast is unnecessary. A significant energy savings potential exist, but future research directed at inhibiting high temperature grain growth is required.

Key Words: Selective emitter, thermal radiator, incandescent lighting, radiative transfer, thermal runaway.

Executive Summary

Introduction

Current incandescent bulbs are inefficient and relatively short lived, but they are inexpensive and versatile. And while there are a number of special purpose lighting options, to date only the fluorescent lamp offers an acceptable level of cost, safety, color rendering and efficiency to be a viable alternative to tungsten-filament incandescent lighting for use as a general lighting source. However, the vast majority of residential lighting is still standard incandescent lamps. For these consumers the advantages of incandescent lighting clearly outweigh its disadvantages. And while, for the most part, commercial and industrial consumers use fluorescent lighting instead of incandescent lamps, the advantages of incandescent lighting, including intensity, full-spectrum illumination, versatility and purchase price) are highly desirable in these sectors as well.

In general, in the published R&D undertaken by various researchers and inventors, the major impediments to developing considerably more efficient general purpose incandescent lighting include one or both of the following: (1) deficiencies in phase stability at high temperatures, (2) deficiencies in spectral selectivity of emitter materials, (3) operational shortcomings in the various means used to heat the emitter. Prior work at Sonsight Inc. with scattering enhanced selective emitters demonstrated that significant spectral selectivity can be attained in optically thick incandescent emitters by combining large optical scattering coefficients with absorption coefficients within the VIS that are much larger than that within the NIR. However the heating mechanism of those emitters limited operating temperatures to roughly 2000 K. The work reported here investigates the possibility of achieving similar spectral selectivities out to 2650 K, and thereby attaining almost three times the energy efficiency of standard incandescent bulbs. A number of energy, economic and environmental benefits such as less energy use and cost, reduced CO₂ emissions, and no mercury contamination would result.

Project Objectives

Project objectives were to:

1. Utilize a novel heating arrangement to attain a stable emitter temperature of 2650 K.
2. Optically and physically structure the composite ceramic oxide emitter such that when heated as designed, it emits, within the visible spectrum, a three times larger portion of its total radiated power than that emitted by a standard 100 W incandescent bulb.
3. Generate stability data supporting the long-term goal of achieving an emitter life of greater than 2100 hours.
4. Obtain updated manufacturing estimates supporting a manufacturing cost goal of approximately \$0.75 per bulb.

Project Approach

Task 1: Determine Baseline Efficiency at 2650 K. This task involved fabricating and testing the simplest form of the emitter body, a solid rod. The body is extruded from a mixture of ceramic oxides having various volume fractions of zirconia, yttria, ceria and calcia, and then sintered. Platinum electrodes are subsequently attached. Insulating end tubes are used to provide a degree of thermal insulation between the electrodes and the emitter body. The emitter body is heated to its turn-on temperature, after which electrical resistive heating applied via the electrodes generates the 2650 K operating temperature. Spectral intensity measurements allow calculation of spectral selectivity. A multi-wavelength pyrometry calculation was developed that allow a determination of the emitter body temperature from the spectral measurements.

Task 2: Fabricate and Characterize Baseline Emitter With Molybdenum Leads and Dual Heater Arrangement. In this task, an external heating coil was used to radiantly heat the emitter body to its operating temperature. Molybdenum electrodes electrically attached to but thermally insulated from the emitter body are used instead of platinum electrodes.

Task 3: Extend Electro-Thermal Stability Model to Include Optical Scattering Media of Arbitrary Thickness, and Characterize Stability of Baseline Emitter. An analytical model that describes the voltage vs. temperature relationship of the emitter body and correlates the onset of thermal runaway with emitter dimensions and heating coil temperature was developed. The model was used to help characterize the thermal stability of the solid rod emitter body.

Task 4: Fabricate and Characterize Tube Emitter. This task involved extruding and testing tubular emitter bodies. Intensity spectra were measured, and the thermal stability analyzed.

Task 5: Investigate Feasibility of Rare Earth Oxide Doping – New Objective. The pronounced emission peaks within the VIS suggests that rare earth oxides would allow greater spectral selectivity than the compositions of yttria, ceria and calcia dopants previously used. Terbium oxide and dysprosium oxide dopants were added to the zirconia matrix, and radiation intensity spectra were obtained.

Project Outcomes

The outcomes of Objective 1 are the following:

- Radiant heating was routinely used to achieve emitter turn-on.
- Thermally insulating emitter end tubes and molybdenum electrodes were used to allow emitter body temperatures of up to 2653 K.
- The new electro-thermal stability model shows that emitter stability is insensitive to emitter dimensions and substantially sensitive to incident radiation intensity.
- There is moderate quantitative agreement between the calculated and the measured minimum coil temperatures needed to prevent thermal runaway, but only qualitative agreement on the operating voltages.

The Outcome of Objective 2 is that,

- Grain growth at high operating temperatures significantly degrades spectral selectivity.

The Outcome of Objective 3 was not met.

The Outcome of Objective 4 was not met.

Conclusions

The work performed allowed the following conclusions:

1. It is possible to routinely operate the emitter at high temperatures (i.e. 2650 K) with insulating end tubes and molybdenum electrodes. Platinum need not be used, making the lamp significantly easier to commercialize.
2. It is possible to operate the emitter without resistive ballast, and use radiant heating instead. Combined with a coil-within-tubular emitter design, this makes possible a direct replacement of the tungsten filament within incandescent bulbs.
3. Significant energy savings are potentially possible, but the degradation of spectral selectivity caused by high temperature grain growth requires correction before proceeding with commercialization.

Recommendations

Research into the effectiveness of various grain growth inhibitors applicable to the pertinent powder compositions should be undertaken.

Public Benefits to California

Benefits to California include:

- Substantial energy savings,
- No mercury contamination,
- Improved health and productivity.

Introduction

Standard incandescent lightbulbs waste roughly 90% of their input power and function for roughly 1000 – 2000 hours, but they are inexpensive and versatile. And while there are a number of special purpose lighting options such as metal halide, high pressure sodium, and sulfur lamps, to date only the fluorescent lamp offers an acceptable level of cost, safety, color rendering and efficiency to be a viable alternative to tungsten-filament incandescent lighting for use as a general lighting source. However, while significantly more efficient and long-lived than incandescent bulbs, fluorescent lighting has been insufficient to sway most residential consumers; the vast majority of residential lighting is still standard incandescent lighting. For these consumers the advantages of incandescent lighting clearly outweigh its disadvantages. And while, for the most part, commercial and industrial consumers use fluorescent lighting instead of incandescent lamps, the advantages of incandescent lighting, including intensity, full-spectrum illumination, versatility and purchase price) are highly desirable in these sectors as well. The invention is a new type of incandescent light source that is projected to combine these advantages with an efficiency and longevity more than twice that of a standard 100 W incandescent light bulb. The efficiency is obtained by tuning the material parameters affecting radiative transfer within a ceramic oxide composition to allow significant selective emissivity within the visible spectrum. The result is a number of energy, economic and environmental benefits such as less energy use and cost, reduced CO₂ emissions, no mercury contamination, and a healthier and more productive optical/visual environment. The applicable PIER program area is **Building End-use Efficiency**.

For an incandescent body radiating at a particular temperature, the intensity as a function of wavelength is the product of the emissivity and the Planck blackbody spectral distribution. The Planck distribution varies strongly with temperature, and therefore, so does the radiated intensity. The hotter the blackbody, the shorter are its median wavelength and the wavelength at which it maximally radiates. As such, up to about solar temperatures (5776 K), the visible-to-infrared (VIS/IR) intensity ratio increases with temperature. Since thermal material properties limit practical incandescent lighting to temperatures less than 3100 K (a standard 100 W tungsten bulb operates at about 2770 K), significant improvements in energy efficiency require making the emissivities within the near infrared (NIR) much smaller than those within the visible spectrum. Selective emitters are incandescent radiant bodies with emissivities that are substantially larger in a selected part of the spectrum, thereby significantly shifting their radiated spectral distribution from that of a blackbody radiating at the same temperature.

Due to their respective advantages, incandescent emitters are typically either optically thin or optically thick. By definition, optically thin emitters are good light transmitters (i.e. $(a_\nu + \sigma_\nu)d \ll 1$, where a_ν is the spectral absorption coefficient at frequency ν , σ_ν is the scattering coefficient, and d is the characteristic emitter width). Such emitters are important because their spectral emissivity is directly proportional to their spectral absorption coefficient (i.e. emissivity = $a_\nu d$), and for certain materials, a_ν can vary by orders of magnitude from the VIS to the NIR. Therefore, while not extremely intense light sources, thin emitters have the potential of being spectrally very selective and therefore very efficient light sources.

Unlike thin emitters, optically thick emitters are opaque (i.e. $(a_v + \sigma_v)d \gg 1$) with an emissivity given by $1 - R_v$ (where R_v is the overall reflectivity), which for small R_v can yield intense emissions. In this case selective emissivity can be obtained by utilizing emitter materials having reflectivities larger within the NIR than within the VIS. However, if the optical scattering coefficient σ_v is not much larger than a_v , R_v is just the single crystal surface reflectivity, and the relatively small variations in R_v exhibited by most refractory materials within the visible and NIR regions are not enough to provide significant selectivity. The tungsten-filament emitter used in standard incandescent light bulbs is an example. Its emissivity, which is almost two times greater within the VIS than within the NIR, provides very little selectivity because even at 2770 K, the total power within the NIR of the Planck distribution is an order of magnitude greater than that within the VIS.

An optically thick emitter resulting in better selectivity than tungsten is the Nernst Glower (Ropp 1993). Commercially produced from 1902 to 1912, it consists of a ceramic oxide filament (typically including zirconia, thoria, ceria and yttria) that glows brightly when resistively heated to up to 2650 K by an electric current. Though its VIS/NIR intensity ratio is greater than that of tungsten, the glower has a negative temperature coefficient of resistance, which causes thermal runaway to catastrophically high temperatures. Ballast in the form of a wire-wound resistor having a positive current vs. voltage curve is therefore required. Energy loss within the ballast decreases overall energy efficiency to about half that of tungsten bulbs. Moreover, since electrical conduction within the ceramic composition occurs only at high temperatures, a separate heater is required to attain “turn-on” temperatures.

As with thick emitters, attempts have been made to exploit the selective emitting potential of thin emitters. However, the need to maintain $a_v d \ll 1$ while providing adequate illumination typically limits the emitter configuration to a selectively emitting semiconducting thin film (McIntosh 1996, Fok 1970, Fok 1962) or ceramic oxide thick film (Chubb et al. 1999) deposited on a low emissivity substrate. However, emissions from the substrate outside the selected spectrum of the emitter are transmitted through the emitter (which has high transmission) and degrade the spectral selectivity. Another approach is to heat freestanding optically thin emitters within a gas flame that does not itself radiate extensively within the NIR. This approach, used with the Welsbach mantle for gas lanterns, utilizes a mixture of ceramic oxides (mainly thoria and ceria) that is impregnated within thin gauze strands and, for strength, arranged within a lattice framework. When first lit, the gauze burns away, leaving the ceramic composition in the form of a lattice of thin ceramic strands. Since, for both thoria and ceria, the spectral absorptivity is much greater within the VIS than within the NIR, and since the ceramic strands are optically thin with spectral emissivity proportional to spectral absorptivity, the mantles radiate at significantly greater VIS/NIR intensity ratios than tungsten bulbs. But gas flame heating is unsuitable for general lighting purposes and the lanterns are limited to mainly outdoor recreational use. The fragility of the ceramic strands is also undesirable.

A relatively recent approach to selective emissivity that combines the potentially high selectivity of optically thin emitters with the versatility of thick emitters is to utilize significant optical scattering within materials having large variations in spectral absorptivity (see for example

Warren et al. 1976, Cadoff 1977, Chubb and Lowe 1993, and McIntosh, 2000). With this scattering enhanced approach, an optically thick emitter can radiate as if optically thin because scattering limits the distance below the surface from which significant amounts of internally generated radiation can emerge (in this case, the overall R_v depends on σ_v and a_v as well as the single crystal surface reflectivity). The greater the scattering the greater is the proportionality between the emissivity and the absorption coefficient. McIntosh (2000) describes such a scattering enhanced emitter in which the body of the disclosed Multi-Element Selective Emitter (MESE) is structured in the form of a hollow bi-layer tube with a tungsten heating coil enclosed within (Fig. 1). The coil does not physically contact the tube, thereby avoiding thermally activated surface-to-surface corrosion. Heating is accomplished by radiant energy transfer. A VIS/NIR emissivity ratio almost three times greater than that of tungsten operating at the same temperature was obtained; however, the radiant heating approach of the MESE yields maximum outer layer temperatures of not much greater than 2000 K. Consequently, though much better than a tungsten emitter operated at the same temperature, the VIS/(VIS+NIR) intensity ratio is no greater than that of a standard tungsten bulb operated at 2770 K. The other implementations proposed by Warren et al. (1976), Cadoff (1976), and Riseberg (1985) suffer from heating limitations, poor thermal stability, and/or low total energy efficiencies.

The current work sought to overcome prior selective emitter design shortcomings by constructing the emitter body in tubular form and of similar materials and radiative transfer design as the MESE, including an internally mounted heating coil that does not contact the body, yet is fully enclosed such that it does not externally radiate and waste energy. As with the MESE, the coil provides radiant heating, but as described below, it also provides thermoelectric stability that obviates the need for ballast. In addition, resistive self-heating like that of the Nernst glower is provided to ensure a high operating temperature of 1650 K can be attained. This is accomplished by sending current through the emitter body via electrodes connected to the emitter ends. As with the Nernst glower, the emitter must be heated to its “turn-on” temperature before electrical conduction and resistive self-heating can begin. The internal heating coil is well suited for this.

The current report summarizes the funded work performed, and is organized as follows. The project objects are presented, followed by sections dealing with the project approach and the project outcomes. This is followed by the conclusions, then recommendations, and then a summary of perceived public benefits to California.

Project Objectives

Project objectives were to:

5. Utilize a novel heating arrangement to attain a stable emitter temperature of 2650 K.
6. Optically and physically structure the composite ceramic oxide emitter such that when heated as designed, it emits, within the visible spectrum, a three times larger portion of its total radiated power than that emitted by a standard 100 W incandescent bulb.
7. Generate stability data supporting the long-term goal of achieving an emitter life of greater than 2100 hours.
8. Obtain updated manufacturing estimates supporting a manufacturing cost goal of approximately \$0.75 per bulb.

Project Approach

Task 1: Determine Baseline Efficiency at 2650 K

Starting with the ceramic oxide and carbon powder compositions used with the MESE, baseline VIS/NIR radiant power and emissivity ratios at temperatures up to 2650 K were determined by fabricating emitter rods with refractory oxide and pore structure configurations projected to yield high VIS selectivity. The powders were mixed within a planetary ball lab mixer at medium speeds after which a sucrose solution binder and castor oil plasticizer were added. The rods were formed via a ram extruder using dies with exit holes in the sub millimeter size range.

Subsequent sintering was performed at approximately 1600 C within a molydisilicide furnace. Short ceramic tubes with a 1 mm wall thickness formed from the same powder composition were also extruded and subsequently sintered to form end tubes and attached to the emitter ends of the emitter rod and cemented on. Platinum wire electrodes were then attached to both end tubes via a zirconia-based cement. The low thermal conductivity of the end tubes helps to maintain electrode temperatures are maintained well below the melting point of platinum. A propane flame was used to initially heat the emitter and attain its turn-on temperature, after which a 10 mT vacuum was applied (air operation is possible but vacuum operation is more stable) within a bell jar. The radiated intensity spectrum for $\lambda = .4 - 1.04 \mu\text{m}$ was measured with an Ocean Optics S2000 fiber optic spectrometer (VIS spectrum wavelengths are $\lambda = .4 - .7 \mu\text{m}$).

Unlike metals, resistivity of an ionic conductor like zirconia depends on other factors besides temperature (Ex. porosity, dopant concentration and oxygen pressure), making it difficult to determine temperature from resistance measurements. Radiation pyrometry was therefore used. Temperatures can be measured optically because the spectral intensity distribution $W(\lambda, T)$ is a function of both wavelength λ and temperature T . Since W is the product of the spectral emissivity and the Plank blackbody distribution, if the emissivity is known T can be determined by measuring W at one or more given wavelengths. Unfortunately, the unknown spectral selectivity of a new emitter body precludes knowing the emissivity. Therefore, the emissivity

and temperature were simultaneously determined via a multi-wavelength pyrometry approach (Gardner, 1980) in which the emissivity model for optically scattering media given by Chubb and Lowe (1993) was used to determine the functional form of the emissivity. However, there are a number of parameters such as surface reflectivity, index of refraction, and the exact absorption and scattering coefficients, which require precise values for a meaningful implementation of the emissivity expression within the model. While ballpark figures exist, precise values for a particular sample are difficult and expensive to determine. This problem was solved by expressing the emissivity in terms of five unknown variables, including temperature (see Appendix II), and fitting the resulting calculated $W(\lambda, T)$ to the measured $W(\lambda, T)$ to simultaneously determine T and the emissivity. An additional benefit is that, once obtained, the emissivity parameters can be used to determine spectral emissivities outside the measured range, thereby projecting the radiated intensity spectra to well within the NIR. This method was used to determine the VIS/(VIS+NIR) ratio out to a wavelength of $1.8 \mu\text{m}$.

Task 2: Fabricate and Characterize Baseline Emitter With Molybdenum Leads and Dual Heater Arrangement

To establish the suitability of using molybdenum leads and using a heating coil instead of the propane torch to attain emitter turn-on temperature, emitters were mounted within external heating coils and placed within an evacuated (i.e. 10 mT) bell jar. First platinum and then molybdenum electrodes were used. As before, end tubes were used as thermal insulation between the electrodes and the ceramic oxide emitter. Two autotransformers were used to separately power the emitter and the heating coil. After energizing the coil to temperatures of up to 2310 K (1900 K , as determined by a Planck function fit to the measured spectral intensity distribution, was typically sufficient to attain emitter turn-on), power to the emitter was increased until it significantly conducted. The heating coil was turned off prior to making emitter spectral measurements.

Task 3: Extend Electro-Thermal Stability Model to Include Optical Scattering Media of Arbitrary Thickness, and Characterize Stability of Baseline Emitter.

The electro-thermal stability model derived by McIntosh (1996) was generalized to include internal optical scattering by utilizing the spectral emissivity expression given by Chubb and Lowe (1993). However, as mentioned above, there are a number of parameters in the model that require precise values but are difficult to determine. As stated, this problem was solved by modeling the spectral distribution of the radiated power, expressed in terms of the emissivity expression and the Planck blackbody distribution, in terms of five unknown variables, including temperature. These variables were then determined by fitting the modeled spectrum to the measured spectral distribution. Utilizing the calculated parameters within the emissivity model, and the emissivity model within the electro-thermal stability model, the stability model was used to estimate the temperature at the onset of thermal runaway, as well as to determine the coil temperature needed to prevent thermal runaway. A detailed description of the model is given in Appendix III.

To obtain a better understanding of the effects of emitter dimensions and incident radiant intensity on emitter stability, and to gain trust in the predictive capability of the stability model, the effects of these parameters on the onset of thermal runaway was experimentally investigated and compared with the model. The emitter was mounted within the heating coil and placed within the evacuated bell jar. Normally, the emitter is connected in series with resistive ballast, but for the purpose of this experiment, the ballast was removed, and except for a series connected ammeter (and a voltmeter connected across the electrodes), the emitter was connected directly across the autotransformer. After energizing the heating coil to a predetermined temperature, the emitter voltage was slowly increased. If normal stable operating voltage and current could not be attained, the heating coil temperature was increased and the process repeated until stable operation ensues. This process was repeated for several emitter diameters and compared with the predictions of the model.

Task 4: Fabricate and Characterize Tube Emitter

Emitter bodies in the form of hollow tubes were extruded with the ram extruder and tube die yielding 1.5 mm and 2.5 mm tube ID's with a 3.2 mm tube OD. Similar powder mixture compositions as that used for the rod emitters were used. And as before, similar short ceramic tubes formed from the same powder composition were extruded and sintered to form end tubes and attached to the emitter ends of the emitter tubes and cemented on. Molybdenum electrodes were then attached to the end tubes. The tube emitter was then mounted within external heating coils and placed within an evacuated bell jar. To investigate the effect of tube wall thickness on emitter stability, a similar experimental procedure as that of Task 3 was followed.

Task 5: Investigate Feasibility of Rare Earth Oxide Doping – New Objective

The fluorescent spectrum of several rare earth oxides is shown in Fig. 2. The pronounced emission peaks within the VIS suggests that these oxides would allow greater spectral selectivity than the compositions of yttria, ceria and calcia dopants previously used. Terbium oxide and samarium oxide are particularly attractive because they have no absorption peaks within the NIR. Various small volume fractions of terbium and dysprosium oxide were added to magnesia stabilized zirconia, and planetary ball milled for several hours to obtain rare earth doped zirconia. Subsequent rod extrusion and sintering yielded emitter rods that were mounted and operated to obtain intensity spectra.

Project Outcomes

Outcomes of Objective 1 (Utilize a novel heating arrangement to attain a stable emitter temperature of 2650 K).

The objective was to demonstrate using radiant heating to achieve emitter turn-on, and to investigate the use of radiant heating coupled with direct resistive heating of the emitter body to

prevent thermal runaway and provide stable emitter incandescent temperatures. Tasks 2, 3, and 4 addressed this objective. The outcomes are the following:

- **Radiant heating was routinely used to achieve emitter turn-on.** Fig. 3 shows one of the emitter mounting configurations used. In this particular example, two thin emitters are mounted vertically on molybdenum electrodes between two magnesium oxide tubes that serve to maintain fixed spacing between the emitters and the heating coil. A heating coil temperature of around 1900 K was typically sufficient to achieve emitter turn-on. A configuration with the emitter mounted concentrically along the axis of the heating coil was also used.

- **Thermally insulating emitter end tubes and molybdenum electrodes were used to allow emitter body temperatures of up to 2653 K.** The maximum temperature obtained with the insulating end tubes before significant corrosion of the platinum electrodes was approximately 2450 K. To attain 2650 K, molybdenum electrodes were used. Operation in a vacuum at approximately 2653 K for extended periods (i.e. over 5 hours) showed no signs of corrosion at the emitter rod – electrode interface.

- **The new electro-thermal stability model shows that emitter stability is insensitive to emitter dimensions and substantially sensitive to incident radiation intensity.** Fig.'s 4, 5 and 6 show the stability curves for rod emitters of radii 1 mm, .5 mm, and .25 mm respectively (see Appendix I for other parameter values). Each figure shows three voltage vs. temperature (i.e. V-T) curves corresponding to coil temperatures of 1000 K, 1800 K and 2300 K. Thermal runaway occurs at negative slopes of the V-T curve because a small upward fluctuation in temperature requires a decrease in voltage to restore equilibrium between power generated and power dissipated (radiated and conducted). But since the voltage is fixed, excessive heat is generated instead, which increases emitter temperature, which, since the temperature coefficient of electrical resistivity is negative, lowers electrical resistance and causes even more heat to be generated (i.e. thermal power = (voltage)²/resistance). The temperature rapidly increases until a positive portion of the slope is reached, where any temperature increase requires a voltage increase. It can be seen in the figures that thermal runaway becomes less severe as the coil temperature increases (i.e. the negative slope becomes less steep), and actually disappears at a 2300 K coil temperature. The physical explanation is that the absorbed radiant power raises the emitter temperature to significantly greater values than otherwise possible at the supplied voltage. Since the radiated power, which is proportional to (temperature)⁴, is now substantially greater (or, from an alternative perspective, the resistively generated power, which is proportional to (voltage)², is now substantially less), thermal power fluctuations are easily radiated away. As a result, in these particular cases, a 2300 K coil can be used to prevent thermal runaway; the 1000 K and 1800 K coils can decrease the rapidity at which runaway ensues, but will not prevent it.

Two emitter tubes fabricated to study the effects of radiant heating on electro-thermal stability (i.e. OD 3.2 mm and ID of 1.5 mm and 2.5 mm) were also modeled. The V-T curves, were similar to those of the rods, implying a similar insensitivity to tube dimension (in this case tube wall thickness) and a similar sensitivity to radiant heating intensity.

- **There is moderate quantitative agreement between the calculated and the measured minimum coil temperatures needed to prevent thermal runaway, but only qualitative**

agreement on the operating voltages. Tasks 3 and 4 summarize the experimental work done to determine the radiation intensities required to prevent thermal runaway. Table 1 compares the theoretically projected with the experimentally obtained minimum coil temperatures required to prevent thermal runaway.

Table 1. Experimental and Calculated Minimum Coil Temperatures

Emitter Type and Size (mm) (All emitter lengths are 10 mm)		Minimum Calculated Coil Temp. (K)	Minimum Measured Coil Temp. (K)
Tube OD = 3.2	ID = 1.5	2100	2173
	ID = 2.5	2100	2190
Rod	OD = 1	2100	2234
	OD = .5	2150	2245
	OD = .25	2150	2221

The table shows moderate agreement between calculated and measured values of the minimum coil temperatures. The tubes seem to require somewhat smaller coil temperatures. This may be probably because they have greater external surface area-to-volume ratios than the rods, enabling them to more efficiently radiate away the thermal power generated within their volume.

Due to the inability to determine emitter body temperature while externally applying radiant heating, the stable portions of the calculated V-T curves could not be experimentally verified. However, although the actual operating voltages used did generally increase with decreasing emitter radius, these voltages were almost an order of magnitude greater than those shown in Fig.'s 4 to 6. We do not have a satisfactory explanation for this discrepancy.

Outcome of Objective 2 (Optically and physically structure the composite ceramic oxide emitter such that when heated as designed, it emits, within the visible spectrum, a three times larger portion of its total radiated power than that emitted by a standard 100 W incandescent bulb).

The objective was to structure the optical scattering and optical absorptivity of the emitter body such that, though optically thick, it's emissivity would be a strong function of its spectral absorptivity, thereby yielding a VIS selective emitter. The outcome is the following:

- **Grain growth at high operating temperatures significantly degrades spectral selectivity.**

Fig. 7 is a micrograph of the emitter surface after sintering, while Fig. 8 shows the surface of a similar emitter after operation at 2540 K. The figures demonstrate a ten-fold grain growth at high temperatures. Fig. 9 compares the spectral intensity spectra of two similar emitters. The emitter operated for 1 hour at 2460K show significantly less selectivity than that operated for 1 minute at 2472 K. This is explained by the grain growth seen in Fig. 8. The majority of optical scattering occurs at the grain-void boundary. Larger grain sizes imply less optical scattering. Since greater optical scattering allows greater selectivities, and high temperature operation significantly increases grain size, extended time spent at high temperatures severely degrades spectral selectivity.

The oxides of cerium, calcium, terbium and dysprosium were used to dope 13 % yttria-stabilized zirconia and 3% magnesia-stabilized zirconia to typical volume fractions of .02 to .2. Within this range, for a particular composition, the VIS/(VIS+NIR) ratios were not particularly sensitive to volume fraction, while for significantly larger volume fractions, stable operation was difficult. Average grain sizes were on the order of 1 μ m or less. Table 2 lists the obtained VIS/(VIS+NIR) ratio for essentially the best doping concentration.

Table 2. Typical Measured VIS/(VIS+NIR) Ratios For Wavelengths of .4 μ m – 1.8 μ m

Dopant	Measurement Temperature (K)	Dopant Volume Fraction	VIS/(VIS+NIR) With Yttria Stabilized Zirconia Matrix	VIS/(VIS+NIR) With Magnesia Stabilized Zirconia Matrix
Ceria	2585	.07	.141	.138
Calcia	2548	.05	.120	.123
Terbium Oxide	2579	.05		.091
Dysprosium Oxide	2554	.1		.103

The corresponding VIS/(VIS+NIR) ratio for tungsten at 2770 K is .095. Therefore, the best efficiency was obtained for ceria doping at 1.5 that of tungsten, while the worst was that for terbium oxide, which was slightly less than tungsten's. This implies that the spectral absorptivity of ceria is the most selective with respect to the VIS at typical operating temperatures. The reason for the sub par performance of the terbium and dysprosium dopants is uncertain, particularly given the allowed energy band transitions implied by Fig. 2.

Outcome of Objective 3 (Generate stability data supporting the long-term goal of achieving an emitter life of greater than 2100 hours).

This objective was not met. In the Outcome for Objective 2, it was determined that high VIS selectivity cannot be maintained for greater than a few minutes, and long term testing with degraded selectivity was not pursued because greater selectivities first need to be obtained.

Outcome of Objective 4 (Obtain updated manufacturing estimates supporting a manufacturing cost goal of approximately \$0.75 per bulb.).

This objective was not met; an emitter configuration yielding greater selectivities must be obtained before a commercial configuration and more accurate manufacturing costs can be projected.

Conclusions

The work performed provided answers to a number of important questions. The first is that it is possible to routinely operate the emitter at high temperatures (i.e. 2650 K) with insulating end

tubes and molybdenum electrodes. Platinum need not be used, making the lamp significantly easier to commercialize.

A second conclusion is that it is possible to operate the emitter without resistive ballast, and use radiant heating instead. This is important because resistive ballast significantly decreases overall lamp efficiency. It should be possible to mount a heating coil within a hollow emitter body, and use the coil both to achieve the emitter turn-on temperature and to prevent thermal runaway. This means that, given a selectively emitting body, the simple coil-within-emitter design depicted within Fig. 1 is possible, and can essentially directly replace the tungsten filament within incandescent bulbs.

Spectral intensity measurements show that, after the first few minutes of operation, spectral output efficiencies of only about 1.5 times that of a standard tungsten bulb are possible. Microscope analysis indicates this is due to significant grain growth resulting in substantially less optical scattering and spectral selectivity. Considering that the spectral efficiency of high temperature halogen bulbs is not far from this value of 1.5, enhanced spectral selectivity must be obtained before proceeding with commercialization.

Recommendations

The main technical obstacle is finding a way to maintain considerable optical scattering for extended periods at high temperatures. Perhaps the best way forward is research into the effectiveness of various grain growth inhibitors applicable to the pertinent powder compositions. For instance, minute amounts of thoria has been effectively utilized within the construction of Welsbach gas lantern mantles to inhibit grain growth. Unfortunately, thoria is radioactive and its inclusion here, even in minute quantities would be undesirable. However, other grain growth inhibitors have been used in other mantle compositions as well, and perhaps it would be best to start with these. Once this hurdle is traversed, long term testing of the emitter and more accurate manufacturing cost projections can be undertaken.

Public Benefits to California

Substantial Energy Savings: According to data taken from the CRC Handbook of Energy Efficiency (Kreith and West, 1997), in 1996 in the U.S., incandescent lighting consumed approximately 9 % of the total U.S. electric energy production. This amounts to about 2.3×10^{11} kWh, which, at 10 cents per kWh works out to \$23 billion every year. For an energy efficiency of the invention projected to be twice that of incandescent bulbs, with 100 % implementation, the associated yearly energy savings would be over 1.1×10^{11} kWh, which translates to a cost savings of over \$11 billion per year.

No Mercury Contamination: According to Lamp Recyclers Inc. (2001), national consumption of mercury-containing fluorescent and HID lamps exceeds 650 million annually. Their disposal results in over 28,000 pounds of mercury entering our environment. Spent lighting products are the second largest source of mercury contamination in our country's municipal solid waste

system. And while new, low mercury lamps have been introduced, they still contain 40 % of the mercury in old style lamps, which make them significant sources of mercury as well. Since projected end-use efficiencies of the proposed innovation is potentially comparable to that of fluorescent lamps, and since they contain no mercury or other toxic substances, they would provide a viable nontoxic alternative.

Improved Health and Productivity: The projected radiated spectrum of the developed invention is broader and more sun-like than other general lighting sources. The advantages of full spectrum lighting in the indoor environment include perceiving fine details clearer; performing visually demanding tasks (such as color matching) more effectively; and reducing glare, thereby lessening eye fatigue and strain. Full spectrum lighting also promotes alertness and improved learning while combating Seasonal Affective Disorders (SAD's).

References

- Brook, R.J., Pelzmann, W.L., and Kroger, F.A., *J. Electrochem. Soc.* **117**, 185 (1971).
- Cadoff, L. H., *Refractory-Oxide-based Incandescible Radiators and Method of Making*, Patent# 4,016,446, (4/5/1977).
- Chubb, D.L. and Lowe, R.A., *J. Appl. Phys.* **74**, (9), 5687 (1993).
- Chubb, D.L., Pal, A.T., Patton, M.O., and Jenkins, P.P., *J. European Ceramic Soc.* **19**, 2551, (1999).
- Fok, M.V., *Incandescent Lamp With a Glower Made of an Alloyed Semiconductor Material*, Patent# 3,502,930, (3/24/1970).
- Fok, M.V., *Optics and Spectroscopy*, **13**, 349 (1962).
- Gardner, J.L., *High Temperatures – High Pressures*, **12** 699 (1980).
- Kreith, F. and West, R.E., *CRC Handbook of Energy Efficiency*, (CRC Press, N.Y., 1997).
- McIntosh, D.R., Spencer, and M., Lindsay, J., *Thermal Runaway in Thin Semiconducting Incandescent Emitters*, Unpublished report written for the Materials Science Research Center at Howard University, (Washington D.C. 1996).
- McIntosh, D.R., *Multielement Selective Emitter: A New High Efficiency Incandescent Light Source – Final Project Report*, DOE Grant No. DE-FG36-99601039, (11/3/1999).
- McIntosh, D.R., *Multielement Selective Emitter*, Patent# 6,018,216, (1/25/2000).
- Nakamura, A., and Wagner, J.B., *J. Electrochem. Soc: Electrochemical Science and Technology*, **127**, (11), 1980.
- Riseberg, L.A., *Candolumiscent Electric Light Source*, Patent# 4,539,505, (9/3/85).
- Ropp, R.C., *The Chemistry of Artificial Lighting Devices* (Elsevier, N.Y., 1993).
- Warren, D.W. Feldman, *Incandescent Source of Visible Radiation*, Patent # 3,973,155, (8/3/76).

Appendix I – Figures

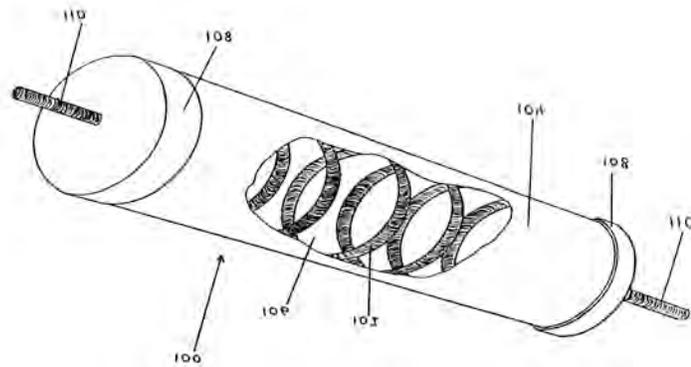


Fig. 1, The Multi-Element Selective Emitter (MESE)

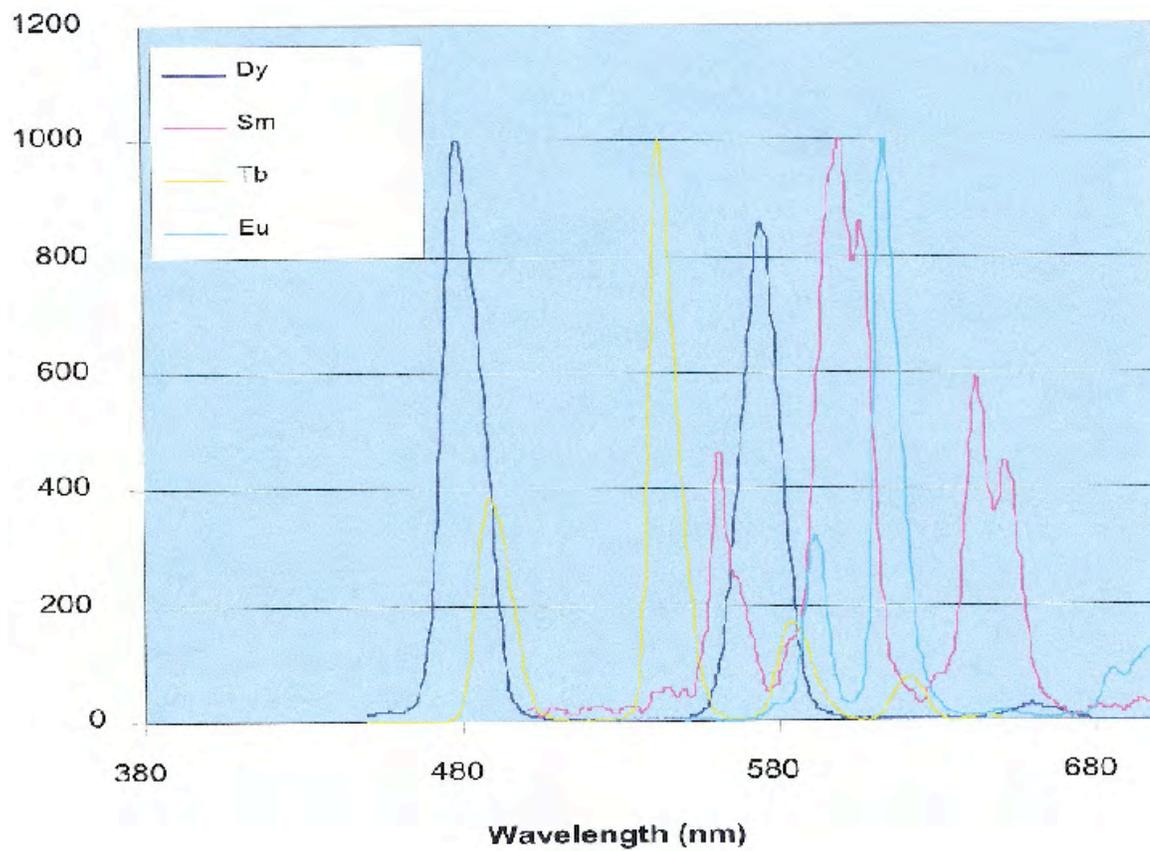


Fig. 2. Rare earth spectra

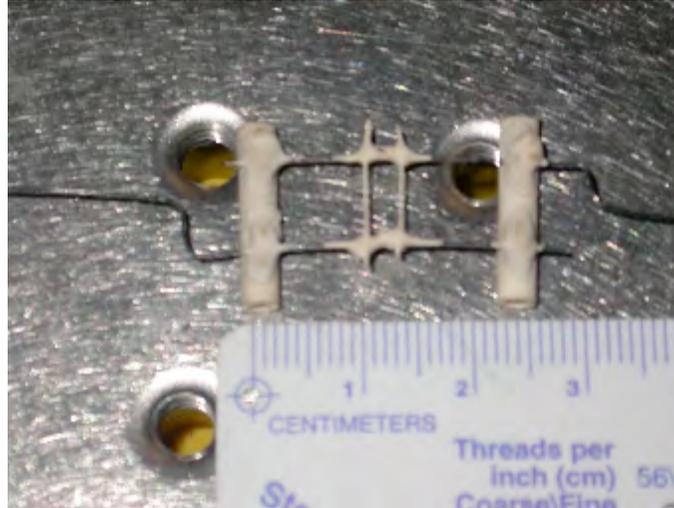


Fig. 3. Two thin emitters mounted on molybdenum electrodes between two magnesium oxide tubes (the tubes double as spacers for mounting within an external heating coil).

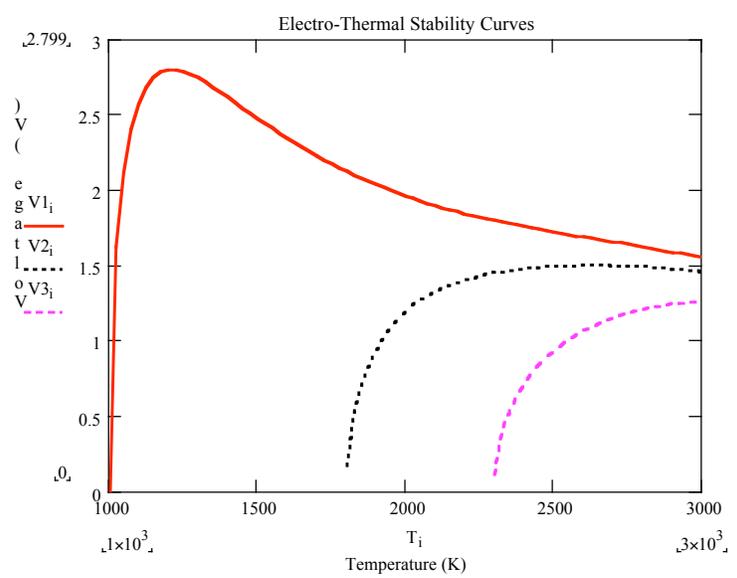


Fig. 4. Rod emitter of radius 1 mm.

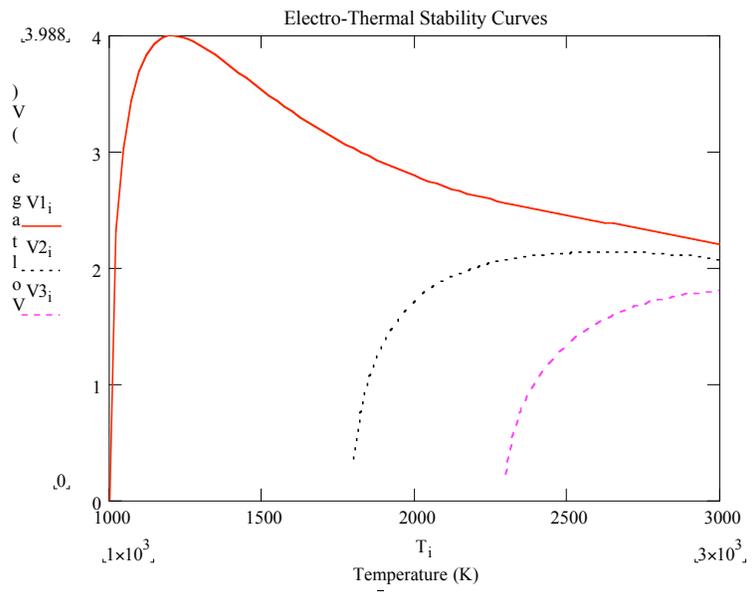


Fig. 5. Rod emitter of radius .5 mm.

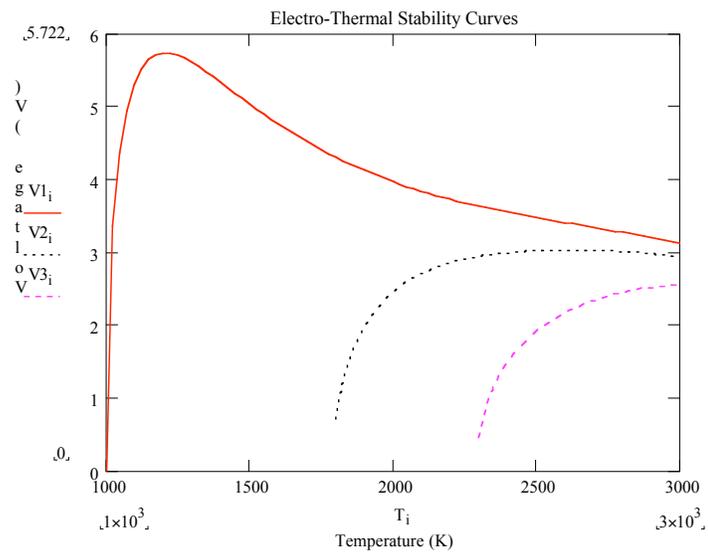


Fig. 6. Rod emitter of radius .25 mm.

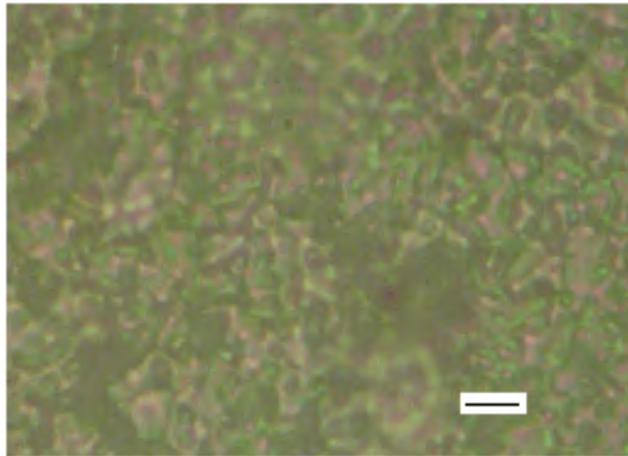


Fig. 7, Micrograph of unpolished emitter surface prior to high temperature operation showing grain sizes on the order of $1\mu\text{m}$ (the line length is $5\mu\text{m}$).

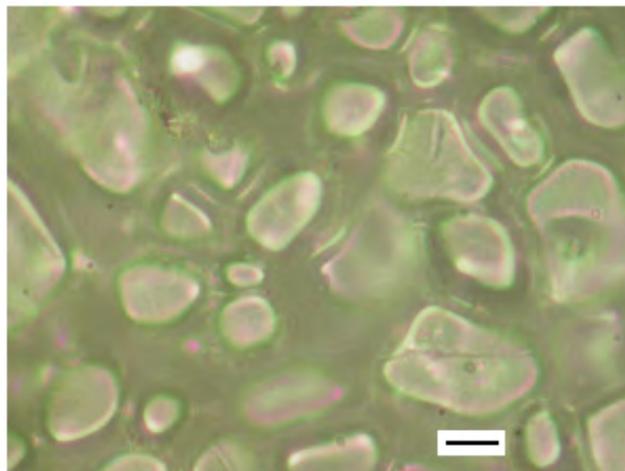


Fig. 8, Micrograph of unpolished emitter surface subsequent to high temperature operation showing grain sizes on the order of $10\mu\text{m}$ (the line length is $5\mu\text{m}$).

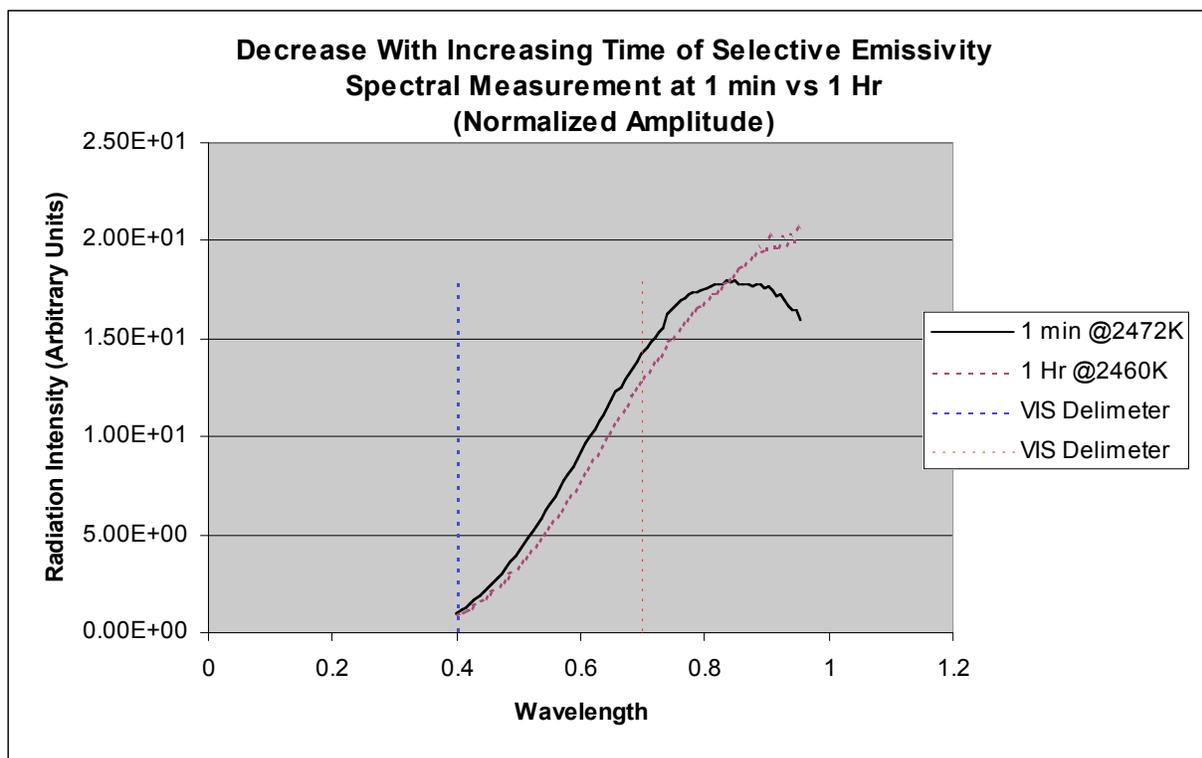


Fig. 9. Spectral distribution of emitters. Due to thermal induced changes in microstructure, the emitter operated for 1 hour at 2460K show significantly less selectivity than that operated for 1 minute at 2472 K.

Appendix II – Emissivity Of The Emitter Bodies

For inhomogeneous media with scattering throughout the body, the calculation of the emissivity ϵ_ν at frequency ν is complicated by the need to account for both optical scattering and thermally generated radiation throughout the body. The governing equation is the following:

$$\frac{di_\nu(x, \omega)}{dx} = -a_\nu i_\nu(x, \omega) + a_\nu i_{\nu b} - \sigma_\nu i_\nu(x, \omega) + \frac{\sigma_\nu}{4\pi} \int_{4\pi} i_\nu(x, \omega_i) \Phi(\omega, \omega_i) d\omega_i \quad (A1)$$

$i_\nu(x, \omega)$ is the intensity at x in the direction ω , a_ν is the absorption coefficient at ν , $i_{\nu b}$ is the blackbody radiant power density at ν at the local temperature, σ_ν is the scattering coefficient, and Φ is the scattering function that tells how much of the intensity in direction ω_i is scattered into direction ω . The emissivity model used is one given by Chubb and Lowe (1993) for a mono-temperature slab of thickness d , index of refraction n_f , and surface reflectivity $\rho_{\nu 0}$, which is uniformly imbedded with isotropically scattering optical inhomogeneities, and which is mounted on a substrate of surface reflectivity $\rho_{\nu s}$ (w.r.t. the slab) and emissivity $\epsilon_{\nu s}$ (w.r.t. the slab) to obtain the emissivity (where ϵ_ν is equivalently defined as the intensity integrated over all angles within the emergent hemisphere divided by that of a blackbody at the same temperature) as a function of optical thickness, scattering and absorption. The emissivity expression is,

$$\epsilon(\nu) = \frac{1 - \rho_{\nu 0}}{DEN} \left\{ \begin{array}{l} \epsilon_{\nu s} [L_1(1)L_2(\mu_M) - L_1(\mu_M)L_2(1)] \\ + l_3(1) \{ L_2(\mu_M) + \rho_{\nu s} [(L_2(\mu_M) - \rho_{\nu 0} L_1(\mu_M))] \} \\ \times (L_1(1) - l_2(1) - L_1(\mu_M)) - l_3(\mu_M) DEN \end{array} \right\} \quad (A2)$$

The L 's, l 's and the DEN are complicated algebraic functions of the reflectivity, the optical depth, the absorption and the scattering coefficients, and the index of refraction. From Chubb and Lowe (1993), these functions are:

$$L_1(\mu) = l_1(\mu) + 2\mu^2 E_3\left(\frac{K_{vd}}{\mu}\right)$$

$$L_2(\mu) = 1 - \rho_{v0} l_2(\mu)$$

$$\mu_M = 1 - \left(\frac{1}{n_f}\right)^2$$

$$l_1(\mu) = \mu^2 \gamma \{A_4[m_2(\mu)A_2 - m_1(\mu)A_1] - m_3(\mu)\}$$

$$l_2(\mu) = \mu^2 \gamma \{A_4[m_1(\mu)A_2 - m_2(\mu)A_1] + m_0(\mu)\}$$

$$l_3(\mu) = n_f \mu^2 \{[1 - 2E_3\left(\frac{K_{vd}}{\mu}\right)] - A_3 A_4 [m_1(\mu) - m_2(\mu)]\}$$

$$m_1(\mu) = \frac{1}{1 + \mu \sqrt{1 - \frac{z_v}{\mu}}} \left[1 - \exp\left(-r - \frac{y}{\mu}\right) \right]$$

$$m_2(\mu) = \frac{1}{1 + \mu \sqrt{1 - \frac{z_v}{\mu}}} \left[e^{-r} - e^{-\frac{y}{\mu}} \right]$$

$$m_3(\mu) = \frac{1}{1 - \mu} \left[e^{-y} - e^{-\frac{y}{\mu}} \right] \quad \text{for } \mu \neq 1 \quad m_3(1) = ye^{-y}$$

$$m_0(\mu) = \frac{1}{1 + \mu} \left[1 - \exp\left(-\frac{y}{\mu} - y\right) \right]$$

$$A_1 = \frac{4w_+}{7u} e^{-y} - \frac{w_-}{4} e^{-r} \quad A_2 = \frac{w_+}{4} + \frac{4w_-}{7} e^{-r-y}$$

$$A_3 = w_+ - w_- e^{-r} \quad A_4 = \frac{z}{w_+^2 - w_-^2 e^{-2r}}$$

$$E_3(u) = \int_0^1 v \exp(-u/v) dv$$

$$w_+ = 1 + \sqrt{1 - z_v} \quad w_- = 1 - \sqrt{1 - z_v}$$

$$\gamma = \frac{3z_v}{8\{1 - [z_v / (1 - u^2)]\}}$$

$$r = 2\sqrt{1 - z_v} K_{vd} \quad y = \frac{3}{2} K_{vd}$$

$$z_v = \frac{\sigma_v}{a_v + \sigma_v} \quad K_{vd} = (a_v + \sigma_v)d$$

While ballpark figures exist for a number of the optical parameters required by the model, precise values for a particular sample are difficult and expensive to determine. These parameters include surface reflectivity, index of refraction, and the exact absorption and scattering coefficients. Since the spectral intensity distribution of a body radiating at temperature T is given by,

$$W(\nu, T) = \epsilon(\nu, T)W_B(\nu, T), \text{ where } W_B(\nu, T) \text{ is the Plank blackbody intensity,}$$

the emissivity and the temperature can be simultaneously determined by using Eqn. (A2) to express the emissivity in terms of the unknown optical parameters, and fitting the resulting $W(\nu, T)$ expression to the measured $W(\nu, T)$ over the measured spectrum. This multiwavelength approach was implemented in Mathcad to obtain emitter emissivities and temperatures.

Appendix III – Electro-Thermal Stability Model

For an electrically heated body at temperature T within a vacuum where heat loss via thermal convection is negligible and where incident radiation is applied to the body via a heating surface at temperature T_1 positioned in close proximity to the body, electro-thermal stability can be characterized by writing an energy balance equation describing a steady state thermal condition. In steady state, the electrical power in is equal to heat loss via radiation and thermal conduction according to the following expression:

$$\frac{\sigma V^2 A_1}{L} = A_2 \int_0^{\infty} \varepsilon(\lambda, T) [W_B(\lambda, T) - W_B(\lambda, T_1)] d\lambda + P_C$$

σ = Electrical conductivity

V = Applied voltage

A_1 = Cross sectional area of the body

A_2 = Surface area of the body

L = Length of the body

λ = Wavelength

P_C = Conduction heat loss rate

For an emitter body connected to electrodes of length l_E and cross sectional area A_E , P_C can be expressed as,

$$P_C = C_\chi (T - T_S) A_E / l_E$$

C_χ = Thermal conductivity

T_S = Temperature of heat sink connected to other end of electrode (typically $T_S \sim 300$ K)

σ is comprised of an ionic component σ_i , and an electronic component σ_e . For zirconia doped with yttria to concentrations similar to that used here and at similar oxygen partial pressures the expressions for these two components are given by Nakamura and Wagner (1986), and by Brook et al. (1971) respectively as:

$$\sigma_i = 97e^{-69/kT} + 929e^{-1.09/kT} + 1910e^{-1.31/kT},$$

$$\sigma_e = 1.5 \cdot 10^7 pO_2^{-.25} \exp(-4.62/kT),$$

where kT is in eV.

The spectral emissivity $\varepsilon(\lambda, T)$ of the selective emitter bodies was obtained by the process described in Appendix I. The integral is solved numerically to yield V as a function of T .

California Energy Commission
Energy Innovations Small Grant (EISG) Program
PROJECT DEVELOPMENT STATUS

Questionnaire

Answer each question below and provide brief comments where appropriate to clarify status. If you are filling out this form in MS Word the comment block will expand to accommodate inserted text.

Questions	Comments:
Overall Status	
1) Do you consider that this research project proved the feasibility of your concept?	<i>Briefly state why.</i> NO
2) Do you intend to continue this development effort towards commercialization?	<i>If NO, indicate why and answer only those questions below that are still relevant.</i> YES
Engineering/Technical	
3) What are the key remaining technical or engineering obstacles that prevent product demonstration?	<i>Being able to inhibit grain growth for extended periods at high temperatures so as to maintain significantly large optical scattering, which yields high spectral selectivity.</i>
4) Have you defined a development path from where you are to product demonstration?	No
5) How many years are required to complete product development and demonstration?	<i>Possibly 3</i>
6) How much money is required to complete engineering development and demonstration?	<i>On the order of \$1,500K</i>
7) Do you have an engineering requirements specification for your potential product?	<i>No, but we hope to have sufficient data to generate one by the end of 2004.</i>
Marketing	
8) What market does your concept serve?	<i>Mainly residential, but there are possibilities for the commercial market as well.</i>
9) Is there a proven market need?	<i>YES, according to the CRC Handbook of Energy Efficiency</i>
10) Have you surveyed potential end users for interest in your product?	No
11) Have you performed a market analysis that takes external factors into consideration?	<i>Yes, excerpts were included within the grant proposal.</i>
12) Have you compared your product with the competition in terms of cost, function, maintenance etc.?	<i>Yes. Some comparisons are also included in the market survey excerpts included within the grant proposal</i>
13) Have you identified any regulatory, institutional or legal barriers to product acceptance?	No
14) What is the size of the potential market in California?	<i>Not certain, but nationally, the market is over \$2billion annually</i>
15) Have you clearly identified the technology that can be patented?	Yes

16) Have you performed a patent search?	Yes
17) Have you applied for patents?	Yes, 1
18) Have you secured any patents?	Yes, utility patent # 6,018,216
19) Have you published any paper or publicly disclosed your concept in any way that would limit your ability to seek patent protection?	No
Commercialization Path	
20) Can your organization develop and produce your product without partnering with another organization?	No, a 2 nd tier manufacturer of complementary high efficiency lighting such as compact fluorescent lighting would be a good partner
21) Has an industrial or commercial company expressed interest in helping you take your technology to the market?	Yes, but only after further development
22) Have you developed a commercialization plan?	Yes, but it has not been updated.
23) What are the commercialization risks?	Successful transition to general lighting of the optical band gap emitter being developed at Sandia for thermo-photovoltaic applications.
Financial Plan	
24) If you plan to continue development of your concept, do you have a plan for the required funding?	Not Completely
25) Have you identified funding requirements for each of the development and commercialization phases?	No
26) Have you received any follow-on funding or commitments to fund the follow-on work to this grant?	No, but DOE is a possibility
27) Have you identified milestones or key go/no go decision points in your financial plan?	Not fully
28) What are the financial risks?	
29) Have you developed a comprehensive business plan that incorporates the information requested in this questionnaire?	No
Public Benefits	
30) What sectors will receive the greatest benefits as a result of your concept?	Residential
31) Identify the relevant savings to California in terms of kWh, cost, reliability, safety, environment etc.	From the CRC Handbook of Energy Efficiency, nationally, the energy savings is potentially 1.1×10^{11} kWh per year, which at 10 cents/kWh is over \$11 billion per year.
32) Does the proposed technology impact emissions from power generation?	Not directly
33) Are there any potential negative effects from the application of this technology with regard to public safety, environment etc.?	No.
Competitive Analysis	
34) Identify the primary strengths of your technology with regard to the marketplace.	Energy efficiency, color rendering, versatility

35) Identify the primary weaknesses of your technology with regard to the marketplace.	<i>Completely new technology, more expensive than standard incandescent bulbs.</i>
36) What characteristics (function, performance, cost etc.) distinguishes your product from that of your competitors?	<i>Combination of efficiency, price and color rendering</i>
Development Assistance	
The EISG Program may in the future provide follow-on services to selected Awardees that would assist them in obtaining follow-on funding from the full range of funding sources (i.e. Partners, PIER, NSF, SBIR, DOE etc.). The types of services offered could include: (1) intellectual property assessment; (2) market assessment; (3) business plan development etc.	
37) If selected, would you be interested in receiving development assistance?	<i>Yes, business plan development.</i>