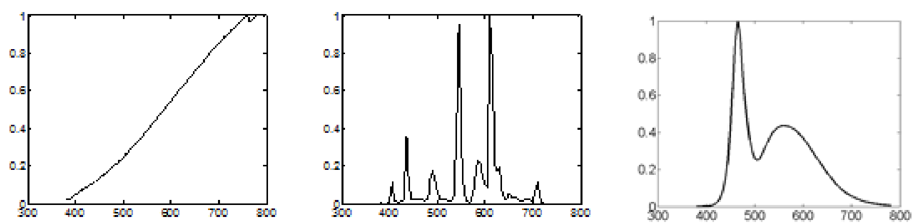
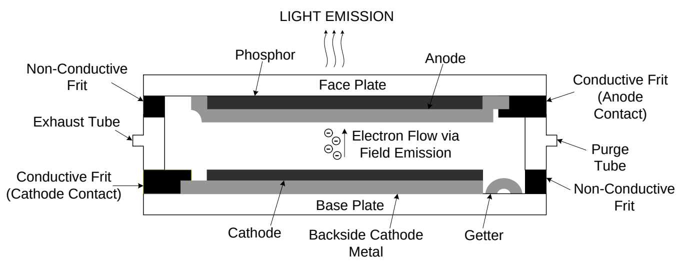
Program Plan. With annual US consumption of electrical power exceeding 1000 TWhr, of which approximately 20% is consumed by lighting[i], clearly, reducing electrical usage, and lighting, in particular, is key in reducing global warming and climate change. The current consumption of energy for lighting could be cut *in half* immediately, if existing energy-efficient lighting technologies were fully exploited. At this time, however, there are basically only five competing commercially-available technologies which are energy efficient, namely (1) fluorescent, (2) LED, (3) infrared-reflecting halogen, (4) OLED, and (5) HID. Although regulatory mandates have put these sources into utilization, voluntary usage of these light sources has been sluggish in the three major sectors of light-source utilization (commercial, institutional-public, and residential), because of multiple problems, including poor color quality (fluorescent and LED), high cost (LED, OLED), high heat dissipation (halogen, HID, LED), high glare (HID, LED), health hazards[ii] (blue-light LED, fluorescent), poor lifetime (halogen, OLED) and insufficient brightness (OLED.) With the US light-source market exceeding $2B annually, and the world market over three times that value[iii], there is no shortage of need, and therefore increasing the options for end-users is interesting, useful and relevant. Light sources make an evident compromise[iv] between efficiency and appearance. This figure[v] clearly shows the spectra of fluorescent or LED lamps are quite unlike the natural-daylight or incandescent spectrum .


Daylight/Incandescent Fluorescent LED

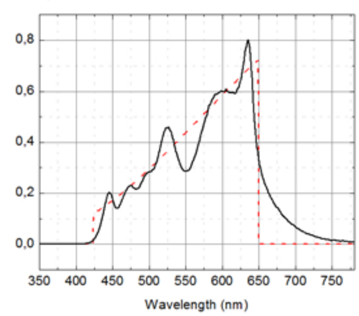
This proposed work is to make prototype light sources, based on Field-Emission Lamp (FEL) technology, which has been invented and demonstrated at UC Davis by the PI and his Research Group. The prototypes would be high-color-quality, efficient light sources with natural-appearing spectral content. The prototypes would also be in sizes, format and function which match products on the market, such as LED or CFL lamps. The Hunt Group demonstrated this technology in small-scale, modular format (1 inch, square, flat lamps with external, table-top power supplies) recently[vi], and multiple venture groups expressed interest, if they could see the technique expanded to a "light bulb" which worked in an ordinary lamp socket, and/or a ceiling panel similar to a 2ft. x 4ft. fluorescent luminaire, such as seen in this figure. There are no technological barriers to preparing such prototypes; but the research funds in the previous project were insufficient. With funding, we feel we can produce what is needed/wanted, considering where this

technology now stands. Commercial light companies and VCs need to see this in a prototype format, as opposed to the “science-project” condition of the prior proof-or-concept stage. Also, entrepreneurial efforts to exploit the technology require recognizable, quality prototypes to satisfy interested parties.

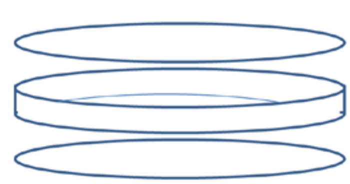
The FEL concept, as published, relies on two major parts, (1) a vacuum lamp, and (2) a driving power-supply. From our publication, the figure shows the vacuum-lamp concept.



The device has a baseplate which has a treated Reticulated-Vitreous-Carbon (RVC) field-electron emitter which emits a “fountain” of electrons towards a phosphor-covered faceplate. The faceplate and baseplate are joined in parallel, using fritting technology, by vertical glass sidewalls. The entire package is pumped to high vacuum, sealed and held at vacuum using an ordinary flash getter. In operation, the electrons cause the phosphors to fluoresce and emit light. Judicious selection of the cathodoluminescent phosphors can give both high efficiency[vii] as well as high-quality (high CRI) white output[viii]. This measured spectrum, of such a mixture clearly emulates natural light better than fluorescent or LED output within the visible spectrum, without making a compromise in efficiency. The power supply is made from solid-state components [ix] which, using a modified Cockroft-Walton configuration[x] works with ac wall-power, and can function with ordinary triac dimmers used in homes. The use of RVC as a field-emission source[xi], as well as the method for treating it[xii] for uniformity is under US patent, through the Hunt Group at UC Davis, and students within the Group[xiii] have demonstrated high uniformity and reproducibility with these. The Hunt Group, and collaborators, have also filed for patent[xiv] on a new method to significantly enhance the efficiency in CL phosphors beyond what was already (acceptably) demonstrated in the Group’s prior publications. The prototyping stage, once completed (as described, following), will also result in multiple improvement patent submissions concerning the design, configurations and packaging.



The original small vacuum lamp concept will be realized in a larger, round (3-inch diameter) configuration with domed face and baseplates. These lamps will be packaged in three popular forms: in a common A19 lightbulb, a common R30 downlight, and (using multiple vacuum lamps, in an array) in a 2’x4’ ceiling-panel luminaire. Calculations show the brightness in each configuration would match that of the competing technologies.



We propose to make 10 lightbulbs (both types) and 5 ceiling fixtures (minimum). For the lightbulbs, the power supply will be potted in the base. For the ceiling fixture, the supply will be inside the luminaire. The power supply will be verified on breadboard, and upon verification, will be transferred to a PC-board realization. The package which holds the vacuum lamp, will be made by 3-d machining in plastic (accomplished at Hacker Lab, in Sacramento) for the two lightbulb realizations (with the power supply in the lamp base.) The planar luminaires will be realized by using commercial T-5 fluorescent 2'x4' units, with the original FL tubes replaced by an array of FEL vacuum lamps.

The fabrication of lamps and power supplies, as well as the testing of the phosphors, and the final assemblies, will be performed in the Vacuum Microelectronics Lab (1217 Kemper Hall, UCD campus.) The PC boards will be fabricated in the ECE Department PCB Lab (Kemper Hall.) All of the glass, phosphors, chemicals, frit, getters, electronic parts and assembly materials will be bought from commercial sources. The capital equipment required for this project is already in place in the Vacuum Microelectronics Lab. However, most of the tools will require fixturing, vacuum seals, pump recharging, and other minor modifications to accommodate this Program. The phosphors need to be tested. Since all batches vary, the color balance using the newly-acquired materials must be formulated. Although the Hunt Group has solid expertise in phosphor testing[xv] and color-balance, a new data-acquisition PC, 1-year Labview software license, data acquisition cards, etc. will be needed. The work will be performed by the PI and three of his graduate students, all of whom have salary support from other sources.

It is estimated, that a startup can make the vacuum lamps for about $1.95 and the power supplies for about $3.70 (each, respectively) in volumes of 100,000. This cost would drop, substantially, with scale. These light sources are not only attractive, efficient and long-lived; but they are also inexpensive. In California alone, annual consumption, looking at A19, R30 lightbulbs and FL tubes (our targeted applications) is approximately $647M[xvi]. For energy-efficient technologies, the competition is fluorescent and LED, which are perceived as ugly and expensive, respectively, and both use non-sustainable, limited-resource, or hazardous (Hg) materials. It is likely that the FEL technology can gain sufficient market share to be a leading contender.

Prototypes, bolstered by improvement patents, would be substantial foundation for a startup company. Alternatively, the major lighting-industry corporations (Philips, Ushio) license or outright buy successful technologies (Sylvania, Osram), historically. One mid-size, energy-efficient wireless controls Company (Redpine Signals, San Jose, Venkat Mattela, CEO 415-218-4107) contacted the PI recently, expressing intent to collaborate (designing wireless controls for the ceiling panels) on this Program if it moves forward, convinced their circuits would be significant value-added in making the FEL a successful product. Other partnership or acquisition opportunities exist as well.

REFERENCES

[i] "Annual Energy Review, 2012", US Energy Information Administration (EIA). Online: http://www.eia.gov/totalenergy/data/annual/?src=Total-f5

[ii] C. E. Hunt, QUALITY ARTIFICIAL LIGHT: POTENTIAL BENEFITS AND HAZARDS DUE TO CHROMATICITY OF ARTIFICIAL LIGHT SOURCES, (Invited) *Meeting of the Blue Light Society*, Tokyo, Japan, October 9, 2012

[iii] Lighting & Bulb Manufacturing in the US: Market Research Report. Online: http://www.ibisworld.com/industry/default.aspx?indid=780

[iv] C. E. Hunt, THE DIFFICULT PARTNERSHIP BETWEEN ENERGY EFFICIENCY, VIEWABILITY AND CONSERVATION, (Invited Keynote) *Fourteenth International Conference of the AIC*, Newcastle, UK, July 9, 2013

[v] Charles E. Hunt, Jesús Quintero, Josep Carreras. APPEARANCE DEGRADATION AND CHROMATIC SHIFT IN ENERGY-EFFICIENT LIGHTING DEVICES (INVITED). *Nineteeth Color Imaging Conference: Color Science and Engineering Systems, Technologies, and Applications*, ISBN: 978-0-89208-29: 5 pages (2011)

[vi] M. M. Cao, R. J. Chacon and C. E. Hunt. A FIELD EMISSION LIGHT SOURCE USING A RETICULATED VITREOUS CARBON (RVC) CATHODE AND CATHODOLUMINESCENT PHOSPHORS. *IEEE Journal of Display Technology*, 7(9) pp. 467-472 (2011)

[vii] N. N. Chubun, A. G. Chakhovskoi, M. Hajra, and C.E. Hunt. EFFICIENCY OF CATHODOLUMINESCENT PHOSPHORS FOR A FIELD-EMISSION LIGHT SOURCE APPLICATION *Journal of Vacuum Science & Technology B (Microelectronics and Nanometer Structures)*, vol.21 (4) pp.1618-21

[viii] Charles E. Hunt and Scott C. Blackstone, HIGH-QUALITY, ENERGY-EFFICIENT AND AFFORDABLE LIGHT SOURCE USING CATHODOLUMINESCENT PHOSPHORS, (Invited "Landmark Paper") *Light Sources 2012*, R. Devonshire and G. Zissis, Ed.s, Lighting Research Center, Tory, NY, p. 395-396

[ix] Ibid. Also, improved recently as part of MS thesis research by (Hunt Group) member, Cameron McCleod (invention-disclosure is pending.)

[x] E. Hara, "A high power symmetrical Cockcroft-Walton type voltage multiplier circuit using silicon diodes", *Nuclear Instruments and Methods,* vol. 54 (1) p. 91 (1967)

[xi] C. E. Hunt, and A.G. Chakhovskoi. FIELD EMISSION CATHODE FABRICATED FROM POROUS CARBON FOAM MATERIAL. United States patent, Number 6,054,801, April 25, 2000

[xii] Ion Bombarded Graphite Electron Emitters, US Patent 6,565,403, 2004

[xiii] R. J. Chacon and C. E. Hunt, FIELD-EMISSION ENHANCEMENT OF RETICULATED VITREOUS CARBON (RVC) DUE TO STRUCTURAL SURFACE CHANGES RESULTING FROM ARGON ION BOMBARDMENT. *Proceedings of the IEEE 21st International Vacuum Nanoelectronics Con.*, p. 168-170

[xiv] C. E. Hunt, H. Baumgart, and D. Gu, DEVICE CONSTRUCTS AND METHODS OF COATING LUMINESCENT PHOSPHORS FOR DISPLAY AND LIGHTING APPLICATIONS, U. S. Patent Application 20120237762

[xv] Many examples, such as Jesús M. Quintero, Charles E. Hunt and Josep Carreras, DE-ENTANGLING COLORFULNESS AND FIDELITY FOR A COMPLETE STATISTICAL DESCRIPTION OF COLOR QUALITY, *Optics Letters*, 37 (23) pp. 4997-4999 (2012)

and: J. Carreras-Molins and C. E. Hunt, EFFICACY AND COLOR QUALITY LIMITS IN ARTIFICIAL LIGHT SOURCES EMULATING NATURAL ILLUMINATION, (submitted to) *Nature Photonics*

[xvi] US Department of Energy: *US Lighting Market Characterization* (Jan 2012) Online: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2010-lmc-final-jan-2012.pdf