DIRECT CONVERSION OF NUCLEAR ENERGY TO ELECTRICITY

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Professor Prelas has been involved in nuclear energy conversion research since 1975. He has published over 300 articles and has numerous books to his credit. Some, such as the Handbook of Industrial Diamond and Diamond Films (1997), are viewed as the most influential text in their respective fields. He holds 13 US and international patents and has 6 patents pending.

Early in his career he developed a keen interest in energy conversion. As part of his undergraduate thesis he worked on the design and development of underwater turbines for extracting energy from ocean currents. As a graduate student at the University of Illinois from 1975-79, Professor Prelas worked with Professor George H. Miley on nuclear pumped lasers which use radiation from nuclear processes as the energy source for driving a laser. Professor Prelas' pioneering work in the field of nuclear-pumped lasers led the discovery of an atomic carbon laser driven directly by ions from nuclear reactions.

In 1979, Professor Prelas joined the faculty at the University of Missouri-Columbia. His early years at Missouri, he received grants to study the direct production of hydrogen from nuclear reactions and published several influential papers. In 1981 he was awarded a Gas Research Institute (GRI) fellowship where he participated in an advisory group mapping out future research directions in the production of fuels from inorganic resources. As part of his work as a GRI fellow he focused on a concept which he had developed earlier in his career using a two step process in which nuclear reactions first produce photons efficiently using an excimer transition, then transport the photons to a transducer. He articulated three potential transducers. The first was to produce hydrogen through direct or indirect chemical processes. The second was to produce electricity using UV photovoltaic cells made with advanced materials. The third was to drive a laser with photolytic excitation. In 1981 he published the concept of a Nuclear Light Bulb, describing a new energy conversion method based on excimer fluorescence sources driven directly with ions and the conversion of the fluorescence to electricity by wide band-gap photovoltaic cells. During this time period he developed several reactor concepts for the nuclear light bulb including an aerosol core reactor which utilized aerosol particles to produce the nuclear reaction and a surrounding gas for producing a weak plasma and fluorescence.

In 1981 the McDonnell Douglas Foundation awarded Professor Prelas a one million dollar gift in support of a superconducting magnetic fusion center. Professor Prelas raised $1,000,000 in matching monies including a gift of $100,000 from Union Electric Corp., a gift of $100,000 from ARMCO, $500,000 from the National Science Foundation. Professor Prelas and his students, pursuing his interest in direct conversion of fusion energy, built a superconducting magnetic test facility and tested four solenoid superconducting coils (39 inches major diameter, 17 inch inner diameter with a peak field at center of 8 Tesla) for the purpose advancing Nuclear Light Bulb research in the area of fusion. Professor Prelas and his students then built a supporting experiment called the Missouri Magnetic Mirror Machine (with peak fields of 1.0 Tesla at center) to model the physics of electron ring production.

In 1984 Professor Prelas was among the first group of the National Science Foundation's Presidential Award winners.

He continued his work on light production from nuclear reactions through funding from the National Science Foundation and produced significant work in UV emissions from nuclear driven fluorescence sources, and continued his work on transducers for the nuclear light bulb for the production of hydrogen, the development of ultraviolet photovoltaic cells and on photolytic lasers. He received a patent on a remotely driven solid state laser with fluorescence generated by nuclear reactions.

He received department of energy funding to develop a laser system using a microwave driven excimer fluorescence source to drive solid state lasers. He was able to demonstrate high efficiency UV excimer sources driven by microwaves. His pioneering work on the development of excimer fluorescence sources continues to draw interest.

AWARD LECTURE

Лекция профессора Университета Миссури-Коламбия, доктора М. А. Преласа будет представлена во время торжественной церемонии награждения в Государственной Думе РФ 29 ноября 2008 г. в 15^{00}.

Lecture of professor of the University of Missouri-Columbia, Dr. M. A. Prelas will be presented during rewarding ceremony in the RF State Duma November 29, 2008 at 15^{00}.

In 1985, Professor Prelas initiated a research effort aimed at the development of diamond and aluminum nitride photovoltaic cells, the second part of his nuclear light bulb concept. He expanded the nuclear light bulb concept to use radioisotopes in advanced nuclear battery concepts. In 1989, DOE supported the development of diamond and aluminum nitride photovoltaic cells. Professor Prelas undertook the challenge of making n-type and p-type diamond and aluminum nitride as building blocks for a UV photovoltaic cell. In this program he, his post doctors, collaborators and students were able to solve some fundamental problems in doping wide band-gap materials. They developed several unique doping methods such as Field Enhanced Diffusion with Optical Activation (FEDOA) which was able to produce n-type diamond and p and n type aluminum nitride and contact diffusion which has been used for impurity addition to crystalline materials in particulate form. They utilized FEDOA to produce a diamond p-n junction in 1996. Wide band-gap materials have properties that are electronically favorable and have broader applications than UV photovoltaic cells. Diamond for example would make a transistor that is more than 30 times faster than a silicon transistor; operate at higher temperatures and at higher radiation levels. Professor Prelas has been an important contributor to the development of wide band-gap materials for electronics, tooling, electrochemistry, radiation resistant coatings, hydrogen storage, chemical sensors, biological sensors and energy conversion. His work continues on all of these applications.

In 1992, Professor Prelas was selected as a Senior Fulbright Fellow and was a visiting Professor at the University of New South Wales, Australia. There he worked with Professor Heinrich Hora and developed several patents on direct energy conversion, solid-state lasers and wide band-gap electronics.

In early 1990's, Professor Prelas and his colleagues began to look at diamond films for a variety of applications in fuel cell technology. Some of this initial work demonstrated that diamond was capable of storing enormous amounts of hydrogen. Additional work was focused on diamond as a suitable electrode material and a potential high temperature replacement material for the proton exchange membrane. This research received funding from Honda Corporation, Daimler Benz, Norton Diamond Film and Rhombic Corporation and continues to show promise.

A conceptual energy conversion technology, which converts the particulate radiation emitted from nuclear reactions (e. g., fission, fusion and radioisotope decay) to electrical energy without intermediate thermalization of the high-grade ion energy, is the topic of this paper. The potential efficiency for this process, alone, is 40 %, nuclear energy to electrical energy. And, if combined with high-temperature thermionic conversion the nuclear to electrical energy conversion efficiency can approach 45 % while the overall size of the system will remain small. The key to the process is to first convert the high-grade ion energy to photon energy, which can then be directly converted to electrical energy. This process is called Photon-Intermediate Direct Energy Conversion (PIDEC). PIDEC is usable with radioisotopes, ion-producing plasma (hot) fusion reactions, as well as fission. In addition to improved efficiency, the PIDEC process also promises advantages in volume, mass, and cost.

This paper will focus on applications using radioisotopes for the PIDEC process. The radioisotope can be introduced as a gas or a solid. Solid radioisotope can take the form of an aerosol (microspheres) or thin films with scale lengths significantly shorter than the range of the alpha or beta particles, dispersed in a fluorescer. In the first step of the process, the ion energy is transported to the fluorescer, and produces photons. Then, in the second step of the process, the photons are transported out of the flourescer to photovoltaic cells, which efficiently convert the photon energy to electricity. This mobile power concept is called the Radioisotope Energy Conversion System (RECS).

Even though there are many possible solid, liquid or gaseous fluorescers that can be used, this paper will focus on a particular gaseous fluorescer called excimers. Efficient production of excimer (non self-absorbing) photons by ions has been demonstrated. Photovoltaics using wide band-gap materials — such as SiC, C (diamond), and AlN — have band-gaps that are acceptable matches for the energy of the photons emitted by excimer fluorescers.

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1. Technical Discussion

Nuclear technology has been in search of a technologically/economically feasible method of converting the energy of nuclear reaction products directly into electricity for many years [1]. NASA has successfully used thermionics with the Radioisotope Thermal Generator (RTG) systems in a number of missions (e. g., Apollo-SNAP-27 generators, Voyager, and Cassini). The energy resulting from the decay of radioisotopes for example starts out as very high-grade energy: multi-MeV, heavy, and highly charged particles. However, in the usual embodiment of radioisotope fuel in the RTG, as a solid, the charged particles are absorbed in a very short distance (micrometers) and thermalized to moderate temperatures (in the range of 600 K). At this temperature, the energy would be considered of significantly "lower grade", because the efficiency of the subsequent thermal energy conversion process is low. This latter process converts the heat into a more usable high-grade form of energy — electricity.

Thermoelectric generation of electricity using the Seebeck (thermocouple) effect has worked successfully for a number of power packages for satellites. Thermionic production of electricity directly inside reactor cores is again being pursued for space power applications.

In contrast, fluorescence produced from the charged particles from the decay of radioactive isotopes has been used to produce low intensity lights for remote applications, such as runway lights. However, all of these applications involve relatively low power output.

Given the inefficiency of thermionics, RTG systems probably will be insufficient for future sophisticated deep space missions. A potential alternative which bridges the energy production of an RTG and nuclear reactors is the radioisotope energy conversion system (RECS), which uses relatively safe isotopes, combined with wide-band-gap photovoltaics. In initial design studies, it appears that such a generator could produce up to 100 kW electric in a relatively compact package.

2. PIDEC and RECS

The pursuit of the production of electrical power from a nuclear light bulb was suggested by the author in 1981. The nuclear light bulb was based on the Photon-Intermediate Direct Energy Conversion (PIDEC) process shown in Fig. 1, and was conceived as a method of energy conversion for a variety of nuclear reactions including fission, advanced fuel fusion and radioisotope decay [2]. Advanced-fuel high temperature fusion, however, will not be available in the foreseeable future. Potential sources of ions from fission reactions and radioisotopes however, are viable near term energy sources. The nuclear-driven fluorescer concept, which was initially suggested as a photolytic driver for a nuclear-pumped laser in 1977 by George Miley (the author's mentor), the author and several other students in Miley's laboratory, was the fundamental component of the nuclear light bulb [3]. This concept makes feasible efficient ion-driven photon sources by removing the nuclear source material from the solid, where it prevented transmission of the photons, and moving it to the volume of the fluorescer gas by one of several methods; a gaseous source, a source embedded in thin films of arbitrary shape and size or as an aerosol source (Fig. 2). A critical component of the nuclear light bulb is that the scale lengths of the solid sources are chosen small enough so that most of the particulate energy escapes into the surrounding gas creating a weak plasma which produces photons. The coexistence of weak plasma with an aerosol introduces a unique set of problems (dusty plasma). Another critical aspect of the nuclear light bulb is that the combination of the photon producing weak plasma and the aerosol source or thin film source remains optically thin to allow the photons to transport out of the system. As will be discussed the nuclear light bulb can be made optically thin. The nuclear light bulb in conjunction with radioisotopes led to the development of the Radioisotope Energy Conversion System (RECS) [4], Fig. 3.

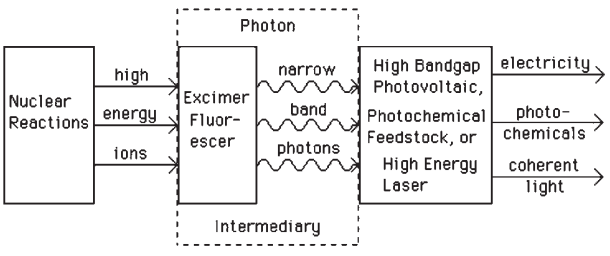

Fig. 1. Schematic Diagram of the Photon-Intermediate Direct Energy Conversion (PIDEC) Process

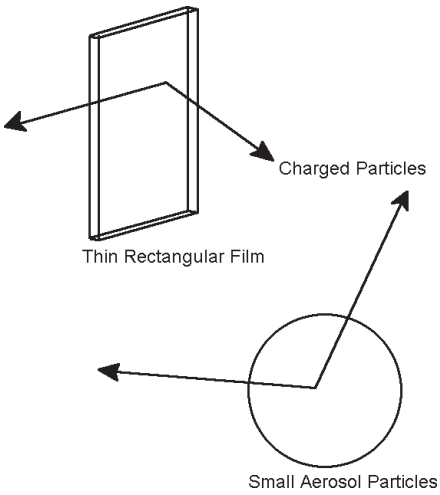

Fig. 2. An illustration of the use of thin solid geometries, which allow reaction products to escape the solid matrix into a surrounding gas [5]

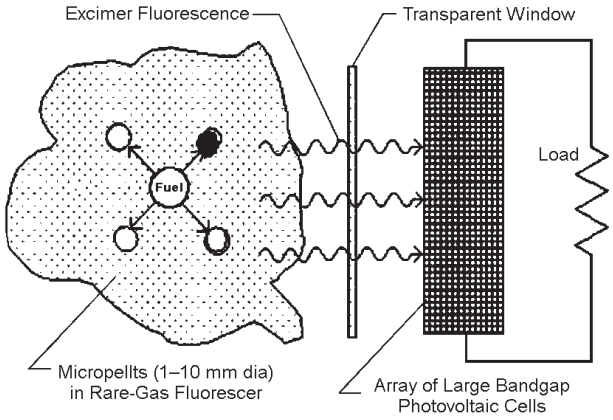

Fig. 3. Schematic Diagram of the Radioisotope Energy Conversion System (RECS) which uses the radioisotope in aerosol form

RECS utilizes a two-step method for directly converting the energy of the charged particles from nuclear reactions into a usable energy form such as electricity, chemicals, or coherent light. In the first step the ions produced by nuclear reactions transfer their energy to an intermediate photon generator — a fluorescer medium. This portion of the RECS comprises what is called the nuclear-driven fluorescer or NDF (a medium which produces incoherent narrow-band electromagnetic radiation). In the second step, the intermediate photons from the nuclear-driven fluorescer are absorbed by a material, which converts the photons into a useful high-grade energy form. This portion of the RECS is the photon energy converter.

The efficiency of the two-step PIDEC process, used for the RECS has two major advantages over thermal energy conversion, which is a many step process. These advantages are: 1) that it is a direct process producing a high grade photon source from a high grade ion source thus avoiding the Carnot cycle efficiency limits imposed by thermalization and 2) that it is mechanically simple, potentially leading to more compact, more reliable, and less expensive systems.

The advantage of the two step process over a one-step direct energy conversion process is that of feasibility. The scale length for the transport of the primary high-grade ion source must generally match the geometrical scale of the energy converter. Energetic ions have a transport length of micrometers while useful energy converters, on the other hand, have a scale length of fractions of meters. For this reason direct conversion of nuclear energy has not previously been possible. What the nuclear light bulb concept provided was an intermediate high-level energy converter that can be intermingled with nuclear material on a micrometer scale-length but produces an energy form that can be transported to meter scale-length direct converters producing useful energy output — a sort of "impedance matching" for the scale length of energy forms. With PIDEC that scale length matching medium is a fluorescing gas, the nuclear-driven fluorescer. The photons it produces can be transported great distances, making it possible to couple them to various energy conversion processes. Also, some conversion processes require greater power densities than the primary energy sources can provide. PIDEC can effectively implement optical concentrators, enabling achievement of the high threshold power density required for a conversion process such as a photolytic laser [4].

The RECS concept of high efficiency production of light from radioisotopes coupled to wide band-gap photovoltaic cells makes the nuclear light bulb especially useful for compact power supply applications.

3. Nuclear-Driven Fluorescers

3.1. The Ion Source

As shown in Fig. 3, the RECS diagram deomonstrates that one type of ion source can come from the decay of radioisotopes dispersed within a fluorescer gas. Effective dispersal is essential so that the ions produced by the isotope decay deposit most of their kinetic energy in the excimer gas rather than in the radioisotope material. There are several methods of achieving the desired dispersal: gaseous radioisotopes, radioisotopes embedded in thin films, or microscopic aerosol of radioisotopes. The efficiency of transport of the ion energy from the radioisotope to the fluorescer medium varies with the scale length of the thin film or aerosol (or in the case of a gaseous radioisotope the transport distance of the particulate radiation in the gas), the chemical form of the radioisotope, and the uniformity of the radioisotope density. The variation of ion energy transport efficiency from a microsphere or thin film to the fluorescer medium is discussed in Reference 6. Energy transport efficiencies are about 60 to 70 % for reasonably designed thin films and 70 to 80 % for reasonably designed microspheres. The average atomic density in the medium must be on the order of $1 \cdot 10^{19}$ particles/cm^{-3}, enough to achieve reasonable power densities but not so great as to significantly degrade the transport of the fluorescence through the aerosol. Combining the constraints of efficiency and optical transparency determines scale length of the thin film or microspheres and number density. For example, a microsphere diameter of 5 mm and number density of $1 \cdot 10^{6}$ cm^{-3}, which should not create significant absorption of the fluorescence [7, 8], results in a source density of 0.63 mg/cm^{-3}, with quite reasonable dimensions and a good average number density ($3.9 \cdot 10^{19}$ atoms/cm^{-3}) of the radioisotope. It is also possible to enhance the average number density by coating the microsphere particles with a thin reflective optical material. In this way one can overcome many of the optical problems that would be encountered with a "dusty" plasma. An alternative, which couples essentially 100 % of the ion energy to the fluorescer medium, is a gaseous radioisotope such as Kr-85. In this way the weak plasma would be self generated with the decay of the Kr-85 radioisotope.

3.2. Excimer Fluorescers

Excimer fluorescers are the most efficient optical radiators known and, because of their unbound lower levels, do not self absorb. They radiate in a single, relatively narrow band of wavelength and are suitable for efficient photovoltaic energy conversion (see Section 4). The intrinsic fluorescence efficiencies of rare-gas and rare-gas halide excimers, based on standard W-value theory, are listed in column 1 of Table 1. Achievable efficiencies should be near the intrinsic values at the power and electron densities characteristic of nuclear reactions.

As will be discussed, experimental data on a number of excimer fluorescers show that the measured efficiencies match well with theory. In fact one group has reported measuring a nuclear-driven rare-gas excimer fluorescence efficiency higher than that predicted by theory (68 % for the Xe excimer vs 50 % from theory) [9]. Experiments with a variety of excitation sources (e. g. electrons, fission fragments, protons) and particle densities have given fluorescence efficiency values ranging from a few percent to as high as 68 % (see review paper by Prelas, et al. [10]). The most efficient excimer fluorescers are the rare-gas excimers. Nuclear-Driven Fluorescers are discussed in much greater detail in the paper "Nuclear-Driven Flashlamps" [10].

4. The Photon Energy Converter

The key to the feasibility of the RECS is the photovoltaic Photon Energy Converter. The common impression of photovoltaics is that they cannot be very efficient. This misunderstanding comes

Table 1

Theoretical maximum intrinsic photovoltaic, η_{pv}, and ion-to-electric, η_{ie}, efficiencies for selected rare-gas and rare-gas halide excimer fluorescers with matched wide-band-gap photovoltaic materials

Excimer	η_f	E_λ (eV)	Photovoltaic Material	Band-gap Energy (eV)	$\eta_{pv} = E_g / E_\lambda$	$\eta_{ie} = \eta_{pv}\,\eta_f$
Ar_2*	0.5	9.6	AlN	6.2	0.645	0.324
Kr_2*	0.47	8.4	AlN	6.2	0.789	0.345
	0.47	8.4	Diamond	5.5	0.655	0.308
Xe_2*	0.48	7.2	AlN	6.2	0.861	0.413
	0.48	7.2	Diamond	5.5	0.764	0.367
ArF*	0.35	6.4	AlN	6.2	0.969	0.339
	0.35	6.4	Diamond	5.5	0.859	0.301
KrBr*	0.33	6	Diamond	5.5	0.917	0.302
KrCl*	0.31	5.6	Diamond	5.5	0.982	0.304
Na_2*	0.46	2.84	ZnSe	2.7	0.951	0.437
	0.46	2.84	SiC	2.4	0.845	0.389
Li_2*	0.42	2.7	$CuAlSe_2$	2.6	0.963	0.404
	0.42	2.7	SiC	2.4	0.889	0.373

E_λ (eV) is the average photon energy E_g is band-gap energy of the photovoltaic material.

from the fact that photovoltaics are most commonly employed as "solar cells." And solar cells are not very efficient, ranging from 5–10 % for commercial units and reaching as high as about 25 % for laboratory cells. However the low efficiency is more due to the characteristics of the solar spectrum than to the photovoltaics devices themselves, especially for the laboratory units with efficiencies of ~25 %. The problem with the solar spectrum is that it is very broadband — its ratio of the average photon energy to the width (FWHM) of the spectrum ($E_{\text{mean}}/\Delta E$) is about 1. This is good for color vision but quite bad for efficient energy conversion. For excimers, however, this ratio is greater than 10. Under these conditions photovoltaics with a good band-gap match can have intrinsic efficiencies of 75–95 %.

Photovoltaic cells for use in the photon-intermediate direct energy conversion of electricity will require the development of a doped semiconductor material with a band-gap that matches the UV photons from the fluorescer. With such photovoltaic cells, a system efficiency of 56 % for fusion ion driven fluorescence has been projected [2, 11]. Studies of fission ion driven fluorescence indicate that system efficiencies of about 40 % are possible [4, 10].

4.1. Photovoltaic Conversion of Narrowband Fluorescence

For a given spectrum, the efficiency of conversion is basically determined by the variation of the irradiance with photon energy and by the substrate band-gap energy, E_g, of the photovoltaic converter. The solar spectrum ranges from the far infrared to the ultra violet. Since most of the solar spectrum lies above the band gap of a silicon photovoltaic cell, this leads to two competing effects on the cell efficiency. The first effect is that the energy of all photons with quantum energy $h\nu<E_g$ is lost because they do not have sufficient energy to excite electrons from the valence band to the conduction band. Competing with this effect however is the fact that, for the photons with quantum energy $h\nu>E_g$ that do contribute, the photon energy in excess of the band-gap energy is lost. Thus the maximum intrinsic efficiency for photovoltaic conversion or the solar spectrum is limited to 30 % due to the spectral width of the solar spectrum [12–14]. The approximately 30 % maximum is thought to be an upper bound on the ability of a single material junction to convert the solar spectrum. The highest known conversion efficiency for silicon, to date, has been 26 % obtained with a highly optimized MIS solar cell [15]. It is possible to layer photovoltaic cells with different band-gaps to improve the efficiency of converting solar energy into electricity. A III-V system based on InN and GaN has been projected as a potential 50 % efficient solar conversion system.

If a narrow fluorescence source with an energy matched to the band-gap of the photovoltaic cell, $h\nu = E_g$, is used, then the theoretical intrinsic efficiency would be 100 %. The closest that we can come in nature to a narrow band source is the laser. A laser however is impractical due to the fact that lasers typically have low energy conversion efficiency. One of the best choices for a fluorescer source is the use of excimers. Excimers have a narrow width and they are produced very efficiently. Since the lower state of an excimer is unbound, excimers do not have the problem of self-absorption that other fluorescence sources have.

Reference 16 examines the coupling of photons generated with fusion reactors to wide band-gap photovoltaic cells. Reference 17 examines the coupling of photons generated with fission reactors to wide band-gap photovoltaic cells. Both studies show that in contrast to the relatively low values for conversion of the solar spectrum, the proposed method uses the narrow band spectrum of excimer fluorescence to obtain efficiencies as high as 80 % using wide band-gap *p-n*-junctions.

4.2. Wide Band-gap Photovoltaic Materials

Table 2 lists several potential wide band-gap photovoltaic materials (15th Row). The author's

Table 2

Properties of Some Wide Band-Gap Materials (20)

Property	GaP	3C-SiC	6H-SiC	4H-SiC	GaN	ZnO	Diamond	AlN	BN
Crystal structure	Zinc blende (Cubic)	Zinc blende (Cubic)	Wurtzite	Wurtzite	Wurtzite	Wurtzite	Diamond	Wurtzite	Zinc blende
Group of symmetry	T_d^2 – F43m	T_d^2 – F43m	C_{6v}^4 – $P6_3mc$	C_{6v}^4 – $P6_3mc$	C_{6v}^4 – $P6_3mc$	C_{6v}^4 – $P6_3mc$	O_h^7 – Fd3m	C_{6v}^4 – $P6_3mc$	T_d^2 – F43m
Number of atoms per cm^3	$4.9\cdot10^{22}$				$8.9\cdot10^{22}$		$1.7\cdot10^{23}$	$9.6\cdot10^{22}$	
Debye temperature, K	445	1200	1200	1300	600		1860	1150	1700
Density, g/cm^{-3}	4.14	3.166	3.21		6.15	5.642	3.515	3.255	3.48
Dielectric const. (static)	11.1	9.72	9.66	9.66	8.9	8.75	5.7	9.14	7.1
Dielectric const (high freq.)	9.11	6.52	6.52	6.52	5.35	3.75		4.84	4.5
Effective longitudinal electron mass, m_l	$1.12m_0$	$0.68m_0$	$0.20m_0$	$0.29m_0$	$0.20m_0$		$1.40m_0$	$0.4m_0$	$0.35m_0$
Effective transverse electron mass, m_t	$0.22m_0$	$0.25m_0$	$0.42m_0$	$0.42m_0$	$0.20m_0$		$0.36m_0$		$0.24m_0$
Effective heavy hole mass, m_h	$0.79m_0$				$1.4m_0$		$2.12m_0$	$3.53m_0$	$0.37m_0$
Effective light hole mass, m_{lp}	$0.14m_0$				$0.3m_0$		$0.70m_0$	$3.53\ m_o$	$0.150m_0$
Electron affinity, eV	3.8				4.1		-0.070	0.6	4.5
Lattice constant, Angstrom	5.4505	4.3596	$a = 3.0730$ $b = 10.053$	$a = 3.0730$ $b = 10.053$	$a = 3.189$ $c = 5.186$	$a = 4.75$ $c = 2.92$	3.567	$a = 3.11$ $c = 4.98$	3.6157
Optical phonon energy, meV	51	102.8	104.2	104.2	91.2		160	99.2	130
Band-Gap, eV	2.26	2.26	3.0	3.3	3.5	3.37	5.47	6.2	6.2–6.4
Breakdown Volt. MV/cm	~1.1	~2	~3	~3	~3		1–10	1.2	2
Electron Mobility, $cm^2\cdot V^{-1}\cdot s^{-1}$	250	1000	380	800	300	80	2200	300	200
Hole Mobility $cm^2\cdot V^{-1}\cdot s^{-1}$	150	50	40	140	350		2000	14	500
Melting, °C	1457	2830	2830	2830	2500	1977	4373	3273	2973
Thermal Conductivity, $W\cdot cm^{-1}\cdot C^{-1}$	1.1	4.9	4.9	4.9	1.3	0.54	20	2.85	7.4
Hardness Mohs Scale	5	9.2	9.2	9.2		4	10		9.5

group has been studying wide band-gap materials such as diamond and aluminum nitride for photovoltaic applications since the early 1980's [1, 2, 18, 19]. The most efficient excimer UV radiation sources, the rare-gas excimers, have larger photon energies (>7 eV) and hence the development of wide band-gap photocells for these excimers is a necessity. Column 5 and 6 of Table 1 matches the more efficient and desirable fluorescers from Column 1 of Table 1 to materials with appropriate band-gaps from Column 4 of Table 1. The theoretical maximum intrinsic photovoltaic efficiency (the ratio of the band-gap to the mean photon energy ranges from 75 to 95 %) while the corresponding theoretical maximum efficiency for conversion of ion energy to electrical energy (the product of the photovoltaic efficiency and the fluorescence efficiency) ranges from 30 to 45 %. If the most optimistic reported values of the fluorescence efficiency were used, the maximum ion-to-electric efficiency would increase to 56 %. The outlook for wide band-gap photovoltaic cells are good given that SiC and GaN LEDs have been in production for a number of years and the author and his group have had success in fabricating wide band-gap photovoltaics from other materials as will be discussed. Rare-gas halide excimers have lower photon energies (3.5 eV for XeF*, 5.0 eV for KrF*, and 6.4 eV for ArF*) and, while their fluorescence efficiency may be lower than that of the rare-gas excimers, their photon energy are good matches for semiconductor materials such as SiC and GaN.

It is difficult to fabricate a wide band-gap photovoltaic cell. However, the author's group was able to demonstrate a diamond photovoltaic cell in the late 1990's [18] and has made substantial progress on an aluminum nitride photovoltaic cell.

Radiation damage to the photovoltaics from particulate radiation is a concern. However, results from the work of Khasiwinah et al. shows that one wide band-gap material, diamond, is radiation resistant [21]. In addition, the author and his group have work on waveguide concepts that can transport the photons around a radiation shield.

The author has identified two materials — diamond, and aluminum nitride — with band-gaps that are a reasonable match for the photon energy of rare gas excimer fluorescence. The wide band-gap of the materials does have some benefit in radiation resistance in that it is more difficult to break the bonds. However, the energies involved in radiation damage are so large that the widest band-gap semiconductor, BN, would still have considerable displacement of atoms. Diamond has an advantage in that when the material is annealed, the structure of the unit cell would be maintained when migrating carbon atoms fill in vacancies. This is not true for the III-V materials (e. g., AlN).

The questions that remain to be answered are many. Some significant ones are:

1) Can durable, radiation resistant ohmic contacts be attached to the photovoltaic cells?

2) What is the optimum cell efficiency?

3) Is the cell efficiency reasonable

4) Can defect density in wide band-gap materials be minimized?

4) Does the cell efficiency degrade after prolonged exposure to UV radiation?

5. Integration of Ion Source to Photovoltaics

5.1. Ion Source

There are many potential ion sources, which can be used for the nuclear light bulb conversion method. It is possible to use fission reactions (e.g.,

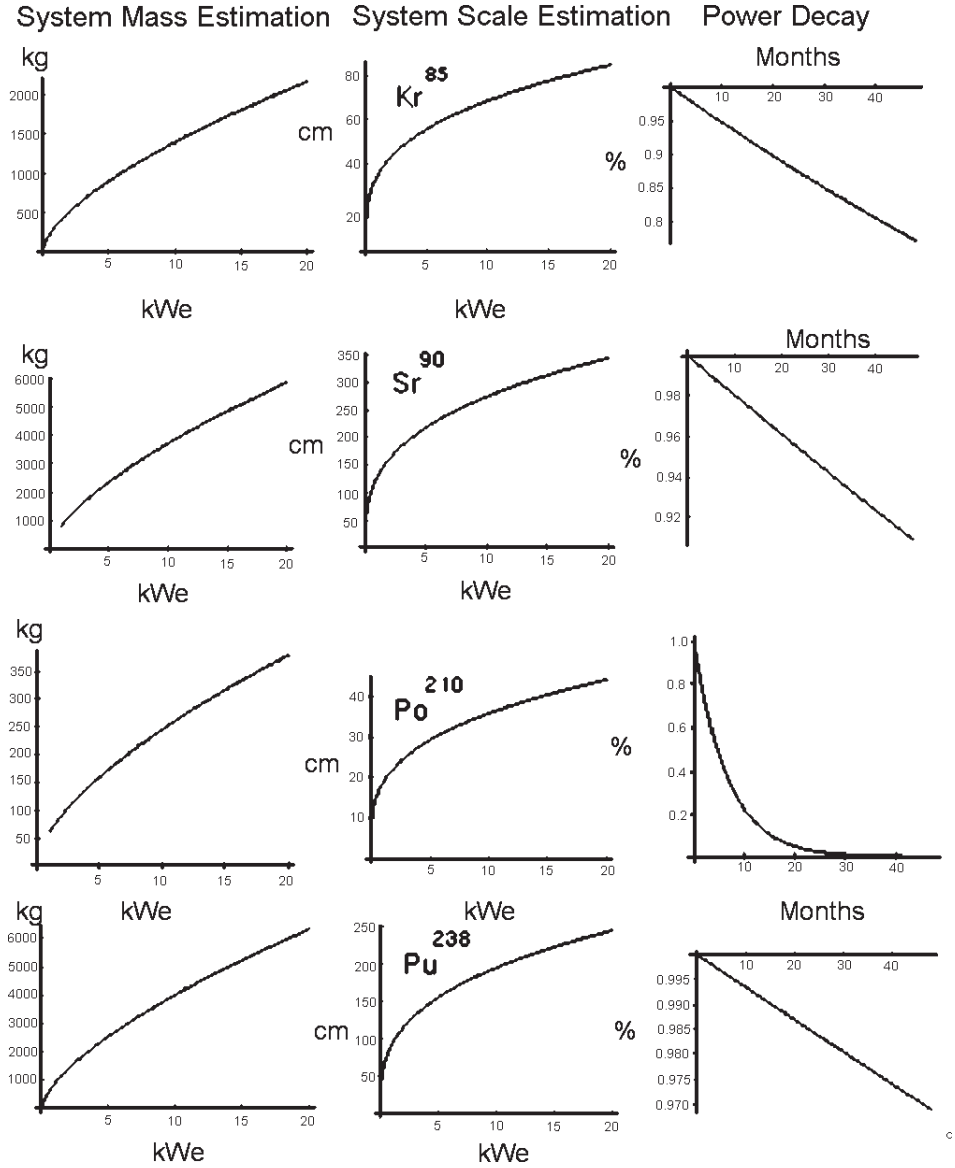

Fig. 4. *Estimation of RECS mass, size, and power decay time are shown for some isotopes Kr^{85}, Sr^{90}, Po^{210}, and Pu^{238}. The geometry is assumed to be spherical with a diameter equal to the system scale estimation. Photovoltaic cells are assumed to surround the fluorescer media and the vessel is shielded with lead*

$U^{233}(n,ff_l)ff_h$, $U^{235}(n,ff_l)ff_h$, or $Pu^{239}(n,ff_l)ff_h$) [17], fusion reactions [16], or radioisotopes [22] (e. g., Ar^{39}, Kr^{85}, Sr^{90}, Po^{210}, Pu^{238}, etc.). The author has chosen in this paper to focus on the use of radioisotopes because there a numerous near term applications for portable long-lived power sources.

In these studies the parameter which influenced the systems scale and power source lifetime was the radioisotope half-life (e.g., Kr^{85} — 10.76 yr., Sr^{90} — 29 yr., Po^{210} — 0.38 yr., and Pu^{238} — 87.74 yr.). Both the scale size and the gamma ray emitted from the reaction influenced the system's mass. A conservative approach was used to estimate the personnel radiation shield by requiring that the contact radiation be less than 2.5 millirems per hour. The gamma radiation dominates the shielding problems the Bremsstrahlung radiation problem contributes a small fraction. Looking at the partial list of the most promising isotopes considered, some have gamma radiation and others do not:

- T^3 — no γ;
- Kr^{85} — 0.514 MeV γ 0.38% of decays;
- Sr^{90} — no γ;
- Po^{210} — 0.802 MeV γ 0.0011 % of decays;
- Pu^{238} — 0.567 MeV γ $5 \cdot 10^{-5}$ % of decays.

5.2 Coupling of Ion Energy to the Fluorescence Source

Based upon the above criteria, the author suggests that compact power sources can be made from radioisotopes using the nuclear light bulb approach. The radioisotope ion source can be gaseous (e.g., Kr^{85} with a half life of 10.76 years which emits a 0.67 MeV beta 100 % of the decays and a 0.514 MeV gamma 0.38 % of the decays), or it can be in the form of a solid (e. g., a thin film or as an aerosol — see Fig. 2). Examples of types of solid radioisotopes which can be used in the mobile power system are: Sr^{90} with a half life of 29 years which emits only a 0.67 MeV beta; Po^{210} with a half life of 138.4 days which emits a 5.305 MeV alpha 100 % of the decays and a 0.803 MeV gamma 0.0011 % of the decays; and Pu^{238} with a half life of 86.4 years which emits a 5.5 MeV alpha 100 % of the decays and a 0.77 MeV gamma $1 \cdot 10^{-5}$ % of the decays. A Pu^{238} source was used to power the RTG used in the Voyager spacecraft. Three RTG units produced 7200 Watts of thermal power and 540 Watts of electricity regulated to 30 volts from 12.900 grams of the isotope. Using the RECS concept, 12.900 grams of Pu^{238} could produce 2.616 Watts of electrical power with optimal combinations of source, fluorescer and photovoltaic material.

Making an integrated system, which produces a significant power density and remains optically thin is a challenge. The use of thin films or aerosols along with thin aluminum or silver coatings has been examined in [7]. With solid materials, an average atomic density of approximately $5 \cdot 10^{19}$ atoms/cm^{-3} can be achieved for a reasonably optically thin system. A thin coating of reflective can enhance the optical transport properties of films or aerosols. Charged particles can penetrate the thin reflective coating without losing significant energy or significantly affecting the coating [7, 10].

5.3 Cooling considerations

As shown in Table 1, about 30 to 40 % of the energy released in the decay process can be converted into nuclear energy [22]. Thus 60 to 70 % of the energy will heat the device. Since wide bandgap photovoltaic will work at high temperatures without a significant loss of performance (diamond for example in a non-oxidizing atmosphere can operate at temperature of 1000 °C) [23], it is feasible to operate the device at very high temperatures. The design of radiative heat transport surfaces RECS would be similar to that of other types of power systems. It is also possible to incorporate a secondary energy conversion cycle which can use the thermal energy to enhance system efficiency (e.g., bryton cycle, stirling cycle, Alkali Metal Thermoelectric Converter, thermoelectric, etc.).

6. Conclusions

It has been 26 years since the nuclear light bulb was suggested. Over those years a great deal of progress has been made on a number of fronts: system designs, excimer fluorescers, wide bandgap photovoltaics and interfaces. The RECS has significant near term prospects. The author has been actively working with industries such as British Nuclear Fuel and Daimler Bentz [24] and recently with U.S. Semiconductor Corp. on RECS commercialization issues.

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Первая Всероссийская интернет-олимпиада «Нанотехнологии — шаг в будущее»

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Московский государственный университет им. М. В. Ломоносова проводит Первую Всероссийскую интернет-олимпиаду в области наноматериалов и нанотехнологий (e-NANOΣ'07).

Целью олимпиады является поиск молодых талантов, желающих участвовать в развитии нанотехнологий. В Олимпиаде может принять участие любой пользователь всемирной сети Интернет в возрасте до 27 лет, при этом дополнительно победителям-абитуриентам (гражданам РФ) будут даны преимущества при поступлении в МГУ, а студенты вузов, показавшие наилучшие результаты, получат, по их желанию, возможность продолжить свою учебу в МГУ. Официальным языком Олимпиады является русский язык.

В жюри олимпиады включены видные ученые и специалисты в области наноматериалов и нанотехнологий, члены Российской Академии наук, профессора МГУ, директора инновационных компаний.