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ELECTRONIC AND PHOTONIC POWER APPLICATIONS

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ABSTRACT

Efficient conversion of radioactive decay to electrical power has been the goal of a number of past research efforts. One of these was the Elgin-Kidde nuclear battery. In this concept promethium-147 was used as a beta source which was then mixed with a phosphor to produce a radioluminescent (RL) source of light. The light source was coupled to silicon photovoltaic converters to create electricity. This photoelectric approach is being re-visited using tritium based solid state compounds and advanced gas concepts to produce RL light sources being disclosed at this conference.

Efficient conversion of the RL light energy to electrical energy imposes certain requirements on the semiconductor converter. These requirements will be discussed. Projections of power source electrical and physical characteristics will be presented based on reasonable design parameter assumptions.

The words "Power Supply" usually evoke a vision of a rotating machine or chemical battery. However, today's technology is making increasing use of photonics, where information and even power can be moved through optical fibers. Brighter volumetric RL light sources open a whole new range of photonics-based applications, while solid state tritiated compounds provide the foundation for improved mechanical adaptability and safety.

INTRODUCTION

Sandia National Laboratories (SNL) has been investigating low level, multi-decade lifetime, nuclear power source concepts which use no special nuclear material (e.g. plutonium) or environmentally sensitive isotopes. The objective is to develop a 1 milliwatt (mW) power source fueled by an abundant and affordable beta-emitting radioisotope with a lifetime of at least 12 years. Additional goals are high reliability and a volume

MASTER

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that is competitive with lithium batteries for equivalent power levels and lifetimes.

DIRECT CONVERSION

Our early concepts were similar to what is known as a direct conversion betacell, first demonstrated at Sarnoff Laboratories [1] in the mid 1950's. As shown in Figure 1, a beta emitting radioisotope is placed in close proximity to a solid state converter consisting of a large area pn junction analogous to that used in solar cells. Beta particles penetrating the converter would create electron hole pairs thereby generating useful power.

Tests at SNL showed that this conversion technique has two major limitations. First, accelerator experiments revealed that beta energies as low as 10 - 20 keV can damage most converters. These damage effects are not normally seen in standard radiation damage studies where the radiation doses are typically <100 megarads. However, in the betacell, doses of the order of 100 gigarads are expected over the life of the device. At this dose level, the damage can be observed as reduced cell performance. Second, since low energy beta emitters (e.g. tritium) are preferred for safety reasons, self-absorption of the beta energy limits the power flux to 1 - 10 microwatts per square centimeter of converter. This is illustrated in Figure 2 where the computer predicted [2] beta particle power flux is plotted as a function of gas thickness for:

1) pure tritium gas @ 1 atmosphere
2) 50% tritium and 50% helium-3 (He-3) @ 1.5 atmospheres
3) 25% tritium and 75% He-3 @ 1.75 atmospheres.

These correspond to the expected gas mixtures and pressures for 0, 1 and 2 half lives respectively. Practically, this means that a large area of converter is necessary to generate even 1 milliwatt of power. If the converter is expensive, the net cost of the betacell could be prohibitive.

A direct conversion conceptual design was generated which would have used tritium gas as fuel and gallium phosphide (GaP) as the converter. Tritium gas/GaP cell combinations were tested in the SNL, Livermore Tritium Research Laboratory (TRL). Those test results indicate that this combination is technically feasible, but that it would be expensive. The first entry in Table 1 summarizes the volume and cost estimate for a 1 mW direct conversion GaP betacell at room temperature with a lifetime of 12.3 years. It would utilize tritium gas at 100 atmospheres, have a 5% semiconductor coversion efficiency (demonstrated in the TRL), assumes a realistic $6 per square centimeter cell cost and uses the current commercial tritium cost of $3/curie.

THE ELGIN-KIDDE NUCLEAR BATTERY

An alternative concept being considered is based on the Elgin-Kidde nuclear battery also developed in the mid 1950's [3]. A schematic of that device is shown in Figure 3. A thin film mixture of promethium-147 (Pm-147) and a phosphor powder dispersed in a plastic was sandwiched between two silicon photovoltaic (PV) cells. The high energy beta decay of the Pm-147 excited the phosphor producing an intense radioluminescent (RL) light. That light, in turn, was absorbed by the PV cells thereby generating electricity. This technique had a significant advantage over direct conversion in that it prevented radiation damage to the PV cells. Its useful life, however, was limited by the 2.4 year half life of the Pm-147 source, and continually improving chemical batteries soon usurped its potential for practical applications.

TRITIUM-BASED VOLUMETRIC RL POWER SOURCES

The maximum light power flux from a standard tritium gas tube RL light has been experimentally shown to be limited to ~2.3 microwatts/cm^2 (1 Footlambert (fL) @ 520 nanometers) because of beta self-absorption in the gas. To be cost competitive with the direct conversion technique, a multi-decade power source using tritium will require light power fluxes higher than this to reduce the total semiconductor area and cost. In fact, the ideal configuration would consist of a non-absorbing volumetric light source, i.e. a "glowing sugar cube", surrounded by PV cells. This is shown conceptually in Figure 4. Estimates of the volume, tritium and semiconductor costs for this case are shown in the second entry of Table 1. To arrive at these figures, the following optimistic assumptions were made:

1) 75% of the beta energy was deposited in the phosphor
2) the phosphor conversion efficiency was 25%
3) 100% of the emitted light was collected
4) the PV efficiency was 35% due to the nearly mono-chromatic nature of the emitted light
5) the PV cells cost $25/cm^2, typical of current III-V cells
6) the lifetime was 12.3 years
7) the electrical output at end of life was 1 mW.

These results indicate that under these conditions, significant volume and cost savings could be realized over the direct conversion technique. For this reason our efforts are now focusing on this radioluminescent photoelectric (RLPE) approach.

POWER SOURCE DESIGN AND PROJECTIONS

For efficient RLPE power conversion, there are several requirements that both the phosphor and semiconductor converter must meet. First, the RL phosphor should have a high beta energy to light energy conversion efficiency. Measured values as high as 28% have been reported for some zinc sulfide (ZnS) based materials. Most oxide based phosphors are under 10%. Second, the RL phosphor photon energy should closely match the bandgap of the semiconductor converter. In theory, the photon energy should be just sufficient to excite the carriers from the valence band into the conduction band. This minimizes the energy lost by exessive excitation above the bottom of the conduction band. Third, the phosphor emission spectrum should also be as narrow as possible for the same reason. Fourth, the phosphor emission spectrum and its conversion efficiency should be as insensitive to temperature in the expected operating range as possible. Fifth, the semiconductor converter must have low electrical leakage. Since the light intensity is only expected to be in the tens of microwatts/cm^2, a leakage of 1×10^{-9} amperes/cm^2 or lower is essential. This can be most easily achieved using semiconductors with band gaps of 1.4 electron volts and above. The III-V semiconductors gallium arsenide (GaAs), aluminum gallium arsenide (AlGaAs), gallium arsenide phosphide (GaAsP), GaP, as well as hydrogenated amorphous silicon (HAS), are examples of materials which can meet this requirement. Note that the higher the band gap, the less sensitive the semiconductor is to temperature variations due to thermal contributions to its leakage. Finally, the semiconductor converter must have a high internal quantum yield for photon wavelengths within the emission band limits of the RL phosphor.

A volumetric light source based on the completely organic, optically clear radioluminescent lights developed at Sandia [4] was considered. However, the low conversion efficiency, <5%, would have required an overall volume significantly larger than an equivalent lithium battery. We therefore concentrated on the higher efficiency inorganic systems.

Power source volume and cost estimates have been made based on the projected brightness of the phosphor/aerogel composite light sources being discussed at this conference. Although a cubic or spherical configuration would be ideal if there were no light loss mechanisms, it is expected that the light scattering and absorption properties of the phosphor/aerogel composite will dictate a slab configuration as being most optimum, with a maximum thickness of 1 to 3 mm for a saturated light output. These sources would be optically coupled to III-V or HAS cells, and the tritium would be incorporated into the aerogel as high pressure gas, tritoxyls, or as a tritiated organic. These volume and cost estimates, the 3rd and 4th entries in Table 1, were made using the following assumptions:

1) an initial light intensity of 22.8 microwatts/cm^2 @ 520 nm
2) no output degradation other than by tritium beta decay
3) a lifetime of 12.3 years
4) an electrical output at end-of-life of 1 mW
5) a phosphor/aerogel composite thickness of 0.1 cm
6) a III-V semiconductor conversion efficiency of 22%
7) a III-V semiconductor cost of $25/cm^2
8) a HAS conversion efficiency of 12%
9) a HAS cost of $0.10/cm^2.

The estimates show that there are tradeoffs among volume, cost and tritium content. The III-V design has the smaller volume, but the HAS design is potentially less expensive due to the lower cost of the cells. The higher tritium content of the HAS design may make it less desirable for some applications where a large tritium inventory may be critical.

The last entry of Table 1 compares the volume and cost of a 12.3 year, 1 mW, lithium/sulfur dioxide (Li/SO$_2$) battery to the direct conversion tritium/GaP betacell and tritium based RLPEs. Although the betacell and RLPE devices would have smaller volumes, the cost is considerably higher than the Li/SO$_2$ battery. Tradeoffs among reliability, use environment and size would therefore dictate the appropriate choice.

For some RLPE designs, the lifetime of the power source could be increased to 20$^+$ years by increasing the total tritium content and only a small increase in the internal volume. The overall volume, including containment, will be dictated by whether pressurized tritium gas would be required to achieve the desired output.

It should be noted that the above models are based on the 520 nanometer emitting ZnS phosphor currently used in most RL light applications. However, other phosphors, when combined with the appropriate semiconductor, might yield a higher overall efficiency, have a smaller volume, or be more appropriate for the intended operating temperature range.

HIGH POWER - PULSE MODE RLPE'S

RLPE's are inherently continuous output, low power devices. However, high power operation in pulse mode is possible if the RLPE is allowed to trickle charge either a rechargable battery or a double layer capacitor (DLC). This is shown schematically in Figure 5. Such combinations could be an attractive alternative to large battery packs, especially if there is no specific need for a continuous high power output.

PHOTONICS

Modern electronics is making increasing use of photonics to replace electrical signals on wires with light signals in fibers. The more intense RL sources being developed offer the possibility of using RL light in some of these applications. As Figure 6 indicates, instead of moving electrons in wires, intense RL light might be transmitted along an optical fiber. That light could then be converted to electricity directly on the IC chip where it is needed. Some of the new optical computing chips might be able to use the continuous RL light for keep-alive purposes, or, if the circuits are sensitive enough, RL light might serve as the main light source for the optical computer.

APPLICATIONS AND POSSIBILITIES

There are a number of potential applications for RL lights and power sources. Some of them are:

Digital memory keep-alive
Weapon applications
Sensors
Remote telemetry Narrow beam optical telemetry
Photonics
Environments too hot for chemical batteries
Environments too cold for chemical batteries
Low radiation environments
Unattended remote site operations requiring high reliability.

The above list is not all-inclusive. As the RL light intensities improve with further work, other uses will undoubtedly materialize.

The new solid state RL lights offer significant improvements over the older gas tube technology. An example is shape flexibility not possible with gas tubes. RL lights, and power sources made with these materials need not come only as right circular cylinders. Flat-pack configurations of nearly arbitrary shape could be fashioned for specialized applications. The new technology promises smaller volume and potentially safer devices together with long life and maintenance free operation.

FUTURE RESEARCH

Our investigations have shown that volumetric light sources are essential to achieve a high brightness, compact RL light, and is the only practical way to make a RLPE. Additional research and development is necessary to improve performance and reduce the cost of novel volumetric light and power source concepts. Our goal is to develop a safe, bright, compact, inexpensive RL lamp which could be used in a variety of applications, not just the limited market available today.

REFERENCES

[1] P. Rappaport, J. J. Loferski and E. G. Linder, The Electron-Voltaic Effect in Germanium and Silicon P-N Junctions, RCA Review, Volume XVII, No. 1, March, 1956.

[2] "Miniature Atomic Powered Battery", Radio and TV News, V.57, page 160, May, 1957.

[3] Calculations done using TIGER-P, an electron/photon transport code that is part of the Integrated TIGER System.

[4] C.L. Renschler, R.L. Clough and T.J. Shepodd, Demonstration of Completely Organic, Optically Clear Radioluminescent Light, J.Appl.Phys., 66 (9), November 1989.

Table 1.

Tritium Device	Converter Volume (cc)	Total Cost (k$)	Qnty. (kCi)	Cost (k$)	Area (cm^2)	Materials Cost (k$)
Direct Conversion GaP Betacell	64	10	3.3	60	10^4	70
Optimistic Volumetric RLPE	6	4	1.3	1	18	5
III-V RLPE	32	10	3.2	10	400	20
HAS RLPE	60	17.4	5.8	0.074	735	17.5
Li/SO2 Battery	360	-	-	-	-	0.1

Note: The volumes for the Betacell and RLPEs do not include the containment or internal supporting structures.

Define terms
such as RLPE.
Define volume. Total Cost?
needs to be cleaned up.

FIGURE CAPTIONS

Figure 1. Direct conversion betacell concept. Beta particles bombard the converter directly creating electron-hole pairs which generate electricity.

Figure 2. Computer predicted power flux vs. gas thickness for tritium gas sources. The squares correspond to 100% tritium at 1 atmosphere, the crosses to 50% tritium and 50% helium 3 at 1.5 atmospheres, and the diamonds to 25% tritium and 75% helium 3 at 1.75 atmospheres.

Figure 3. The Elgin-Kidde nuclear battery. Beta particles from the decaying Pm-147 excite a phosphor making light. The light is absorbed by photocells which generate electricity.

Figure 4. Volumetric tritium-based RLPE power source concept.

Figure 5. RLPE based electric power alternatives. Low power continuous output alone, or high power pulsed output using a DLC or rechargeable battery.

Figure 6. RLPE based electric power or photonic power alternatives.

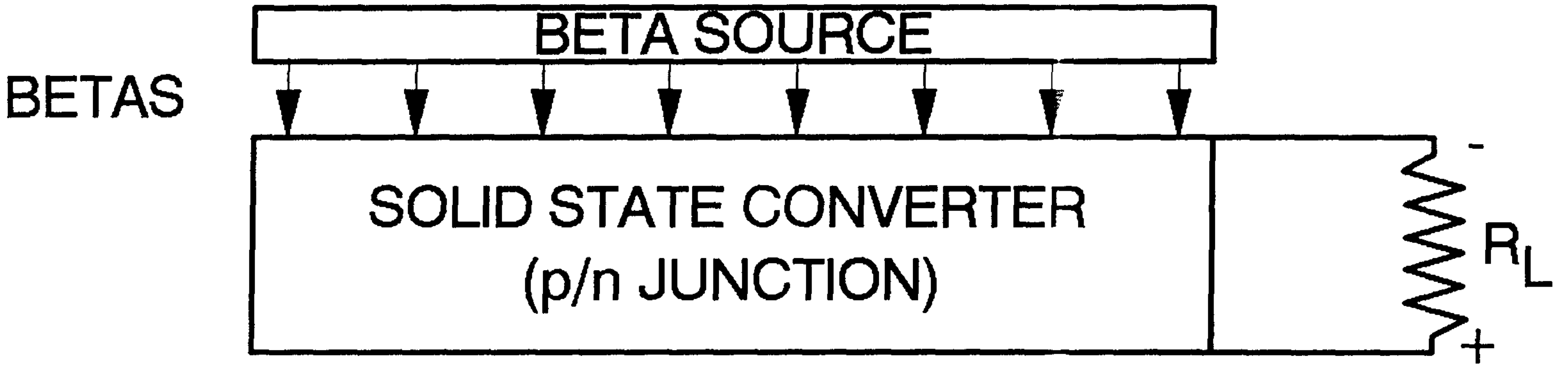

FIGURE 1

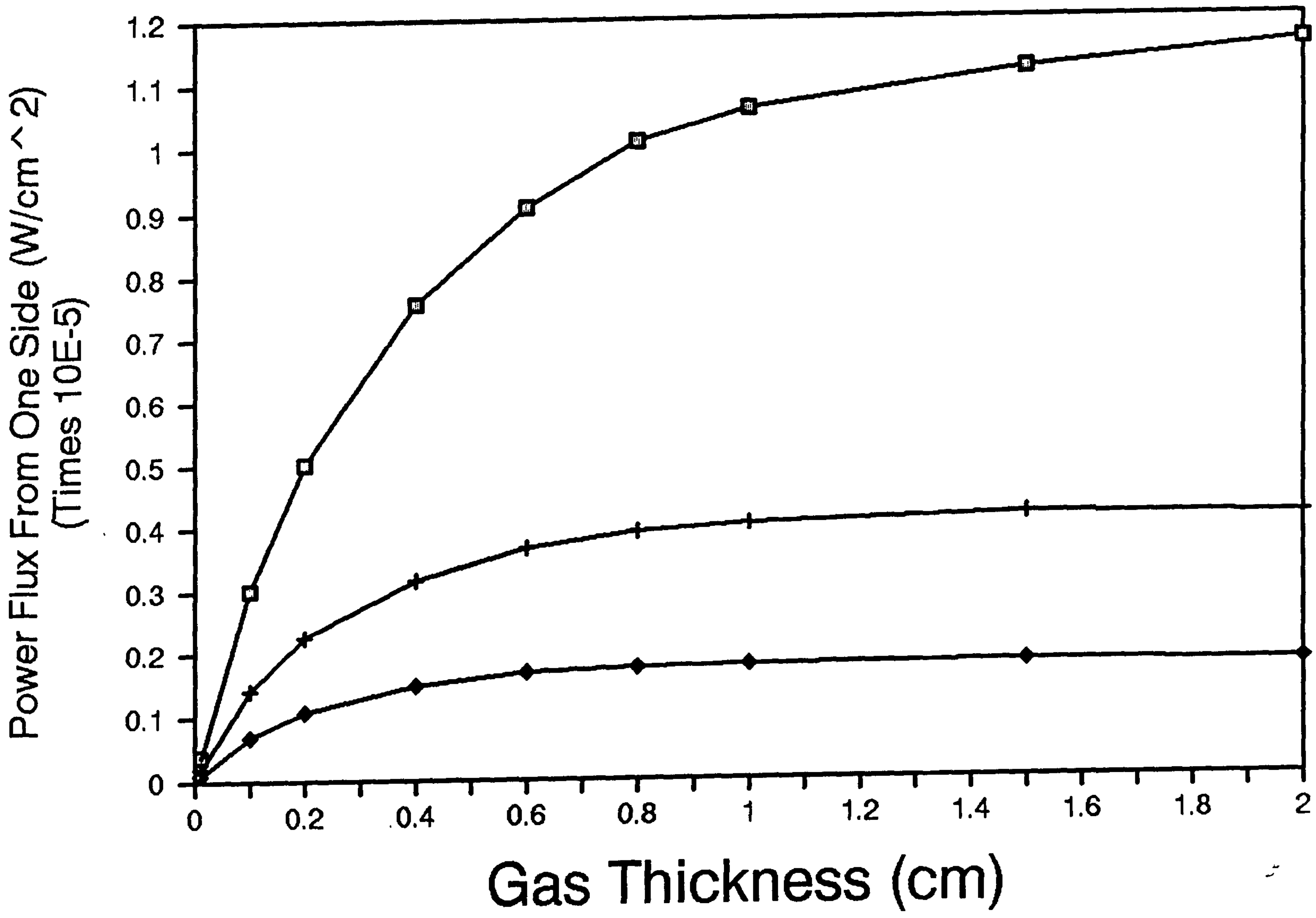
Power Flux From One Side (W/cm ^ 2)
(Times 10E-5)
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Gas Thickness (cm)

FIGURE 2

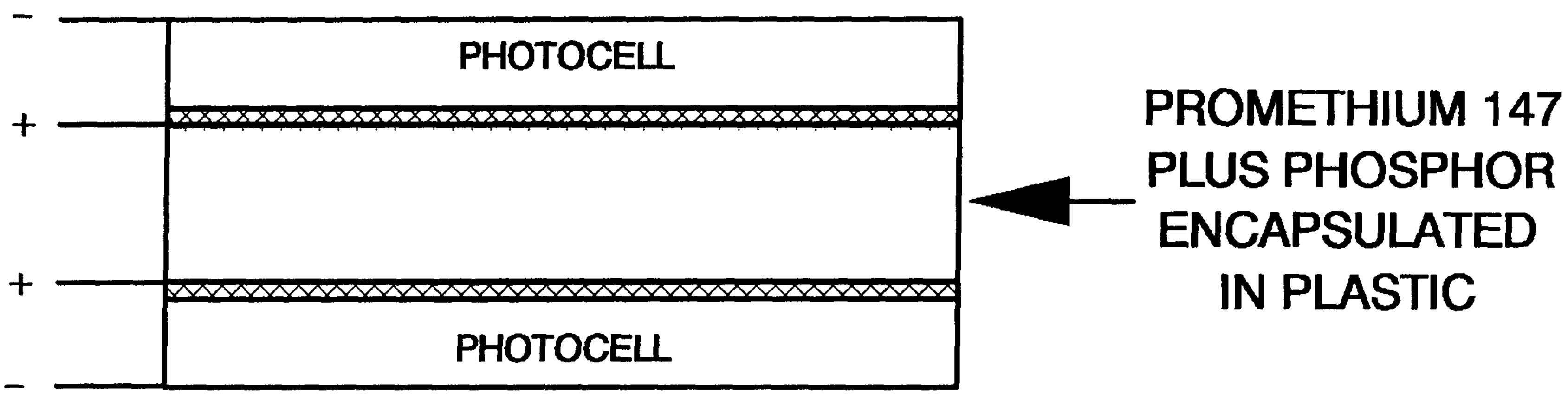
−
PHOTOCELL
+
PROMETHIUM 147
PLUS PHOSPHOR
ENCAPSULATED
IN PLASTIC
+
PHOTOCELL
−

FIGURE 3

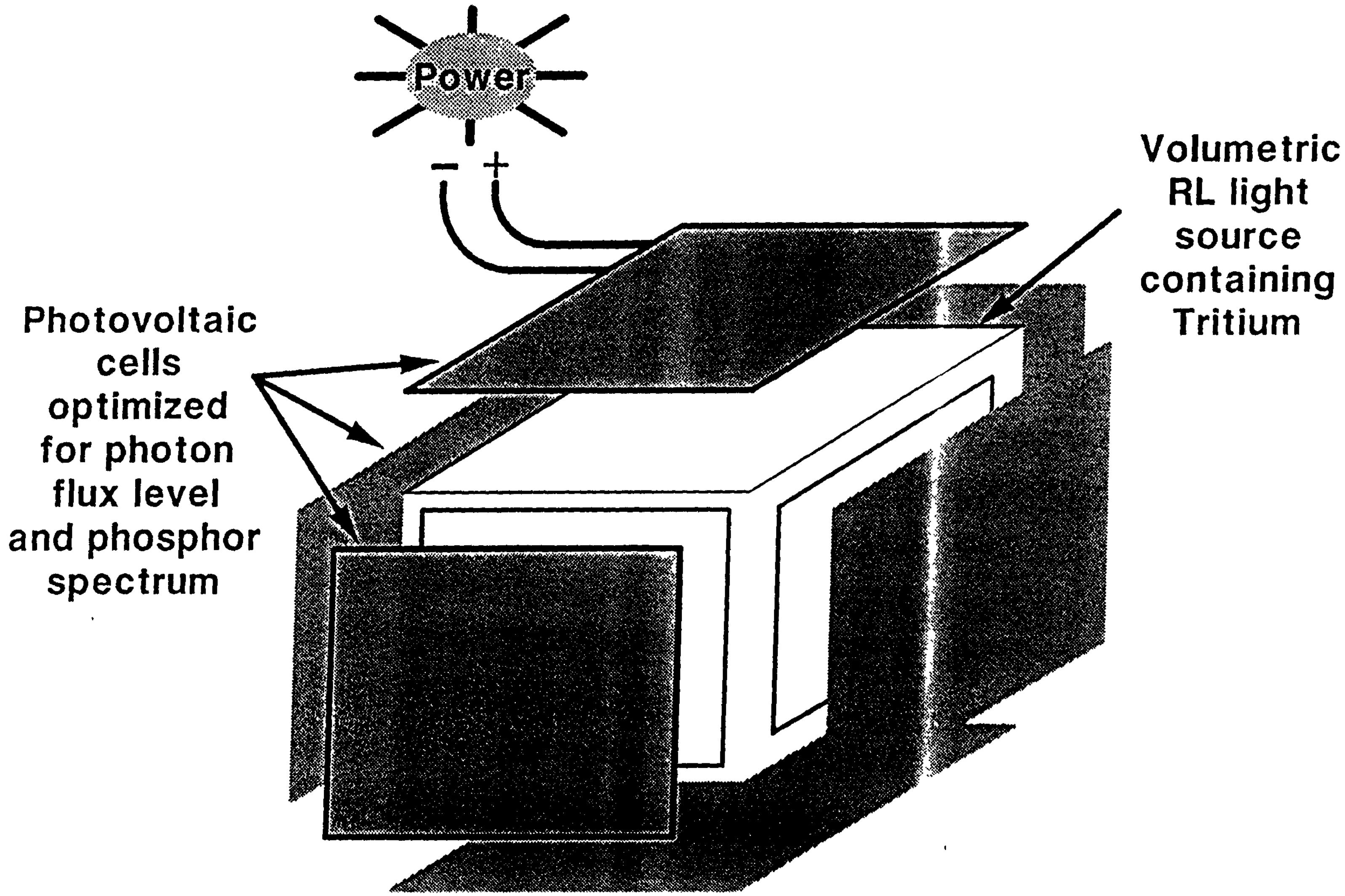
Power
−
+
Volumetric RL light source containing Tritium
Photovoltaic cells optimized for photon flux level and phosphor spectrum

FIGURE 4

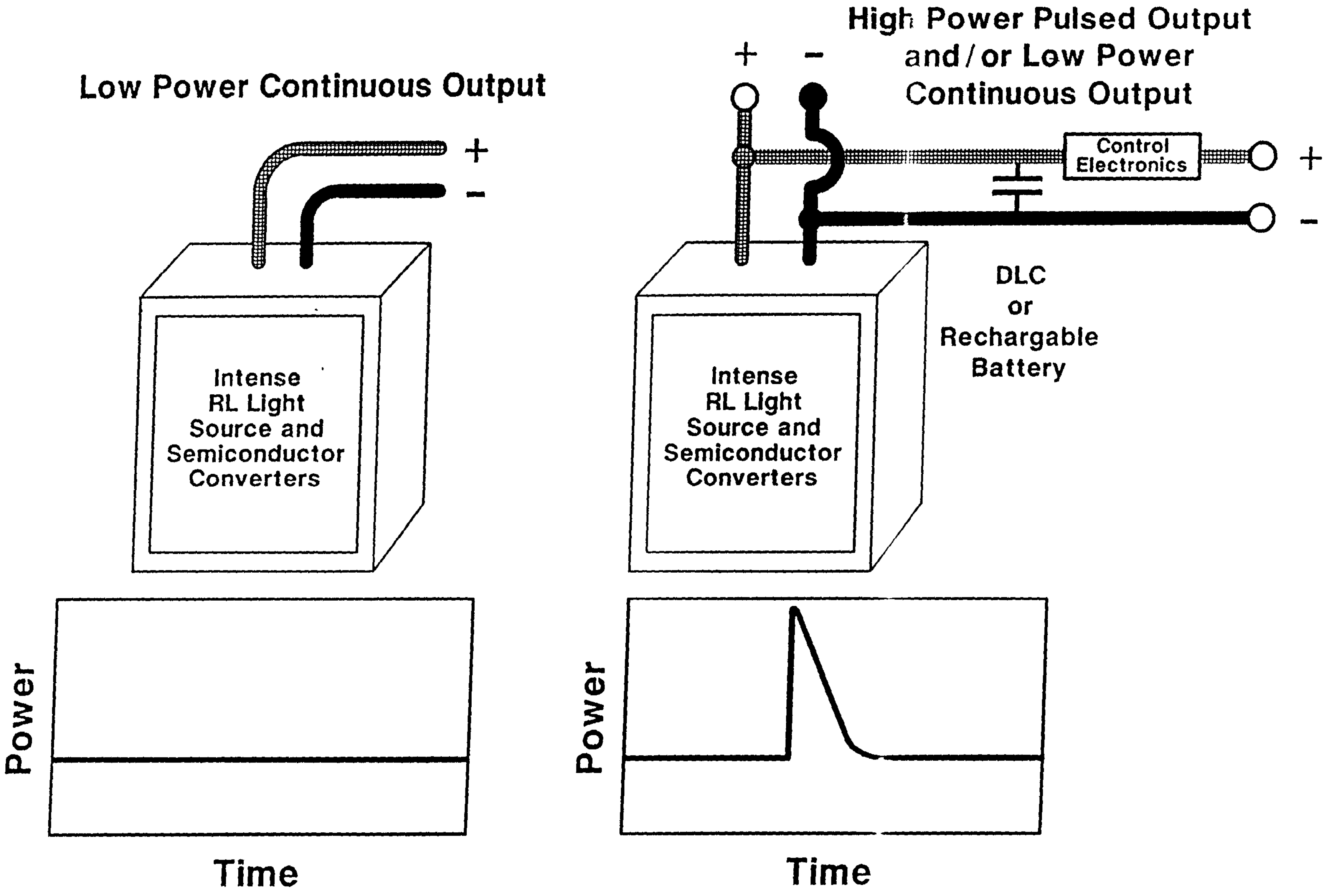
Low Power Continuous Output
+
-
Intense RL Light Source and Semiconductor Converters
Power
Time
High Power Pulsed Output and/or Low Power Continuous Output
+
-
Control Electronics
+
-
DLC or Rechargable Battery
Intense RL Light Source and Semiconductor Converters
Power
Time

FIGURE 5

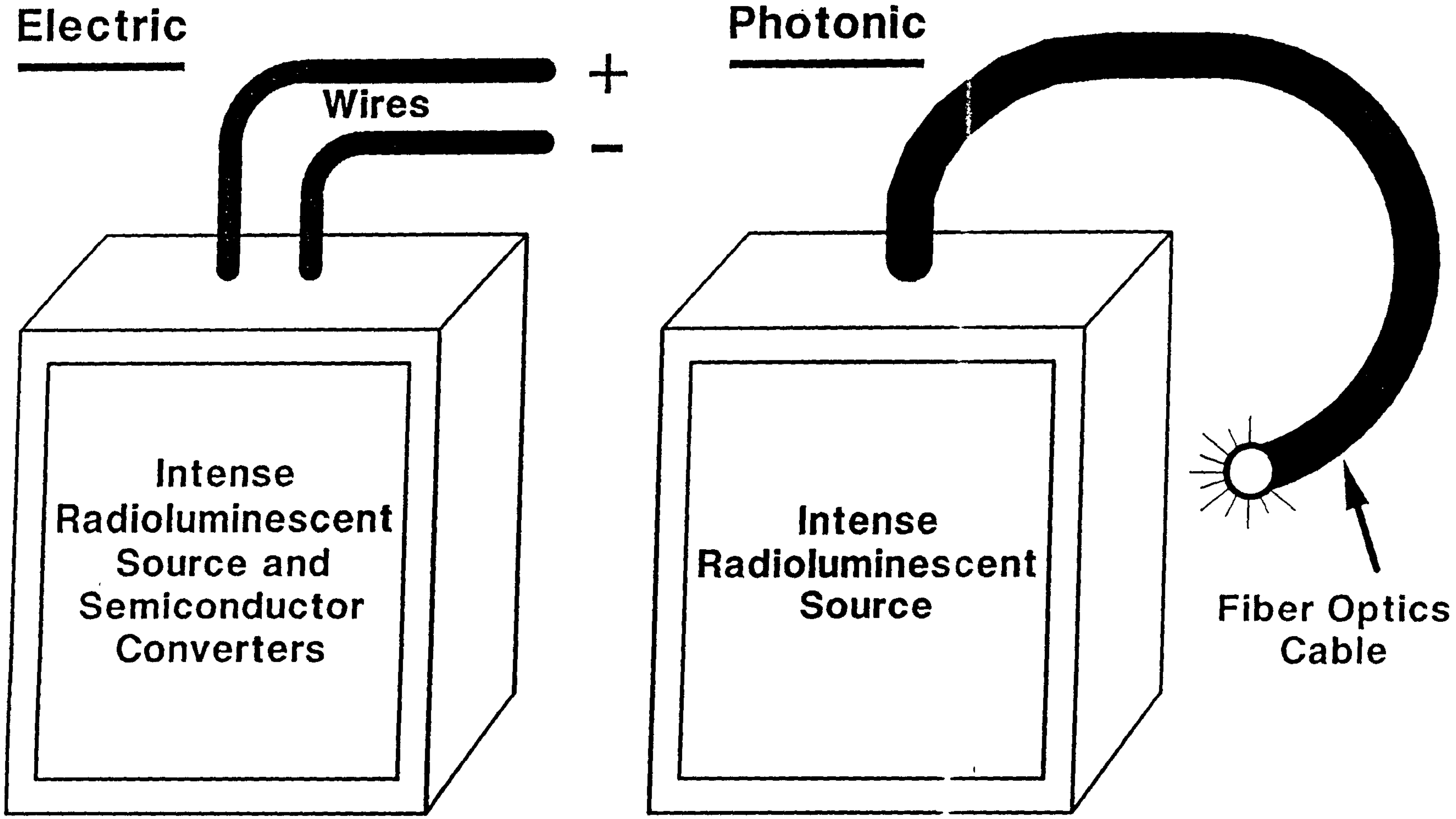
Electric
Wires
+
-
Intense Radioluminescent Source and Semiconductor Converters
Photonic
Intense Radioluminescent Source
Fiber Optics Cable

FIGURE 6