# Power Sources for Ultra Low Power Electronics

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DARPA asked JASON to examine the issue of power sources for low power electronics with a specific emphasis on the properties of nuclear batteries and integrated power sources combining power and electronics. During the 1998 Summer Study a workshop was held to provide background for the study, with participants listed in Appendix A. These people told us about topics including glucose fuel cells (Heller, Palmore), thin film Li batteries, solar cells, and supercapacitors (Bates, Lanning, and Kaschmitter), piezoelectrics and thermoelectrics (Hagood and Lyon), and nuclear batteries (Aselage and Emin).

This report discusses the conclusions of our summer study.

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# Contents





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# EXECUTIVE SUMMARY

- Battery power is critical for: dismounted soldiers for radio communications, global positioning via GPS, and new battlefield awareness systems; unattended sensors for sensor power, and communications, with long life especially desirable; and distributed sensor networks, such as those for the "smart ship" project to provide sensor power, and networked communications.

- Ultralow power electronics permits the use of new types of power sources which provide lower power levels than previously required. Exploiting power sources naturally available in the field will be investigated under DARPA's new Energy Harvesting Program.

- Using ultralow power electronics, milliwatt power levels will permit substantial computation and signal processing at mega-instruction per second (MIPS) rates. The availability of low power parts will greatly reduce the power required for battlefield awareness systems, geo-positioning, biomedical systems, and the like, and make feasible the use of alternative power sources. However, current military electronics is far less efficient, with power consumption typically measured in Watts rather than milliwatts. A large gap exists between fielded systems and what is currently possible.

- Communications will continue to dominate power consumption, because relatively high transmit powers are required to overcome scattering and attenuation in terrestrial radio links. The transmit power required to reach a specified signal-to-noise ratio is proportional to bandwidth, increasing dramatically for video and other high bandwidth communications over voice and low speed data. For these reasons, bandwidth is perhaps the single most important factor in determining power requirements in the field for future systems.

- Nuclear beta batteries are attractive for unattended sensors which require modest power for long periods of time. A $TiT_2$ beta cell could provide power $\sim 100\mu A/cm^3$ at 0.5V for 12 years, sufficient to power sensors, low power processors, and memory, while producing no detectable radiation external to the device. When sunlight is available, solar cell/battery combinations can provide greater power at lower cost for periods of several years.

- Nuclear alpha batteries are problematic. Alpha particles produce far more structural damage than beta particles of the same energy, because they are more massive. The proposed use of a $^{244}Cm$ alpha source with an icosahedral boride cell is impractical, because the combination results in a potent source of fast neutrons.

- Integrated power sources are attractive for certain applications. The development of thin film Li batteries and high current carbon aerogel supercapacitors create new possibilities for small integrated systems which combine a battery and/or supercapacitor with low power electronics. The possible applications include unattended and/or networked sensors, memory backup, and power for actively powered "smart cards". However the lifetime will be limited for configurations in which the volumes occupied by batteries and electronics are comparable.

# 1 INTRODUCTION

Portable electrical power is critical to a wide range of military applications. Dismounted soldiers need to carry tens of pounds of batteries to power radio sets, geo positioning systems, and new battlefield awareness systems. Unattended sensors rely on batteries or solar cells to provide sensor power and communications. Distributed sensor networks, such as those considered for new "smart ships", could benefit from locally supplied electrical power for sensors and network communications. The development of ultralow power electronics creates opportunities to use a wider range of power sources for military applications. The new DARPA Energy Harvesting Program relies on naturally available sources to power electronics in the field.

DARPA asked JASON to examine the issue of power sources for low power electronics with a specific emphasis on the properties of nuclear batteries and integrated power sources combining power and electronics. During the 1998 Summer Study a workshop was held to provide background for the study, with participants listed in Appendix A. These people told us about topics including glucose fuel cells (Heller, Palmore), thin film Li batteries, solar cells, and supercapacitors (Bates, Lanning, and Kaschmitter), piezoelectrics and thermoelectrics (Hagood and Lyon), and nuclear batteries (Aselage and Emin).

This report discusses the conclusions of our summer study. Section 2 describes projected energy use for computation and communication, including the effects of ultralow power electronics. Section 3 describes different approaches to portable power sources, including energy harvesting, and nuclear batteries.

# 2 ENERGY USE

This section describes the characteristics of ultralow power electronics and discusses the impact on computation and communication.

In the near future, power requirements for signal processing and computation will fall to low levels, measured in milliwatts, creating new opportunities for battlefield awareness and biomedical systems, for example. However most currently fielded electronics systems are far behind current low power technology with power consumptions measured in Watts rather than milliwatts.

Power for communications, specifically transmit power, will become dominant. High power levels are required for reliable terrestrial radio links due to scattering and attenuation, and these levels will not decrease in time. Because the power required is proportional to data rate, the use of high bandwidth communications such as video and high speed networks will be severely limited by power contraints. The development of efficent transmitters and low power system design are high priority issues.

## 2.1 Computation

Low power processors are desirable for a wide range of applications, and the design of ultralow power processors is aggressively being pursued for applications in the commercial sector. To give an overview of the capability of commercial processors, Figure 2-1 presents the power consumption in mW/MIP for a range of common processors over the past ten years. While the original Intel Pentium (1993) consumed $\sim$ 300 mW/MIP, more recent processors use less, and processors specifically designed for low power operation consume 1 to 2 mW/MIP. The current state of the art in low power

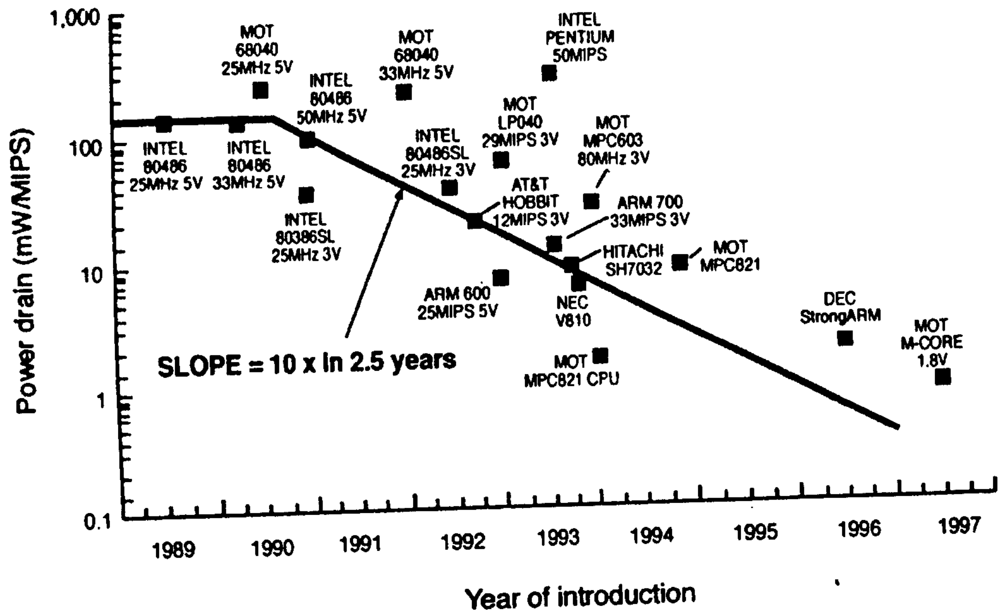


Figure 2-1: Power consumption in mW/MIP of recent microprocessors vs. year of introduction.

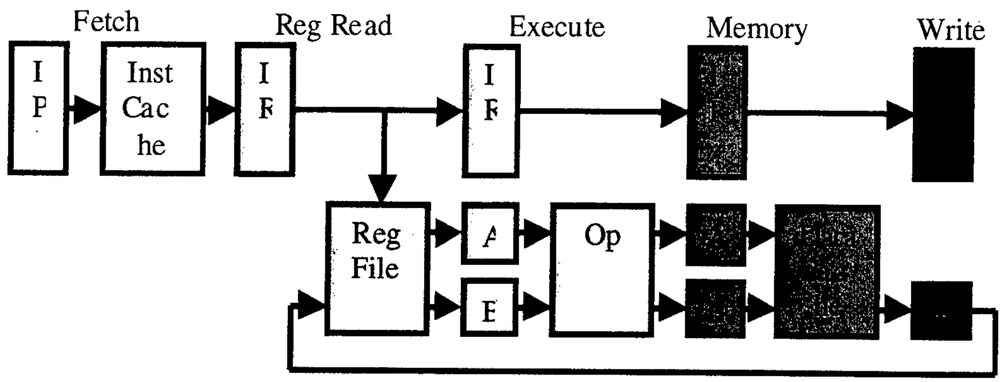


Figure 2-2: Structure of RISC pipeline.

microprocessors is represented by the DEC Strong Arm 1500 (200 MIPS, 32 bit fixed point arithmetic, consuming 400 mW, for 2 mW/MIP), the TI 320VC549 (40 MIPS, 16 bit fixed point arithmetic, consuming 50 mW for 1.25 mW/MIP), and the Lincoln Lab Systolic Array (45GOPS, 0.3 mW/MIPS).

Note that special purpose processors such as the Lincoln Labs Systolic Array can achieve much lower power consumption, because the overhead associated with general purpose processors can be avoided.

It can be misleading to associate power consumption with arithmetic operations, because arithmetic alone typically consumes $< 10\%$ of the power in programmable processors. Most of the power is associated with the other tasks associated with the instruction, especially moving data. This means that a large power saving can be achieved through specialization. A reduction by a factor $\sim 10$ can be achieved by eliminating overhead required for general purpose computation. And a reduction by a factor of 2 to 4 can be gained by tailoring the word length to the task, because power increases quadratically with word length.

Figure 2-2 shows the structure of a typical RISC pipeline in order to illustrate where the power goes in a microprocessor. The steps are fetching an instruction, register read, execute operation, transfer to memory cache,

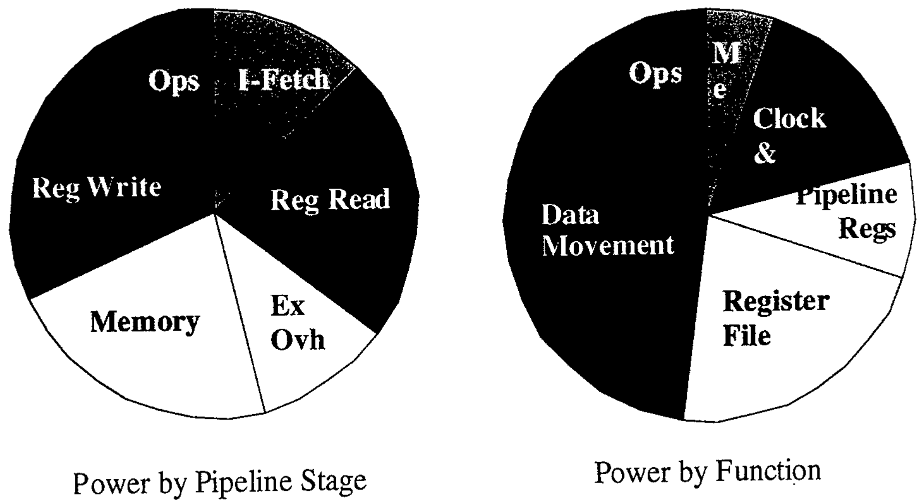


Figure 2-3: (a) Power consumption by RISC pipeline stage. (b) Power consumption by function.

and write to memory. Figure 2-3 shows estimates of power consumption by (a) pipeline stage and (b) by function. As shown in Figure 2-3 (b) less than 10% of the power is consumed by arithmetic operations, while about one third of the power is consumed by data movement. Data movement is especially inefficient because the data lines which must be charged have large capacitance relative to gates.

Power consumption of integrated circuits will decrease in the future as processing moves toward smaller feature sizes. Assuming that the current exponential trends will continue, gate length L will be halved every 3 years. Because the switching energy is proportional to $L^3$, the energy consumption per function is halved every year. These factors predict a substantial decrease in power consumption of information processing integrated circuits, as indicated in Figure 2-4. The bottom line is that substantial computational power will become increasingly available at power consumptions measured in milliwatts rather than Watts.

The fundamental limit to the power required for computation set by

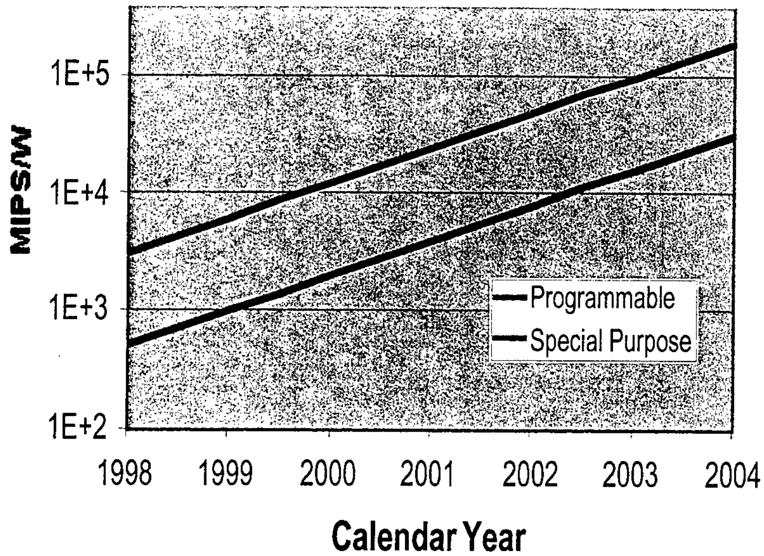


Figure 2-4: Computational power in MIPS/W vs. calendar year for general purpose programmable microprocessors and for special purpose processors.

thermal fluctuations is far below current levels. Assuming that an energy $\sim 100\ \mathrm{k_BT/bit}$, with $k_B$ Boltzmann's constant, is required for an acceptable error rate, the lower limit to power consumption is $\sim 0.4$ pW/Mbps. Each instruction requires flipping $10^5$ bits so the minimum power required for computation is $\sim 100$ nW/MIPS, a factor $\sim 10^4$ below current levels $\sim$1 mW/MIPS.

## 2.2 Communication

Radio communications currently have large power demands, and will increasingly dominate power consumption in the future. The problem is not receiving a signal, but transmitting at a level which can be reliably received. The fundamental limit to receiver sensitivity is currently approached by receivers with low power consumption. The limit set by thermal fluctuations is $P_R \sim 0.4$ pW/Mbps for 20 dB signal to noise ratio. The transmitted power must be far greater (a) because most power is lost, not received, even in free space and (b) scattering and attenuation greatly increases power requirements for terrestrial communications.

The transmitted power required for communications in free space is:

$$P_T \sim \left(\frac{1}{\Omega}\right)^2 \left(\frac{R}{\lambda}\right)^2 P_R \tag{2-1}$$

where $\Omega$ is the solid angle of the antennas, $R$ is the range, and $\lambda$ is the wavelength. In free space, such as between satellites, the transmitted power required to achieve the fundamental limit to received power is quite modest, for example $P_T \sim 1$ mW/Mbps for $R = 10$ km, $\lambda = 1$ m, and $\Omega = 2\pi$.

Scattering and attenuation greatly increase the power required for reliable radio links above free space values. These effects are highly variable and difficult to quantify, as they depend on terrain, foliage, and frequency of operation among other variables. One can make rough estimates starting with the transmit power currently used for voice communications on field radios $P_T \sim 10$ W/10 kbps for $\sim 10$ km. This is a factor $\sim 10^6$ greater than the free space limit above. The weight in batteries needed to supply this power for one week in the field is near the upper limit that a soldier can carry.

The high transmit powers required to overcome scattering and attenuation in terrestrial communications have important consequences for system design. The power required to achieve a given signal to noise level in a radio link is proportional to the bandwidth. Scaling field radio power levels to bandwidths required for video and high speed data links requires powers $P_T \sim 1$ kW/1 Mbps well beyond current battery technology. In addition these rf power levels are high enough to be dangerous to the operator. Proposals have been made for high speed networked battlefields of the future, in which images and data are widely disseminated. However, power consumption will place severe limits on the bandwidths available to soldiers (and remote sensors) in the field, and these limits must be included in the overall design of the system. Bandwidth is likely to be the most important factor determining total power consumption of field communications in the future.

Various proposals have been made to improve battlefield communications. This topic was considered in a previous JASON report (JSR-96-605) as well as a number of government studies. From the point of view of power consumption, a cellular network is attractive. The unit carried by each soldier would be similar to a cellular (or PCS) telephone, with transmit power $< 1$ W. In order to complete the links and provide long distance communications a network of portable ground stations is required, located for example on trucks, UAVs, or satellites. For upward links to UAVs and satellites, the scattering and attenuation are less, and lower transmit powers may be suitable. UAVs make high visibility targets for the enemy. Satellites for commercial cellular telephone networks are under development by COMSAT. A single such satellite placed in a geosynchronous orbit can provide cell phone communications to users located across the continental United States. By using a large antenna on the satellite, sufficient sensitivity can be obtained with conventional cell phone equipment and transmit powers.

# 3 ENERGY SOURCES

## 3.1 Energy Harvesting

In order to obtain fuller battlefield awareness and improved soldier performance, soldiers are envisioned to wear and transport a variety of electronics in the battlefield. Power is required for computing, sensing, and display systems that will be worn or otherwise transported by the soldier into battle. Such systems might include heads-up displays, video, chemical and biological sensors, and computing capabilities in support of these and other desired functions.

At present, a serious limitation for such soldier-mounted electronic systems involves the weight and volume of the power sources (typically batteries) that the soldier must transport. As electronics advance in the future, either more computing capability can be obtained for the same power requirements, or the power requirements may be eased to sustain the current level of system performance. Clearly, the availability of ultra-low power electronics would open up a number of interesting new options for enhancing the performance and battlefield awareness of the soldier.

Similarly, power requirements place a severe design constraint on the performance of unattended ground sensors is their power requirements. Again the mass and volume of the power sources are often serious limitations on the fieldable capabilities of such systems, and the availability of ultra-low power electronics would be of great interest here as well.

This JASON study addresses the opportunities that would be opened by the development of ultra-low power electronic devices. Such devices would permit harvesting of energy at low power from the battlefield environment, and would greatly reduce the burden on the soldier for transporting the power sources for such systems. A secondary focus of the study is to outline the degree to which design tradeoffs in current electronic systems can be exploited to facilitate operation in ultra-low power mode without severely degrading overall system performance levels.

*Ultra-low Power Devices*

We have considered four distinct scenarios:

a) the power-generating device is to be left fully unattended for its operational lifetime and is to be located in a highly concealed, indoors, location;

b) the power-generating device is to be left fully unattended for its operational lifetime and is to be located in a concealed, outdoors location but with some access to the external environment;

c) the power-generating device is to be carried by an isolated, autonomous soldier and is never to be recharged;

d) the power-generating device is to be carried by a soldier and can be recharged when the soldier must obtain a renewal of his food and/or logistics supplies.

There are, of course, existing benchmarks that are already in use for each scenario. References for scenarios a) to c) are Li-ion or Ni/NiH batteries. Typical mass-based and volume-based energy and power densities for these two types of batteries are provided in Table 1. Energy from a diesel-powered generator is one reference system for scenario d). The performance of these power systems provide useful reference points by which to judge the capabilites of any other proposed power system.

Table 1.

| | Specific Energy Density (J/g) | Energy Density ($J/cm^3$) | Power Density ($mA/cm^3$) | Mass Density ($g/cm^3$) | Lifetime* (hr) |
|---|---|---|---|---|---|
| Li-ion | 115 | 406 | 1000 | 3.53 | 30.5 |
| Ni-NiH | 171 | 498 | 1000 | 2.91 | 45.4 |
| Beta battery** | 2700 | 11,000 | 0.1 | 4 | 1600 |
| Direct methanol fuel cell | 3600 | 2800 | 0.1 to 1 | 0.8 | 954 |
| Solar cell/battery | 30,000 | 87,000 | 1 | 3 to 4 | 8000 |

*For 1 g of device at a constant load of 1 mW, until full discharge
**Assumes 100 plates, of thickness $10^{-2}$ cm each, stacked into a cell.

### 3.1.1 Power sources for fully autonomous, buried, concealed devices

In scenario a), the power-generating device is to be left fully unattended for its operational lifetime and is to be located in a highly concealed, indoors, dark, location. In this highly constrained situation, when it is initially deployed the power system device must contain all of the energy to be output over its lifetime. Two systems are compared in their performance to Li or Ni/NiH batteries in this application: betavoltaic batteries and fuel cells.

*Beta-Decay Batteries*

These nuclear-decay powered batteries are the subject of a previous JASON report, JSR-86-503. The "betavoltaic" battery, which might use $TiT_2$ as a source of beta decay electrons, produces power by having these electrons produce electron-hole pairs in a conventional photovoltaic p-n junction. The photovoltaic then produces a photocurrent through the device in the same fashion that current is produced in conventional photovoltaic solar cells.

Due to the relatively low emitted flux of beta decay electrons, the betavoltaic battery has a low power density but a high energy density. Its initial proposed design consisted of 1000 stacked cells, each 10 micron in thickness, which would produce an initial power density of $3 \times 10^{-4}$ W/cm$^3$ and an energy density of approximately $1 \times 10^5$ J/cm$^3$ (approximately 500 watt-hours/in$^3$) over a lifetime of 10–20 years. In practice, it would be difficult to make such thin plates because the semiconductor layer was assumed to have been grown with no substrate, which is technically challenging at the present time. Thus, a more realistic estimate would likely assume a plate thickness of $10^{-2}$ cm. This produces a power density of $3 \times 10^{-5}$ W/cm$^3$ and an energy density of $1 \times 10^4$ J/cm$^3$. The betavoltaic battery runs continuously and, of course, cannot be "shut off", because the nuclear decay processes of the tritium-containing source occur regardless of whether or not electrical current is being collected through the terminals of the photovoltaic device.

*Fuel Cells*

Because the chemical processes involved in fuel cell reactions have significant kinetic impediments at room temperature, fuel cells are typically run at high temperature, where such reactions are more rapid. However, if fuel cells are to be operated at low power densities, they might make interesting power sources for certain applications at room temperature.

The energy density of a well-designed fuel cell is essentially that of the fuel itself, because the electrodes and membrane occupy a relatively small fraction of both the mass and volume of the device. For a direct methanol fuel cell, the anode reaction is:

$$\mathrm{CH_3OH + H_2O = CO_2 + 6H^+ + 6e^-} \qquad (3\text{-}1)$$

and the cathode reaction is:

$$\mathrm{(3/2)O_2 + 6e^- + 6H^+ = 3H_2O} \qquad (3\text{-}2)$$

The total reaction is thus:

$$\mathrm{CH_3OH + (3/2)O_2 = CO_2 + 2H_2O.} \qquad (3\text{-}3)$$

The free energy of formation of $CH_3OH$ is $1.66 \times 10^5$ J/mole, which corresponds to $4.1 \times 10^3$ J/cm$^3$ of pure $CH_3OH$ (of a density of 0.79 g/cm$^3$). We assume that the methanol is fed into the electrolyte in order to dilute it for oxidation, but that the volume of the electrolyte is small compared to the volume of the methanol feed, which will dictate the volume of the overall device. We also assume a 70% efficiency for conversion of the fuel energy into electrical power. This produces a useable energy density of approximately $2.8 \times 10^3$ J/cm$^3$ (12.5 W-hr/in$^3$) and a specific energy density of $3.6 \times 10^3$ J/g.

At room temperature, the output voltage of a methanol fuel cell is approximately 1.0 V. The current density from direct $CH_3OH$ fuel cells at room temperature is approximately 0.1 mA/cm$^2$. This leads to a power density of 0.1 mW/cm$^3$ assuming that only one set of fuel cell electrodes is used to extract the power, and that the electrode area is 1 cm$^2$. Of course, these are design parameters that could be altered if higher current densities are desired, so that a power density of 1 mW/cm$^3$ ought to be feasible (at a shorter overall cell lifetime).

This type of fuel cell thus has a slightly higher specific energy density than the 100 plate/cm beta-battery, although the fuel cell has a somewhat smaller energy density (by about a factor of 2). One other difference is that it is possible to shut off the fuel cell by interrupting the electrical connection between the anode and the cathode, whereas the beta battery discharges continuously regardless of whether the energy is being harvested or not. If the fuel cell is operated at a 20% duty cycle, then its discharge-limited lifetime is a factor of 10 longer than that of a beta battery of comparable mass, when each system is run at the same output power level. The fuel cell also does not produce waste heat during non-operating periods.

The use of fuel cells for low power density applications overcomes one serious problem at the present time in direct methanol fuel cell technology;

the lack of materials that have a low overpotential for the electrochemical reactions of Equations (3-1) and (3-2). Conventional electrode materials will suffice for the low power device, because the required current densities are small. The remaining issue in constructing such a fuel cell, and in all direct methanol fuel cells, is the methanol "cross-over" rate, i.e., the rate at which methanol traverses the membrane and enters the cathode compartment from the anode compartment. This leakage might be reduced in the low power methanol fuel cell by using membranes which are too resistive for conventional fuel cell designs; a somewhat higher cell resistance can be tolerated in the low power fuel cell because the device runs at such a low current that even a resistance of 100 ohm only produces a 10% loss in power (for the 1 V output of the fuel cell).

### 3.1.2 Power sources for fully autonomous devices that can be exposed to renewable energy sources

We now address power sources for scenario b), where the power-generating device is to be left fully unattended for its operational lifetime and is to be located in a concealed, outdoors location that has some exposure to the environment. Of course, all three systems (conventional batteries, beta batteries, and fuel cells) discussed above for use in a fully concealed location are still available, but the ability to use renewable energy sources opens up additional options that, as described below, appear to be more desirable under this scenario.

We first discuss augmentation of battery power with electrical energy obtained from sunlight using conventional photovoltaic devices. We then evaluate the performance of other potential power sources in the environment which are interesting options when low power sources are an option.

*Solar Cells*

Solar cells have the advantage that the device does not need to carry its own energy source. In this section, we explore the capabilities of solar cells, in conjunction with an energy storage unit, for low power applications relative to the capabilities provided by beta batteries and fuel cells.

The solar constant 1376 W/m$^2$ is the average solar power incident on the outer atmosphere. Average levels absorbed at the earth's surface vary nearly sinusoidally from about 425 W/m$^2$ on the equator to 50 W/m$^2$ at the poles Fig. 1.1 of Gill, 1982 "Atmosphere-Ocean Dynamics" A.E. Gill, Academic Press, New York, 662 pages). A production-line Si photovoltaic cell can typically yield 15% efficiency in solar-to-electrical energy conversion. Accounting for this factor yields an average power production of approximately 60 W/m$^2$ to 8 W/m$^2$ of illuminated area. The voltage is 0.5 V, which is comparable to that of a beta battery or a fuel cell. The lifetime of solar cells can exceed 20 years in the field.

The thickness of a Si photovoltaic cell is approximately 200 microns. GaAs cells can be made thinner, and if integrated onto the energy storage unit, the cell material and contacts can be as thin as 10 microns while maintaining a significant level of photovoltaic performance. However, as described below, the thickness of the solar cell itself is not the dominant factor in the energy density of the power unit.

An energy storage device is needed in order to accommodate the diunural variations in insolation as well as the daily fluctuations in power. We assume an approximately equal mean power drain during daytime and nighttime periods; thus, 50% of the power produced by the solar cell during the daylight will be consumed during the day, while the remainder must be stored for use at night. The available mean power for the device in any total 24 hour period is therefore 30 W/m$^2$ to 4 W/m$^2$ of illuminated solar cell area.

Assuming 80% efficiency in charging the battery, the capacity of the storage device must be: (30 $W/m^2$ to 4 $W/m^2$) $\times$ (12 hr) $\times$ (3600 sec/hr)/0.8 = (1.6 $\times 10^6$ $J/m^2$ to 2.1 $\times 10^5$ $J/m^2$).

A typical Li-ion battery provides energy densities of $4 \times 10^8$ $J/m^3$. Every 1 $m^2$ of illuminated solar cell area, 10 micron thick (if GaAs is used), then must be accompanied by a battery of thickness 2.7 mm. The total thickness of the solar cell/battery combination is thus dominated by that of the battery. However, a renewable source is being used, so the output energy density of the device is much higher than that of the battery alone. In practice, the lifetime of the device will probably be dominated by the cycle life of the battery. Assuming 1000 deep discharge cycles before performance degradation, this solar cell/battery combination then has a lifetime of (1 cycle/day) $\times$ (1000 cycles)/(365 days/yr) = 2.74 years. During this period, it has provided a mean power density of 30 W/2.7 $\times 10^{-3}$ $m^3$ = 1.1 $\times$ $10^4$ $W/m^3$ to 4 W/2.7 $\times 10^{-3}$ $m^3$ = 1.5 $\times$ $10^3$ $W/m^3$ and a total energy density of 3.5 $\times 10^{11}$ $J/m^3$ to 5 $\times 10^{10}$ $J/m^3$. For a longer lifetime of the solar cell/battery combination, one could increase the ratio of the battery thickness/device volume, thereby decreasing the number of battery charge/discharge cycles; this would result in a lower energy density but of course would maintain the same delivered energy, over a longer operational unit life. For a 20 year lifetime, we merely need to increase the battery thickness by a factor of 20/2.73 = 7.32, i.e., to a thickness of 2 cm. The power density and energy density are now reduced by an equal factor of 7.32, so that the 20 year operational device has a mean power density of 1,500 $W/m^3$ to 200 $W/m^3$ and a total energy density of 5 $\times$ $10^{10}$ $J/m^3$ to 7 $\times$ $10^9$ $J/m^3$. Because the photovoltaic device is so thin, the density of the device is dominated by that of the battery, and thus the specific energy density of the entire device is approximately $3 \times 10^7$ J/kg. For a measure of the increase in performance that is gained by using a renewable energy source to power the device, all three of these performance measures are greater than those of the beta battery for a comparable 20 year device lifetime.

## 3.2 Nuclear Batteries

*Neutron Generation in Icosahedral Boride Energy-Conversion Devices*

Neutrons were originally discovered as an unusually penetrating radiation that was produced when naturally radioactive alpha emitters were mixed with light elements – especially beryllium and boron. Substantial numbers of neutrons are also generated from alphas stopped by $^{19}$F, $^{13}$C, $^{7}$Li. A typical yield from completely stopping 5.48 MeV alphas from $^{241}$Am in boron of natural isotopic abundance (19.78% $^{10}$B, 80.22% $^{11}$B) is 13 neutrons per million alpha particles. Both isotopes contribute to the neutron yield, with a harder energy spectrum coming from $^{10}$B (Q = 1.07 MeV) than from $^{11}$B (Q = 0.158 MeV). The 5.79 MeV alphas from $^{244}$Cm would produce a slightly higher yield of neutrons and a slightly harder spectrum than that produced by $^{241}$Am.

The proposed icosahedral boride energy conversion devices will be designed to release about 2 W of thermal energy, which would mean that they would generate about 2 W/5.79 MeV/alpha = $2.2 \times 10^{12}$ alphas/sec, which is an alpha activity of 58 Ci (comparable to 58 grams of pure radium). Neglecting any other elements besides boron in the device, we can estimate a conversion rate of $1.3 \times 10^{-5}$ neutrons per alpha particle, so some $2.8 \times 10^{7}$ neutrons/sec would be generated, and the neutron activity would be 0.8 mCi. The presence of other elements besides boron in the device would most likely diminish this activity, while the neutron-induced fission of a $^{244}$Cm alpha emitter would increase it, typically by a percent or so.

So the proposed icosahedral boride energy conversion device will not be a trivial source of neutrons, and its effects would have to be considered in connection with the proposed application. For example, according to the entry on "Neutrons" from the McGraw-Hill Encyclopedia of Science and Technology: "The currently accepted health tolerance levels for an 8-hour day correspond for fast neutrons to a flux of 20 neutrons/cm$^2$sec or 130 neutrons/in$^2$sec; for slow neutrons, 700 neutrons/cm$^2$sec or 4500 neutrons/in$^2$sec." The neutrons from the icosahedral boride energy conversion device have an energy spectrum that peaks at about 3 MeV and can be considered to be "fast". Assuming an inverse-square law attenuation of the neutrons with distance the 8 hour tolerance level would be exceeded for anyone closer than 3.34 m (about 11.0 ft) from the source.

Neutrons cause negligible ionization in matter, so neutron shields depend entirely on scattering by the nuclei of the shield. The small nuclear cross section requires that neutron shields be bulky and heavy. Most practical shields contain hydrogen or other light elements, to ensure that the recoil of the nuclei from elastic scattering collisions efficiently slows down the neutrons. The resulting thermal neutrons can be resonantly absorbed, preferably by nuclei like $^6$Li and $^{10}$B, which do not emit gamma rays when they absorb neutrons. Typical shields consist of several feet of water, paraffin, or concrete – where the water of hydration is important in slowing down the neutrons. The shields are often loaded with boron-containing compounds for efficient absorption of the slow neutrons. To cite a representative example, Aronson has shown that the fast neutron dose rate from a point source of fission neutrons can be attenuated by a factor of 100 by 38 cm of water. Such a shield would reduce the dose rate at the outer surface of the shield to about the 8 hour tolerance level. The mass of a water shield, 38 cm in radius, is 230 kg or 506 lbs.

The biological shielding needed for icosahedral boride energy conversion devices will dominate their weight and needs to be considered carefully in any proposed applications.

Additional problems are posed by the proposed use of $^{244}$Cm as a source:

Cost — The isotope is available from Oak Ridge National Laboratory at \$180/mg with a substantial minimum shipping cost (\$1720), and maximum activity per shipping container. If we ignore shipping entirely, the base cost projects to about \$100,000 per Watt. Although there may be substantial reductions if the batteries lead to a "production line", perhaps even located at Oak Ridge, these are not going to be low cost batteries.

Decay Product — $^{240}$Pu. If the basic idea could be salvaged by finding a stable carrier molecule (or perhaps a molecule that will adequately survive the alpha-particle bombardment long enough to be worthwhile (e.g. a few months) and then can be annealed to restore its structure) consisting entirely of atoms with small $(\alpha,n)$ cross sections, but the cost remains a killer in spite of "mass production", why not use $^{238}$Pu? It would take 4 times as much for the same power and the lead shielding would have to be thicker to stop the 104 keV gammas that would be emitted $\sim 1\%$ of the time (instead of 43 keV gammas with $^{244}$Cm). However the psychological baggage (**plutonium**) is already there and $^{238}$Pu is much more readily available. We do not seriously propose this alternative, but use it to point out the seriousness of the problems with $^{244}$Cm.

# References

[1] *Neutron Sources for Basic Physics and Applications* Edited by S. Cierjacks (Pergamon Press, Oxford, 1983). McGraw-Hill Encyclopedia of Science and Technology.

[2] *Reactor Handbook* (Interscience Publishers/John Wiley & Sons, New York, 1962) p. 73.

# A APPENDIX

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