ORNL/TM-13360

ornl

OAK RIDGE NATIONAL LABORATORY

LOCKHEED MARTIN

Instrumentation and Controls Division

Compact Portable Electric Power Sources

Dwayne N. Fry
David E. Holcomb
John K. Munro
Lester C. Oakes
Michael J. Maston

February 1997

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MANAGED AND OPERATED BY
LOCKHEED MARTIN ENERGY RESEARCH CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

ORNL-27 (3-96)

DISCLAIMER

Portions of this document may be illegible electronic image products. Images are produced from the best available original document.

ORNL/TM-13360

Instrumentation and Controls Division

Compact Portable Electric Power Sources

Dwayne N. Fry
David E. Holcomb
John K. Munro
Lester C. Oakes
Michael J. Maston

February 1997

Prepared for the
United States Special Operations Command

Prepared by the
OAK RIDGE NATIONAL LABORATORY
managed by
LOCKHEED MARTIN ENERGY RESEARCH CORP.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-96OR22464

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

This report provides an overview of recent advances in portable electric power source (PEPS) technology and an assessment of emerging PEPS technologies that may meet U.S. Special Operations Command's (SOCOM) needs in the next 1–2-and 3–5-year time frames. The assessment was performed through a literature search and interviews with experts in various laboratories and companies. Nineteen PEPS technologies were reviewed and characterized as (1) PEPSs that meet SOCOM requirements; (2) PEPSs that could fulfill requirements for special field conditions and locations; (3) potentially high-payoff sources that require additional R&D; and (4) sources unlikely to meet present SOCOM requirements.

1. INTRODUCTION

This report provides an overview of advances in portable electric power source (PEPS) technology during the last 2 years and an assessment of emerging PEPS technologies that may meet U.S. Special Operations Command's (SOCOM) needs in the next 1–2-and 3–5- year time frames. For this report, we conducted a literature search of PEPS technology as well as conducting interviews with experts in various laboratories and companies. The emphasis of this study is on lighter weight, higher power capacity, high-reliability PEPS technology that is reaching a point where it may be economically feasible to implement in the next few years. A section on "exotic" portable power sources is also included although none of these will be available in the next 5 years.

2. POWER SOURCE REQUIREMENTS

Portability and reliability are key requirements that any candidate PEPS must meet. Weight is a major factor in field-deployable power sources. Weight requirements can be met in some cases by dividing power sources into separate field assemblable units. These units need not be comprised of a single technology (e.g., solar battery chargers). Energy density of candidate sources should be considered in selection of new sources. For example, the energy density of diesel fuel is 10,000 W·h/kg, whereas available Li/SO_2 batteries have energy densities of 280 W·h/kg. A typical battery currently used by the Army is a lithium–sulfur dioxide unit (BA-5590/U) that weighs about 1 kg and delivers 175 W·h.

This survey is limited to *portable* electric power sources. Thus, only power supplies in which the heaviest component weighs no more than ~40 kg are considered. The survey is not limited to the soldier of the future system in that larger, assemblable units are considered (e.g., flywheels that do not scale well to small size, yet are of interest for applications such as watercraft propulsion).

Another feature that has been requested by military forces is a battery energy-remaining indicator. Existing primary (nonrechargeable) batteries have virtually flat discharge voltages, making state-of-charge difficult to monitor. This results in excess costs and waste generation for discarding nearly new batteries. Portable devices already exist to measure the state-of-charge for some batteries (e.g., BA-55901U) used by Special Operations Forces, but built-in monitors would be a significant advantage for batteries critical to mission success.

Reliability is an essential ingredient for mission success and for safety of users. Batteries and other PEPS technologies can be pushed close to theoretical energy density limits but the resultant systems may be inherently unstable during storage and transportation or in the field. Maintenance of

PEPS and overall support infrastructure can result in significant costs associated with training, inventory, disposal, replacement, and repair costs.

For field deployable units, the noise associated with power generation must be kept to a minimum. This is not a problem with batteries but can be a factor when using mechanical methods for power generation. Another concern in the field is the thermal signature associated with a power source. Both thermal and acoustic signatures can be used by opposing forces for targeting.

Also, any power source intended for field use must be able to withstand environmental temperature extremes, submersion in water, and exposure to dirt, dust, and other environmental contaminants. Also, for field deployment, PEPSs must operate under any physical orientation.

Finally, cost is a major factor in selection of PEPS. Costs to the military can be significantly reduced if a large commercial market exists for the same power sources. Such applications as electrical vehicles, laptop computers, portable video cameras, and the proliferation of battery-operated hand tools are providing the incentive for commercial development of PEPSs.

A general range of Special Operations Forces power requirements is given in Table 1. Typical voltage requirements are 3, 6, 12, or 24 Vdc.

Table 1—Power Requirements

Power Range [Watts]	*Daily Requirements [Watt-hours]*	*Mission Length [days]*	*Total Energy [Watt-hours]*
0-50	100	30	3000
0-100	200	7	1400
0-300	1667	3	5000
1-1000	----	----	8000

3. POTENTIAL POWER SOURCES

3.1 BATTERIES

Batteries are the traditional workhorse of portable electric power systems. Their widespread availability, high reliability, relatively low cost, low signature, and simplicity of use allow them to dominate the portable power market. Increasing power demands, coupled with the performance limitations (hazardous and toxic materials, limited temperature range, and the lack of an obvious power-remaining indication) of current batteries, has driven the search for improved PEPS. One restriction to advancing battery technology is that currently available batteries (for all common types) are within 50% of their theoretically achievable power density for practical systems. Hence, barring revolutionary developments, no dramatic increases in battery energy density are foreseen. The largest changes in battery technology over the next few years are likely to be in price, safety, availability, and manufacturability.

Several recent reviews of the state-of-the-art in battery technology are readily available.[1-5] Therefore, this report will not address battery chemistry or technology in depth but tried instead provide an overview of recent developments in the most promising battery technologies.

Batteries are conventionally classified as primary (nonelectrically rechargeable), secondary (electrically rechargeable), or reserve (one-time mechanically activated) type cells. The terms fuel cells and mechanically rechargeable batteries both represent the same devices and are presented in the fuel cell section (Sect. 3.2).

Lithium-based technology has dominated the development of high power density batteries for the past decade. Lithium cells exhibit (1) higher voltages (up to 4 V compared to ~1.5 V for most competing batteries), (2) high energy density (>200 W·h/kg and 400 kW·h/m^3—optimally 600 W·h/kg and 1200 kW·h/m^3), (3) wide operational temperature range (−40°C–70°C typical), (4) good power density (some designs permit rapid discharge), (5) a flat discharge curve, and (6) superior shelf life (primary cells >5 years). Lithium cells are available as primary, secondary, and reserve power sources.

3.1.1 Li/SO_2

Lithium/sulfur dioxide ($LiSO_2$) cells are among the most widely available lithium-based primary cells. Available cells have energy densities of up to 280 W·h/kg and 444 kW·h/m^3. $LiSO_2$ cells are particularly well suited to high-current applications. $LiSO_2$ cells use lithium as the anode material, a porous carbon as the cathode structural material, SO_2 as the active cathode, and an electrolyte consisting of sulfur dioxide, acetonitrile, and dissolved lithium bromide. Safety remains a continuing concern for $LiSO_2$ technology. The U.S. Army Communications-Electronic Command has recently issued an urgent safety message regarding the use of $LiSO_2$ cells (BA-5590/U).[6] Deep discharge of the cells can result in cell venting, rupture, fire, and methane and cyanide production due to an exothermic reaction of lithium with acetonitrile in the absence of SO_2(Ref. 1, p. 14.18).

3.1.2 Li/$SOCl_2$

Lithium/thionyl chloride (Li/$SOCl_2$) cells are readily available from several manufacturers and have among the highest voltages and energy densities of any practical system. Li/$SOCl_2$ cells have a metallic lithium (or lithium alloy) anode, a high surface area carbon cathode, and a nonaqueous thionyl chloride/salt ($LiGaCl_4$ or $LiAlCl_4$) electrolyte. Li/$SOCl_2$ cells are available in a wide variety of capacities (up to 20,000 A·h) and discharge rates. Cells designed for high discharge rates are required to incorporate safety pressure vents and internal fusing since thermal runaway of the cells and cell rupture (exposing toxic, flammable cell components) may result from too large a current drain or overdischarging the cells.. Cells stored for long periods at elevated temperatures can exhibit several hundred seconds of lower voltage operation because of passivation (formation of an excessively thick LiCl layer) of the anode. Because of their high voltage (3.67 V nominally) and energy density, Li/$SOCl_2$ cells are likely to be a dominant type of PEPS for the next several years. Li/$SOCl_2$ cells are also available (although less widely) with BrCl and Cl_2 additives, which enhance both cell safety (allow higher current draws), operational temperature range, voltage, and energy density.

3.1.3 Li/MnO_2

The lithium/manganese dioxide ($LiMnO_2$) cell is a widely available (for low and moderate rate applications) solid electrolyte lithium cell. Li/MnO_2 cells use lithium for the anode, an electrolyte containing lithium salts in an organic solvent, and MnO_2 for the cathode. The cells have a practical voltage of ~3 V and energy densities of >230 W·h/kg and 550 kW·h/m^3. Commercially available cells range in capacity from about 30 mA·h to 5 A·h. $LiMnO_2$ rechargeable cells are commercially available on a limited basis (because of continuing safety concerns). One characteristic of these cells is their continuous decrease in voltage with usage, providing a direct state of charge indication.

3.1.4 $Li/(CF)_n$

Lithium carbon monofluoride cells [$Li/(CF)_n$] are commercially available (although not in widespread usage) solid cathode lithium cells. They are typically employed for low and moderate rate applications. They have operating voltages of ~2.5 V and energy densities of ~250 W·h/kg and 600 kW·h/m^3. While a variety of different electrolyte materials have been developed, solid polymer electrolytes are the most common.

3.1.5 Lithium Polymer Electrolyte

Polymer electrolyte lithium batteries contain all solid components. They use lithium as the anode material, a thin polymer film as the electrolyte, and a transition metal chalcogenide or oxide as the cathode. Polymer electrolyte lithium cells are currently under active development by 3M under a contract from the United States Advanced Battery Consortium.[7] The goal of this second phase project is to create an electric vehicle battery pack by the late 1990s. The target energy density for polymer electrolyte lithium batteries is 200 W·h/kg.

3.1.6 Lithium Ion

Lithium ion battery technology remains at a laboratory stage of development.[8] Lithium ion batteries' anodes consist of carbon to which lithium ions are intercalated or deintercalcated during charge/discharge. The cathode material is lithiated metallic oxide intercalation compound to which lithium ions can be extracted or inserted during charge/discharge. Overall, it is unlikely that this technology will be available for widespread usage in the next 5 years.

3.1.7 Li/BrF_3

Extensive fundamental electrochemistry remains to be developed before Li/BrF_3 cells can be commercially developed. However, these cells have the highest theoretical energy density of any proposed battery system. They exhibit open circuit voltages of 5.2 V and have a theoretical energy density of 2680 W·h/kg (twice that of $Li/SOCl_2$).(Ref. 3, p. 372). Without extensive fundamental research, these batteries will not become available. However, this technology is worth monitoring since it is the only battery-type power source with the potential to greatly increase the capacity of already available systems.

3.1.8 Lithium Reserve Cells

Lithium reserve cells are available for one-time-use operations requiring long shelf life.[9] Lithium reserve cells are liquid electrolyte systems in which the electrolyte is encapsulated in a glass ampoule that is broken to activate the cell. Lithium vanadium pentoxide (Li/V_2O_5) and lithium thionyl chloride systems reserve cell systems are commercially available.

3.1.9 Nickel-Metal Hydride

Secondary nickel-metal hydride (NiMH) cells have recently become widely available in the consumer market. Although NiMH cells continue to cost more than conventional NiCd batteries, their lack of a toxic heavy metal constituent and their improved energy density mean that NiMH cells will be the secondary battery of choice for the next several years. NiMH cells are available with energy densities >80 W·h/kg. They provide for 1000 charge/discharge cycles and can be recharged in <1 hour.[10] NiMH cells can be discharged at ~20% of rated capacity per hour at 1.2 V and at up to three times rated capacity at 1 V.[11] Nickel oxyhydride is the active metal of the battery positive electrode. The negative electrode is a hydrogen storage alloy (often nickel hydride) with hydrogen serving as the active component.

3.1.10 Thermal Batteries

Thermal batteries are pyrotechnically initiated molten salt reserve batteries. The electrolyte in thermal batteries is a solid nonconducting inorganic salt at ambient temperatures. A pyrotechnic heat source is used to melt the electrolyte. The anode of a thermal battery is an alkaline metal. Inert metals serve as the cell cathode. A common system is a lithium metal anode, a lithium-chloride/potassium-chloride electrolyte, and an iron disulfide cathode. Thermal batteries are physically rugged, have high power densities (up to 1 kW/kg), and have many-year maintenance-free lifetimes.[5] An obvious limitation to thermal batteries is their thermal observability signature (surface temperatures, typically ~250°C).

3.1.11 Intelligent Batteries

Intelligent batteries are rechargeable battery systems composed of a battery, a microprocessor, and possibly a memory chip. The microprocessor and memory are used to control charging rate, measure total stored charge, maintain a history of the number of times a battery has been recharged, and possibly monitor many other parameters. Microprocessors used in these systems can be designed to communicate state of charge and battery history information according to a standard format on a communications bus built into the equipment powered by the battery system. The same protocols and bus standards can also be used by battery rechargers to tailor each recharge to the conditions of the battery, that is, the cell electrochemistry, materials used, and type of cell construction.

Smart battery technology was first introduced commercially[12] in 1989 by Sanyo Energy USA in the form of a fast-charge control module for NiCd and nickel metal hydride (NiMH) batteries. The company integrated the module into battery packs for a variety of Original Equipment Manufacturers (OEM) customers. Duracell (battery manufacturer) and Intel (computer chip manufacturer) have recently jointly developed the Smart-Battery Specification.[13] This specification attempts to address the three major problems that equipment designers and end users have with batteries: (1) the amount of battery operating time remaining, (2) the ability of a battery to supply power for an additional load, and (3) the ability to tailor battery charger operation to a specific battery chemistry. The commercial drivers for development of this technology has come from laptop computers, cellular phones, and video cameras.

The Smart-Battery Specification consists of two primary parts: (1) a two-wire, bidirectional, power-management communications bus for batteries and various components, the System-Management Bus (SMBus)[14]; and (2) the smart-battery data and charger specification[15] that describes the batteries' data set and charge-control schemes.

The SMBus adds a software protocol defining bus transfers, commands, etc., to an I^2C-bus[16] backbone (physical layer). SMBus has much in common with Access.bus,[17] another protocol based on I^2C. SMBus is intended to be used as an **internal** bus connecting nonremovable components (except for the battery), while Access.bus is an **external** bus for making "plug and play" connections between external peripheral devices. Access.bus specifications can accommodate SMBus devices, however, making it possible for a single controller to be used with them both.

Figure 1 shows an example of how a smart-battery implementation might be used. Table 2 shows a subset of the 34 parameters in the data set defined by the specification.

Intelligent batteries provide the much-needed foundation for a rechargeable battery management system that not only optimizes battery performance, thereby reducing costs, but also supports greater reliability in battery use. A record exists not only of the state of charge (a frequently stated need in the past), but also of significant parameters that characterize the entire history of use of that battery. The need for such information became critical with recent widespread use of laptop computers and video cameras. Users of these devices needed to know whether enough capacity was left to accomplish their particular missions (e.g., to be able to record a 1-h event).

Adoption of the Smart Battery technology can do far more than provide the user with information about its state of charge and history of use. Systems powered by Smart Batteries can be designed to use power consumption information to better manage their own power use. Since each Smart Battery maintains its own information, it is possible to use a mixture of batteries having different chemistries or charge states in a device.

Smart battery technology also provides the capability to monitor and enforce a charge-control scheme that will prevent overcharging or too high a rate of charging, the most common forms of abuse of rechargeable batteries. The problem of polarity reversal that can occur with NiCd batteries is also eliminated.

Now is an appropriate time to consider making a major technology base shift to low-power microelectronics and Smart Battery power management, especially for communications, enhanced vision support devices, and portable computer support.

If it has not already done so, SOCOM should consider using intelligent battery technology for all missions and mission training. This technology addresses significant concerns expressed in recent past surveys. These concerns and how they are addressed are summarized in Table 3. Concern about the

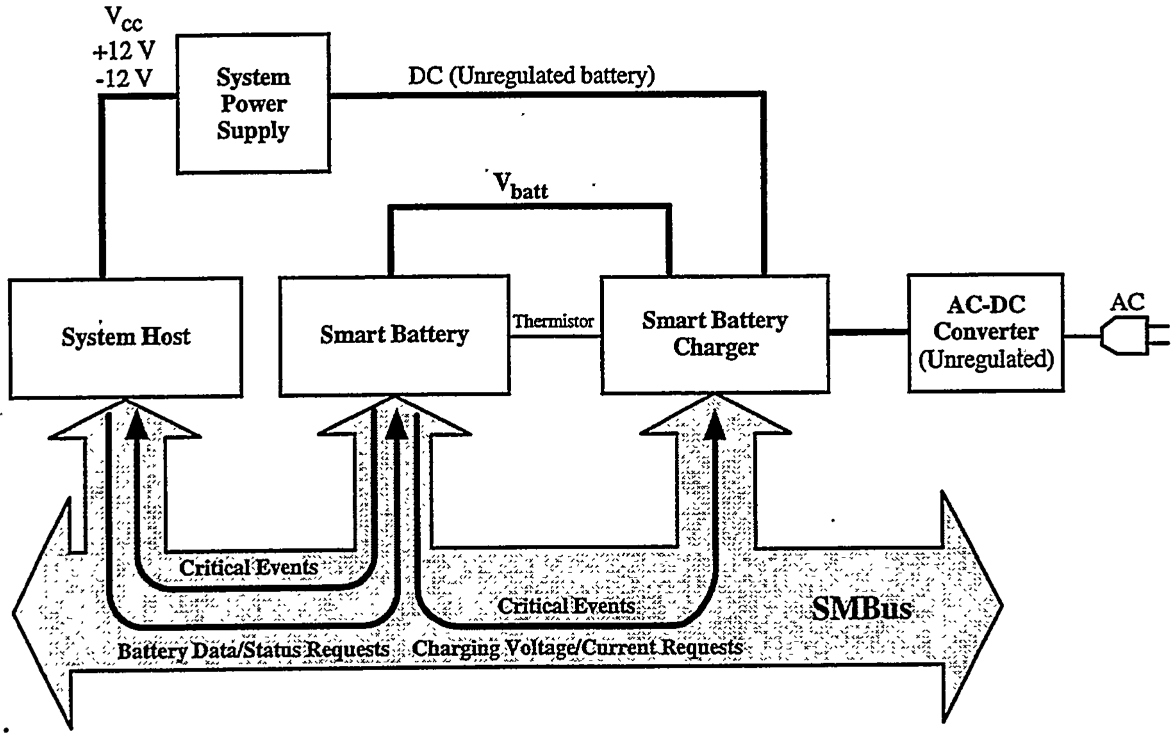

Figure 1—Example Use of SMBus

Table 2—Example SMBus Data Set Elements

Variable Name	*Comments*
temperature	
voltage	
current	
AtRateTimeToEmpty	The predicted remaining operating time if the battery is discharged at the AtRate
RunTimeToEmpty	The predicted remaining battery life at the present rate of discharge
AverageTimeToEmpty	A one-minute rolling average of the predicted remaining battery life
AverageTimeToFull	A one-minute rolling average of predicted time until the battery reaches full charge
RemainingCapacity	In units of either current or power
RelativeStateOfCharge	Predicted remaining capacity as percent of full-charge capacity
FullChargeCapacity	Predicted pack capacity when fully charged
CycleCount	Number of charge/discharge cycles of the battery

Table 3—End User Concerns Expressed About Batteries

Stated Concern	Solution Provided by Standard
Need to know state of charge	*State of charge is a data item that is always tracked.*
Want xx% power increase	*Batteries based on different chemistries can be mixed, allowing for increase in power in some cases.*
Reduce weight to capacity ratio	*Batteries based on different chemistries can be mixed, providing more flexibility in how batteries are used.*
Need capabilities for more rapid recharging	*Chargers designed to operate according to standard will charge at optimal rate for given battery chemistry.*

history of use and amount of capacity remaining for a particular battery was not stated. This concern was dealt with simply by disposing of any battery about which any such concern existed and starting a mission with new batteries that presumably could be trusted and carrying a few extras in case one of the new ones failed. Adoption and implementation of the Smart Battery Specification group of standards should not just reduce this practice leading to battery waste; it should eliminate it.

3.1.12 Thin Film

Recently, with the development of microelectronic devices, thin-film solid-state batteries are receiving more attention with the aim to fabricate a battery that can be completely integrated with microcircuits.[18] However, thin-film batteries have low capacities which makes their applicability to SOCOM's needs questionable. Bates et al.[19] have designed a $LiMn_2O_4$ battery that has a cell capacity, in the 4.5- to 3.8-V range, of 50 to 120 µA-h/mg (~480 W·h/kg). Some unique features of these batteries are: wide operating temperature range (-20°C to 100°C); thousands of charge-discharge cycles (long cycle life); and very long shelf life (no measurable change after years of storage).

Eveready Battery Company has developed a thin-film microbattery that has a capacity between 35 and 100 µA-h/cm^2 with an open circuit voltage of 2.5 V.[20] Eveready has fabricated batteries as large as 10 cm^2. Even with these breakthroughs, microbatteries are not intended for the large capacity loads required by the majority of SOCOM users.

However, as the military relies increasingly on integrated circuit technology, these types of batteries may be the most reliable and cost-effective means to power these devices.

3.2 FUEL CELLS

3.2.1 Principle of Operation

Fuel cells (Fig. 2) are electrochemical devices that convert chemical energy into electricity without combustion as an intermediate step. Fuel cells are similar to batteries in that they both produce low-voltage dc current using an electrochemical process; they also both contain an anode and a cathode separated by an electrolyte. Unlike batteries, however, fuel cells are externally fueled. Fuel cells function by converting energy in a hydrogen-rich fuel directly into electricity.

The general operating principles of all fuels cells are similar. Proton exchange membrane (PEM) cells are particularly well suited for portable applications, so their processes are selected for description. In the first step in fuel cell electricity production, fuel (H_2) is fed into the anode chamber and an oxidizer (air) into the cathode chamber. The hydrogen then adsorbs on the surface of the anode and disassociates with the aid of a platinum family catalyst. The hydrogen ions then diffuse across the PEM to the cathode. At the cathode, oxygen is adsorbed and disassociated, and the hydrogen and oxygen ions combine to form water. The electrons liberated by the hydrogen disassociation conduct across a graphitic cell interconnect to the cathode of the adjacent cell where they supply the electrons necessary to form water. The basic anode and cathode reactions are as follows:

anode $2H_2 \rightarrow 4H^+ + 4e^-$

cathode $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$.

Fuel cells have several advantageous features for producing moderate amounts of power (0.1–100 kW). First, they have the potential to be highly efficient. Since fuel cell electricity conversion does not involve the chemical to thermal to mechanical to electrical energy conversion cycle, they can avoid the Carnot efficiency limitation. Currently available cells have efficiencies of 55%, and future designs have predicted efficiencies of greater than 75%.[21] Also, compared to conventional heat engines, fuel cells have few moving parts and hence are likely to have high reliability and very quiet operation. Additionally, fuel cells have very low emissions—in the case of pure hydrogen feed, the only waste product is water.

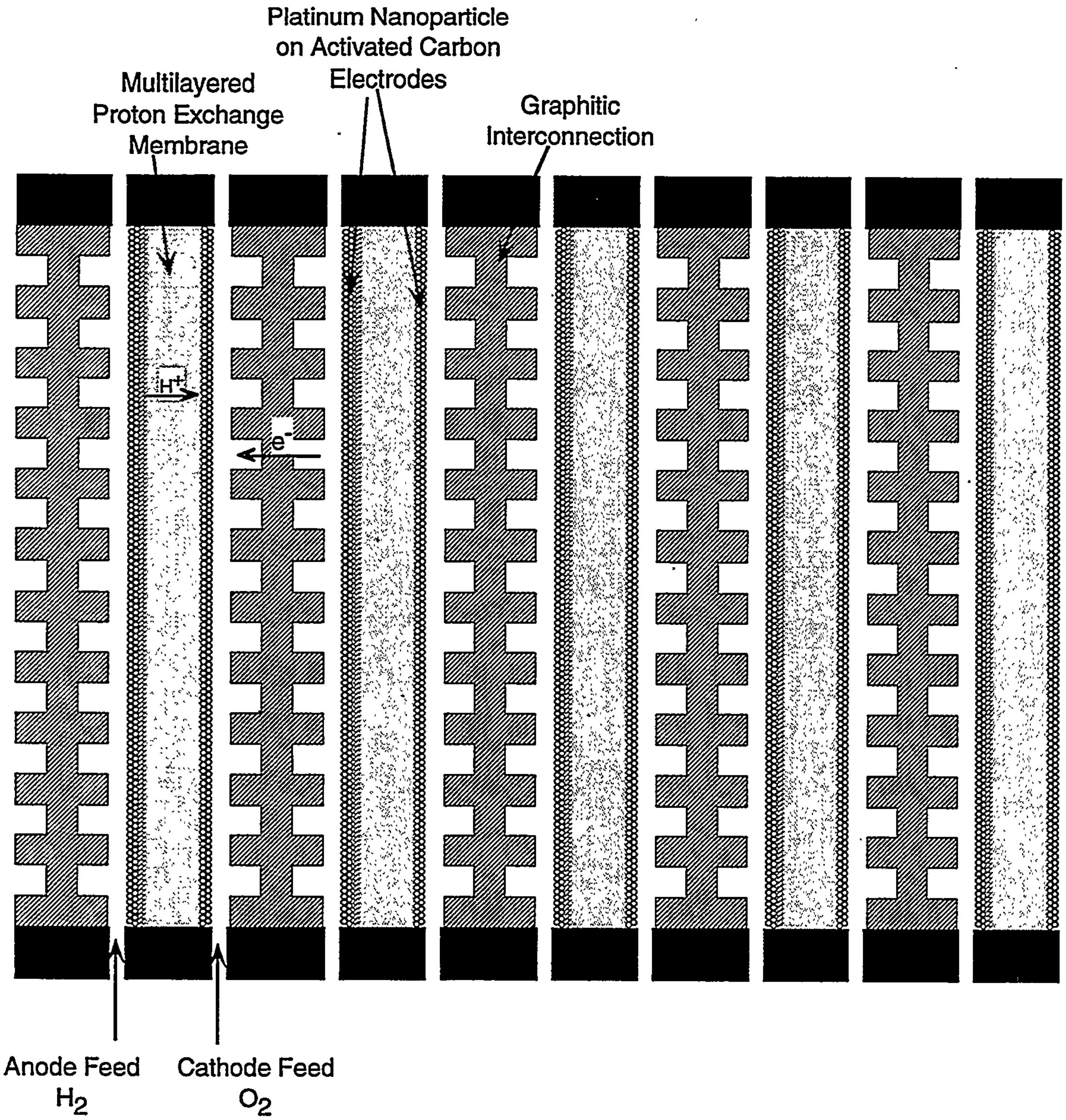

Figure 2—Fuel Cell Stack Cross Section

A major limitation of fuel cells is size and weight. Recently, major strides have been made in power density. Ballard Power Systems in October 1995 announced a PEM fuel cell capable of producing 1×10^6 W/m^3 and 700 W/kg.[22] Manufacturability also remains a fuel cell limitation. Each layer of a fuel cell requires a fuel and oxidizer supply as well as water removal. Reliably manifolding and sealing the cells around the manifolds has proven to be a continuing challenge. Establishing reliable, low-loss, electrical contact between all cell layers (electrical contacts over large areas) is also a difficult manufacturing problem. Maintaining a proper water balance and removing waste heat are also significant design concerns. Additionally, the higher temperature types of cells (molten carbonate and solid oxide) have challenging materials compatibility problems.

Hydrogen is the only practical fuel for current fuel cells. Hydrogen, however, is difficult to transport in sufficient density to be practical in a portable system. In fact, developing a hydrogen distribution infrastructure is likely to be the most challenging aspect of implementing fuel cells as a standard PEPS. Compressed gas has low density, and cryogenic storage suffers from continuous boiloff (and high energy requirements for the initial cooling). Hydrogen adsorption on carbon is promising but has not yet been developed sufficiently. Metal hydrides tend to be expensive and need high temperatures to liberate the stored hydrogen.[23] Ammonia is an easily produceable and transportable, high-density hydrogen storage medium. Its main limitation is that ammonia reacts with acidic electrolytes requiring an efficient chemical scrub after cracking (disassociation into N_2 and H_2). Methanol is another available high-density storage media for hydrogen. Methanol is easily and inexpensively derivable from most hydrocarbon materials (oil, biomass, coal, etc.). Methanol oxidization, however, is difficult to catalyze (oxidization activity of methanol is lower by two orders of magnitude than that of hydrogen).

3.2.2 Types of Cells

3.2.2.1 Alkaline

Alkaline fuel cells use an aqueous solution of potassium hydroxide as an electrolyte. They use pure hydrogen and oxygen (or CO_2 free air) as fuel and oxidizer since they are sensitive to carbonate formation. Alkaline fuel cells operate at room temperature and produce the highest voltage (at comparable current densities) of any fuel cell. Operation in excess of 15,000 h has been demonstrated.[24] Since hydrogen disassociates more readily under alkaline conditions, a wider selection of catalysts (notably nickel instead of platinum) is suitable for use in alkaline fuel cells. Some alkaline fuel cell systems also use a circulating electrolyte system that permits easy removal of water and waste heat. The electrolyte solution is corrosive so cell sealing and proper material choice are significant engineering concerns. The space shuttle currently uses an alkaline fuel system as the main on-board electrical power source.

3.2.2.2 Proton exchange membrane

PEM fuel cells use a polymer membrane assembly as their electrolyte. They operate at temperatures below 100°C. Pure hydrogen/air fuel/oxidizer systems are the typical portable system. PEM technology is also used in direct methanol fuel cells (Sect. 3.2.2.6). Energy Partners Inc. has recently demonstrated a 10 kW fuel cell stack. The stack weighs 65 kg and has a volume of 3.7×10^{-3} m^3.[25] The main advantages of PEM systems are: (1) no corrosive liquids, (2) relatively easy fabrication, (3) minimal material compatibility and corrosion problems, (4) long-life, and (5) the ability to operate under high driving pressures. Their main weaknesses are the cost of the polymer membrane, difficult water balance management, and low tolerance to CO (Ref. 24, p.73). Analytic Power Corporation is currently demonstrating (at Fort Benning, Georgia) much smaller units (150 W; 3.9 kg - without fuel) for individual soldier use.[26] Pure hydrogen/air PEM fuel cell systems will most likely just be approaching commercial viability for PEPS in 5 years.

3.2.2.3 Phosphoric acid

Phosphoric acid fuel cells (PAFCs) are in the process of being commercialized for on-site cogeneration type uses (50–1000 kW ac). PAFCs have been optimized for using fuels with a higher carbon content (up to 5%) such as reformed (natural gas, light distillates, or gassified coal). The ONSI Corporation commercially produces a PAFC system that converts 50 m^3 of natural gas per hour into 200 kW of ac power and 22 kW of thermal energy at 120°C.[27] PAFCs operate at ~200°C and use H_3PO_4 bound in polytetrafluoroethylene matrix as the electrolyte. It is unlikely that PAFC technology will be applied to portable systems in the next decade.

3.2.2.4 Molten carbonate

Molten carbonate fuel cells (MCFCs) use an electrolyte of lithium and potassium carbonates and operate at ~650°C. The high operating temperature is used both to achieve high conductivity in the electrolyte and to avoid the requirement for precious metal oxidation and reduction catalysts. MCFC technology is actively being developed by several companies worldwide.[28] However, MCFCs are targeted for large stationary generation stations. Overall, it is very unlikely that a portable style of MCFC will be developed within the next 5 years.

3.2.2.5 Solid oxide

Solid oxide fuel cells (SOFCs) use an electrolyte of yittria stabilized zirconia and operate at ~1000°C. They are currently being demonstrated in a 100-kW unit.[29] The high operating temperature permits easy use (by internal hydrogen reforming) of most hydrocarbon materials as fuel and allows the use of nonprecious metal electrodes. The development of suitable high-temperature materials is the primary challenge for commercializing the technology. Overall, it is highly unlikely that a portable style of SOFC will be developed within the next 5 years.

3.2.2.6 Direct methanol fuel cells

Direct methanol fuel cells (DMFCs) either use a sulfuric acid electrolyte or a PEM and operate at <200°C. The main advantage of PMFCs is their use of an easily transportable liquid fuel. The sulfuric acid is used to reject the carbon (as CO_2) released from the methanol oxidization. DMFCs exhibit significantly lower size, weight, and temperature than competing fuel cell systems. They also provide easier thermal management through the use of fuel as coolant. DMFCs, however, remain less developed than other fuel cells. They suffer from corrosion due to the acid electrolyte and slow reaction kinetics. An additional remaining problem is methanol migration across the membrane, creating a chemical short circuit. Jet Propulsion Laboratory (JPL) has recently developed a significantly improved DMFC. The JPL system uses a PEM electrolyte, and each layer in the cell stack produces 0.5 V at 300 mA/cm^2 (Ref. 24, p. 155). The Defense Advanced Research Projects Agency has initiated research projects with several leading research universities to develop PEM-DMFC systems.[30] This appears to be a promising technology for portable power production. However, it remains at a research stage, and it is unlikely that a commercial system will be available in the next 5 years.

3.2.2.7 Metal–air fuel cells

Several metal–air fuel cell systems are candidates for portable power systems. Both mechanically (fuel cell) and electrically (battery) rechargeable-type systems are available. Zinc, aluminum, and lithium are the most commonly used metals (calcium, magnesium, and iron have also received a limited amount of attention). The main advantages of metal–air batteries are high energy density, flat discharge voltage, long shelf life (dry storage), limited environmental problems [alkaline (KOH) electrolyte only toxic material]. Their major limitations are: drying-out (or flooding) limits shelf life once opened to air; limited power output (sharper voltage drop-off with increasing current than other systems); limited operating temperature range (5°C–35°C typical); H_2 from anode corrosion; and sensitivity to CO_2 (carbonation of alkali electrolyte).[31] Electrically rechargeable cells are required to have both electrodes for adsorbing/reducing oxygen during discharge and evolving oxygen during recharging. The design of an efficient air electrode has proven to be challenging. In some designs, separate oxygen evolution and reduction electrodes are used while others incorporate a bifunctional electrode.

Zinc–Air

Primary zinc–air batteries are commonly available in both button cells and larger industrial styles. Zinc is selected as an anode material since it is the most electropositive metal that is relatively stable in both aqueous and alkaline solutions without significant corrosion. Creating a reliable electrically rechargeable cell remains a significant design challenge. Replating the zinc during recharging often creates dendrites, which penetrate the electrolyte and cause a chemical short circuit. Also, electrical recharge requires several hours. Mechanically rechargeable systems avoid these limitations. Lawrence Livermore National Laboratory has developed an advantageous, prototype, mechanically rechargeable zinc–air battery.[32] In this design the fuel consists of pellets of zinc metal entrained in a liquid alkaline electrolyte (KOH). The zinc/electrolyte mixture is fed from hoppers into reaction cells, where it forms a loose pack structure allowing complete oxidation of the zinc and transport of the reaction products and waste heat with the electrolyte. This system is easily refuelable (few minutes), has a high power density (350 W/kg; 300 kW/m^3 and 140 W·h/kg; 250 $kW{\cdot}h/m^3$), and provides for simple environmentally benign fuel/electrolyte recycling (simple electrolysis unit). This technology is in a demonstration stage and could be ready for small-scale deployment within 2 years, with more widespread usage developing within 5 years.

Lithium–Air

Lithium–air batteries are attractive because lithium has the highest theoretical voltage and energy density of any metal system. However, lithium–air systems suffer from high corrosion rates and rapid self-discharge. Polarization within the air cathode also limits the achievable cell voltage. In view of the safety and materials limitations of lithium–air systems, it is unlikely that these cells will be commercially available within 5 years.

Aluminum–Air

Aluminum–air fuel cells are attractive because of their high energy density and voltage and the availability and low-cost of aluminum. Recent engineering developments have focused on low-corrosion aluminum alloys and on developing an electrolyte management system to remove the reaction products.[33] Specialized application versions (notably for marine use) of aluminum–air batteries have been commercially available for several years. Overall, however, aluminum–air fuel cells are less reliable than batteries because of the mechanical systems required to remove the reaction products, they are sensitive to attitude, and they exhibit a slow turn-on time (~30 min typically). Current versions of aluminum–air fuel cells may be attractive for underwater propulsion applications using seawater as the electrolyte. With a significant development effort, aluminum-air fuel cells may overcome their remaining engineering hurdles. However, lacking this, they are unlikely to be generally useful as a portable power source within the next several years.

3.2.3 Future Prospects

Fuel cell technology has been evolving for more than 30 years. The level of technological development has been significantly advanced in recent years both by improved materials as well as the concentrated efforts to develop environmentally benign, alternative sources of electrical power to imported hydrocarbons. Portable fuel cell technology development is being driven by electric vehicle requirements. As such, the continued advancement of fuel cells is driven by both the price and availability of oil as well as the environmental regulation of vehicular emissions. The U.S. military is also actively supporting fuel cell development efforts (~$9 million annually). The greatest difficulty in field deployment of fuel cells in scale will be in developing a new support infrastructure to distribute hydrogen.

Some fuel cell systems are emerging as viable portable electric power supplies. In particular, direct methanol, PEM fuel cells and ammonia-fueled alkaline fuel cells are likely to be available, reliable, relatively inexpensive power systems with tolerable mass and a low observability signature within 5 years. Zinc–air fuel cells will also continue to be of increasing utility in applications requiring small primary cells as well as larger mechanically rechargeable systems. Fuel cell systems have not yet become standard commercial PEPS, mostly because of material and weight problems and the need to develop a full-scale manufacturing and support infrastructure. Recent results in fuel cell demonstration are very promising, and 5 years is a reasonable time frame for the initiation of widespread usage.

3.3 ULTRACAPACITORS

Ultracapacitors are very high capacity charge storage devices capable of handling very high power densities (~10,000 W/kg) over short time intervals (less than 1 s), making them very attractive options for load leveling in electric or hybrid vehicles. Because of their very large electric charge storage capacities, they could be used as effectively as batteries for many low- power applications, especially microelectronics devices. They are rechargeable far many more times than rechargeable batteries (>600,000 cycles [34]) and can be recharged exceedingly rapidly compared to rechargeable batteries. Units developed for use in electric vehicles weigh on the order of 100 kg, so more development would be required to make this option more attractive as a portable power supply. Its value may lie in its use in combination with other power sources. Current research in ultracapacitors (for electric vehicles) is being conducted at the following institutions:

- Auburn University, Auburn, Alabama
- Federal Fabrics
- General Electric Corporate Research and Development, Schenectady, New York
- Lawrence Livermore National Laboratory, Livermore, California
- Los Alamos National Laboratory, Los Alamos, New Mexico
- Maxwell Laboratories, San Diego, California

- Pinnacle Research Institute, 141 Albright Way, Los Gatos, California
- Sandia National Laboratories, Albuquerque, New Mexico

3.4 THERMOPHOTOVOLTAICS

3.4.1 Conceptual Description

Thermophotovoltaics (TPVs) are being developed as a method of producing small electric power units for both commercial and military applications. The concept underlying TPVs was developed in 1960 at the Massachusetts Institute of Technology.[35] An energy source of almost any type is used to elevate a selective or blackbody emitter to incandescent temperatures (see Figure 3). The radiant energy is filtered to produce the desired spectrum and then captured by an array of photovoltaic (PV) cells that produce dc power. The emitter temperature ranges from 1000–3000 K (727–2727°C). Because of this high temperature, the PV cells must be cooled. With proper combination of PV cells and spectrally matched emitters, TPV systems may achieve power densities approaching 250 W/kg (this, of course, does not include the weight of fuel for the energy source—typical fuels have energy densities on the order of 10,000 W·h/kg). Theoretically, TPVs can operate with efficiencies of 15% or greater. Therefore, it should be possible to design a 2 kg package that can deliver 250 W for 5 h or an overall energy density of 700 W·h/kg (each 1 kg of fuel buys another 5 h).

3.4.2 Current TPV Development

Energy conversion can be very efficient in TPVs, where emitted radiation is near the bandgap energy of PV cells. Efficiency greater than 50% is theoretically possible with near bandgap radiation at high power densities with ideal PV cell designs.[36] In practice, efficiencies of 5% are more likely. Current research is directed toward bandgap engineering of materials suitably matched to the emission spectra of the radiation sources. Also, advanced emitters are being designed to produce radiation that can be used to generate electricity from existing PV cells.

One goal of R&D efforts on TPVs is to develop a compact and efficient configuration for the combined thermal source and emitter system. Quantum Group, Inc., is developing a laboratory model TPV generator under Defense Advanced Research Projects Agency funding.[37] The generator uses methane/oxygen combustion, ytterbia selective emitter, and spectrally matched silicon PV cells to produce 2.4 kW in a lab based system. Quantum is also developing a 100–500 W man-portable TPV generator with shock mounting, which increases the ruggedization for portability.[38]

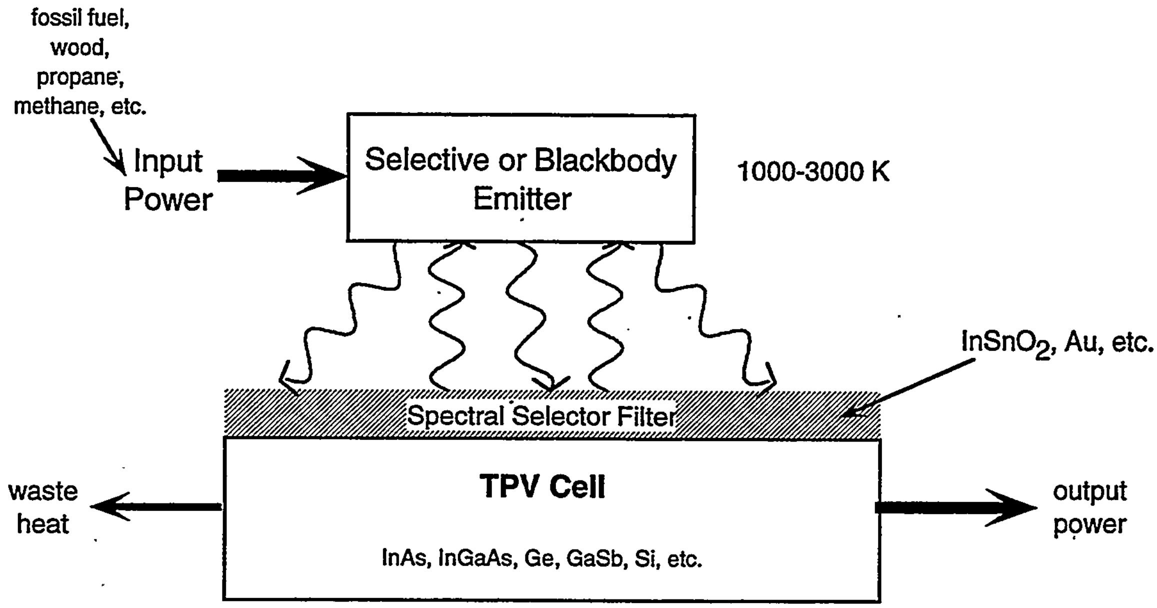

Figure 3—Thermophotovoltaic System Concept

Babcock & Wilcox and JX Crystals, Inc., have developed an innovative design for a compact, 500-W, 28-Vdc TPV power system using JP-8 fuel.[39]. This system is approximately 18 x 18 x 43 cm (7 x 7 x 17 in.), not including a fuel tank and controls. The system weighs as little as 7 kg without fuel. Average exhaust temperature is 332 K (137°F), resulting in a relatively low thermal signature. The acoustic signature is also very good in that the system is inaudible at 3 m (9.8 ft).

JX Crystals, Inc., and Western Washington University are developing a TPV using a blackbody infrared emitter heated with natural gas and integrated with a photovoltaic cell array to produce enough power to run a household appliance.[40]

Another effort by the Gas Research Institute has the goal to develop a 300-W TPV prototype for a self-powered gas furnace.[41]

3.4.3 Future Outlook

The interest in TPV for power generation is growing, as evidenced by the increasing number of conferences, workshops[42] and publications on TPV research. A variety of potential commercial markets exists including electric grid independent appliances such as gas furnaces that produce their own heater electric power; hybrid vehicles; underwater vehicle power; recreational vehicles; remote electricity supplies; and military applications. These potentially lucrative commercial markets are driving intense R&D to produce reliable and low-cost TPV power sources. However, Rose[43] concludes that while TPVs offer a promising method of producing small portable electric power units, the technology is not mature enough for major market penetration and is too costly. This situation could change over the next 5 years as a viable consumer market is developed.

3.5 THERMOELECTRIC GENERATORS

The thermoelectric generator is a reliable and silent energy converter with no moving parts that transforms heat into electrical power. One of the primary uses has been for spacecraft power systems that utilize radioisotopes as the heat source. Two problems that have continually prevented widespread commercial application of thermoelectric power during the last 30 years of research are low efficiency (<5%) of thermoelectric materials and the high cost of fabrication. Advanced thermoelectric materials might eventually enable thermoelectric generators to achieve conversion efficiencies greater than 12%.(Ref. 43, pp. 213–220), thus making them more competitive with alternative energy conversion technologies.

The cost of manufacturing thermoelectric generators is also expected to be reduced as a result of a project underway at the School of Engineering Systems Design at South Bank University in London[44] in which a new fabrication process for thermoelectric generators, which is both simple and continuous, is being developed.

Teledyne Brown Engineering is marketing nonportable thermoelectric generators in the 10–90 W range to provide electrical power in remote or inaccessible areas.[45] These generators are weather-resistant and run on a variety of fuels, including propane, butane, and natural gas.

The Army has attempted to produce thermoelectric generators for field use, but their efficiency is less than 5%. A design study funded by the U.S. Marine Corps[46] has proposed a 500-W system using segmented lead telluride modules. This system would weigh approximately 20 kg and have an efficiency of near 9%. However, the potentially high thermal signature and low power density (25 W/kg) may preclude field use except in special situations such as where a naturally occurring heat source is available or if a silent source other than battery power is desired.

3.6 MECHANICAL

3.6.1 Engine Driven Generators

A 1992 workshop[47] on the use of small engines to supply soldier portable power needs concluded "there is enormous potential for improving small engine performance through the innovative use of new materials and technologies." It was further concluded that progress in engine driven portable power is limited by the availability of development funding. Some of the major issues identified with the application of engine-driven generators are size and weight; acoustic signature; thermal signature; fuel management; emissions; and the ability of the system to operate in the wet, dirty, cold, or hot environments encountered in the field. The following sections describe three technologies where continued research seems to hold the promise of alternative engine-driven sources of portable power. These are miniature hybrid-diesel-powered generators, Stirling engines, and microturbines.

3.6.1.1 Miniature hybrid diesel generators

The Oak Ridge National Laboratory (ORNL), the Oak Ridge Centers for Manufacturing Technology, and Davis Diesel Development, Inc., have proposed to develop a modified 2-stroke internal combustion diesel engine coupled with a high efficiency (95%) axial air gap permanent magnet generator and smart controller.[48] The system weighing approximately 5 kg will deliver 500-W, resulting in a power density of 100 W/kg. Toxic gases such as carbon monoxide and oxides of nitrogen will be very low with use of the hybrid diesel engine. A large silencer will be used to control acoustic noise. Active noise suppression will also be designed into the system using vibration and acoustic wave canceling devices. If development of miniature diesel generators is initiated in 1997, a system could be available for field testing in 4–5 years.

3.6.1.2 Stirling engines

A great deal of effort has gone into the development of Stirling engines. However to date, they have not received the widespread application one might expect based on the simplicity of the concept. This is due in part to the high cost of developing one-of-a-kind devices, coupled with the fact that the Stirling engine has not found a large number of applications where its unique features are sufficiently advantageous to supplant the more conventional power sources. Use in military portable power systems may provide an application where certain desirable features of the Stirling engine would justify its use. Military application would probably create sufficient demand to reduce the unit cost to an acceptable value.

The major components of a Stirling engine are the displacer piston, the power piston, the regenerator, the heat and cooling sources, and the interconnection piping (see Fig. 4) A thorough treatment of the theory and practice of Stirling engines can be found in the book *Principles and Applications of Stirling Engines* by C. D. West.[49] In a Stirling engine, a fixed amount of gas is contained in a piston system. One end of the piston (referred to as the displacer piston) is heated and the other is cooled. As the piston moves, gas is transferred between the hot and cold ends (via external tubing). When more of the gas is in the hot end, the system pressure rises. The pressure rise is used to drive a separate piston (referred to as the power piston) whose shaft is connected to a linear alternator (producing power). The power piston shaft is driven back in when the system is at low pressure (gas at the cold end of the displacer piston). Net work is obtained by the pressure difference between driving the power piston and reinserting it. Stirling engines typically cycle at ~3000 rpm and have stroke lengths of a few millimeters.

A major advantage of Stirling engines is that virtually any source of heat can be used. The heated portion of a Stirling engine is sealed, making the internal workings virtually immune to contamination. Additionally, pressure variations within Stirling engines are continuous (as compared with the explosively varying pressures of conventional internal combustion engines), resulting in quiet operation. The largest remaining hurdle for practical Stirling engine development is the development of a high-efficiency seal around the power piston.

A vast number of styles of Stirling engines have been built and tested. Most of them have been built in response to a specific need or function. West's book describes an innovative concept of Stirling engine invented by E. H. Cooke-Yarborough of Harwell Laboratory. It appears to be a good candidate design for easy portability. The general layout of this device is shown in Fig. 4. In this engine, the displacer piston is about 260 mm in diameter. It has a shaft power output of 150 W. The push rods shown are connected to a linear alternator in Fig. 4 and have a motion of only 2 mm. Even with this small displacement, the linear alternator operates at 95% efficiency. This unit was manufactured commercially by HoMach Systems Ltd., and English company. Later models have been manufactured by U.S. companies using bellows instead of the articulated diaphragm shown in Fig. 4.

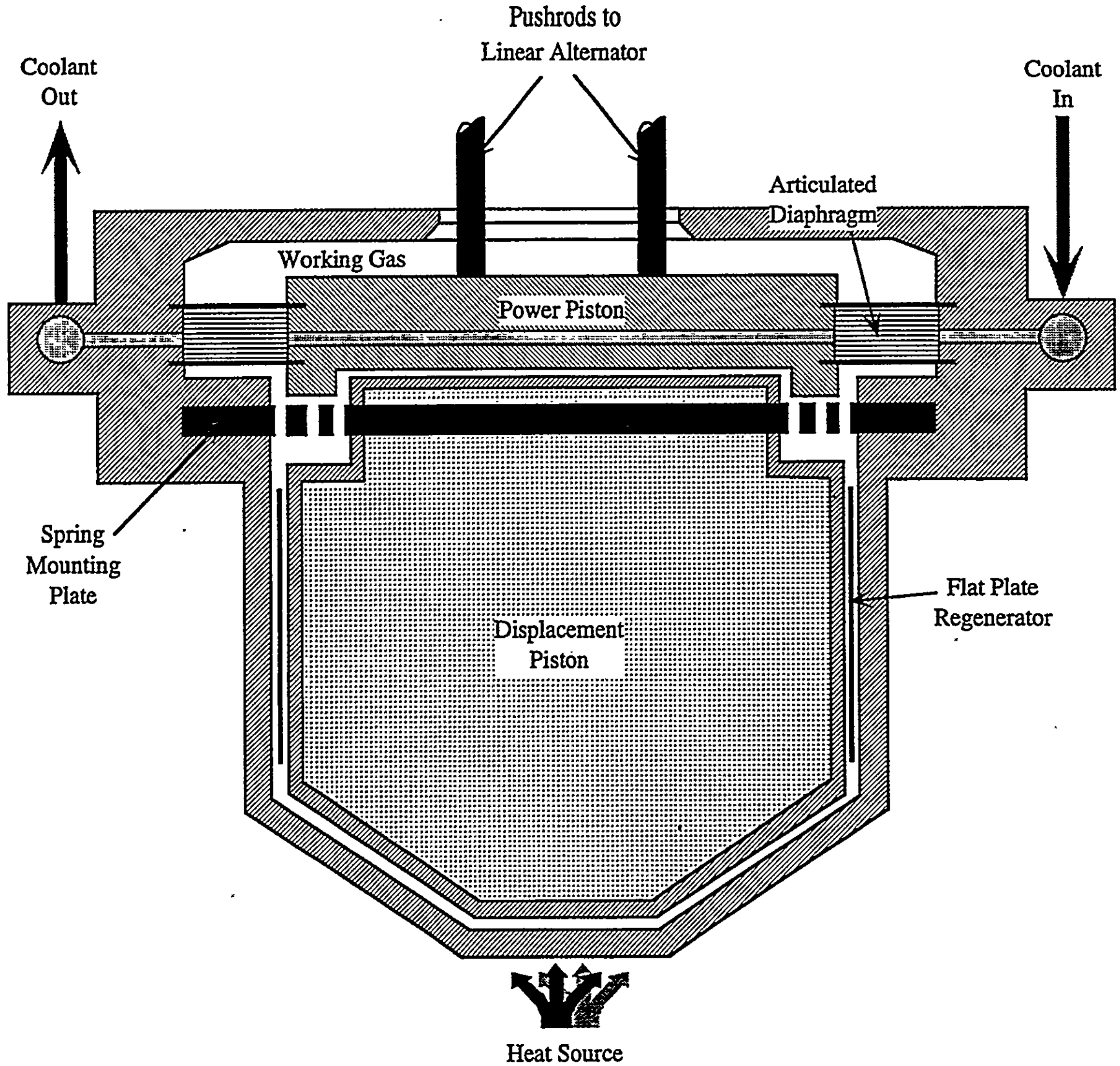

Figure 4—Stirling Engine

Subsequent developments by U.S. companies have produced small engine/generators in the 100- to 500-W range.[50] Most of them employ some form of linear alternator. Although the mass of Stirling engines is in the range of 6 to 7 kg/kW of mechanical power equivalent, the mass rises significantly to 15 to 20 kg/kW(e) with the addition of the linear alternator and controls. The generator is two-thirds of the total weight of the unit. Some improvements have been made by utilizing a three-cylinder Rinia engine configuration using three linear alternators. This configuration gives a specific capacity of 13 kg/kW(e). Significant improvements may be possible by using the ORNL-developed permanent magnet axial-gap generator. In addition to generating the desired 28 Vdc, it does so at 95% efficiency.[51] A 500-W version of the generator weighs 0.9 kg, or 1.8 kg/kW(e) [Larger generators, 50 kW(e), have specific capacities of 0.17 kg/kW(e).] In all but the most exacting cases, a simple passive voltage regulator will probably suffice. The magnets are made of samarium-cobalt (SaCo), which will stand the higher ambient operating temperatures of Stirling engines.

3.6.1.3 Microgas turbine generators

Microfabrication of refractory ceramics is enabling the development of microgas turbines and generators (millimeter to centimeter diameter). Power densities are expected to approach those of full-size engines (10^5 kW/m^3). Microturbine high performance requires a high turbine inlet temperature (~1600 K), high speed (3 x 10^6 rpm) and low leakage/high tolerances (~1 μm). Development goals are to produce a 50-W generator with an energy output of 175 W·h and weighing only 50 g (energy density of 3500 W·h/kg). The Army Research Office is supporting development of microturbines with funding in 1995 of approximately $1.174M. Cost of micro-turbine generators could be low, given sufficient demand of approximately 10^8 units/year.[52] With continued development funding, these systems may be available for field deployment in 3–5 years.

3.6.2 Piezoelectric Power Generators

There is an enormous amount of literature on piezoelectric devices. Very little of it deals with useful power generation. Most of the applications mentioned are for sensors and signal generators.

However, a few attempts have been made to produce useful power output from piezoelectric transducers. The Defense Nuclear Agency is funding a project to explore the use of piezoelectric transducers[53] to produce energy from low-level waste heat at acceptably high efficiency and reasonable cost. The system will consist of a natural heat engine developed at Los Alamos Laboratory working with a high-efficiency transducer developed by Ballistic Missile Defense Organization. The system will develop between 5 and 10 kW(e). It is not obvious how this device, still under development, would be applicable to portable power use. The likely size of a system required to recover energy from low-level heat would most likely militate against portability.

Piezoelectric transducers have also been used as power sources for motors and stepping motors.[54] These applications are highly specialized and would require considerable R&D to adapt them to produce power suitable for military end-use applications.

An attempt was made to utilize the pressure developed on the bottom of a soldier's boot during walking to actuate a piezoelectric transducer to charge a battery. This method of power production was considered by Comprehensive Technologies International, Inc., in 1993.[55] Their conclusions were that the power generated was too low and the cost too high for the system to be used in a practical application.

Based on the available literature on piezoelectric devices, it is unlikely that a usable product could be made available in the time frame in which we are working.

3.6.3 Hand-Crank Generators

The development of axial-gap and radial-gap permanent magnet motors has made possible the construction of highly efficient motors of low weight per unit of output energy. When used as a generator, they are highly reliable. Efficiencies in excess of 95%[56] are obtainable in current designs. Efficiencies approaching 100% are predicted as anticipated permanent magnet flux increases are achieved. An axial-gap generator was designed recently at ORNL[57] to produce 0.5-kW. It weighed approximately 1 kg and was housed in a cylinder having a diameter of 9 cm and a length of 5.7 cm. Thus, its energy density is ~450 W·h/kg.

A generator producing somewhat less output and suitable for military field use could be built. Mechanical power input could be supplied by troops with hand cranks or other means. The energy produced would be available for immediate use or could be stored in batteries or other energy storage devices. A 100-W scaled-down version of the 0.5-kW generator mentioned above could probably be built and housed in a package the size of a fishing reel. The flat geometry of the generator permits consideration of a variety of packaging shapes.

Gauzzoni[58] built a prototype hand-crank generator 20 years ago which he passed on to engineers at Harry Diamond Laboratories. New magnets and a harmonic drive were incorporated into a design capable of delivering as much as 200 W of power. A hybrid Special Operations Power Source (OP-177) currently available for use in the field combines hand-crank, solar, and ac/dc converter capabilities [59].

The advantages of a hand-crank power source for field use are, especially for emergency backup power, that it is low weight per unit power output (easy portability), could be made very rugged and reliable and impervious to severe environmental conditions, and could have unlimited life expectancy. The operating noise level would be very low. A high-efficiency hand-crank generator could be developed and tested in 2–3 years if sufficient R&D funds were available.

3.6.4 Water-Driven Generators

In considering sources of power to drive portable generators, one might include water power. Although not universally available, sources of water power may be found in certain theaters of operation. For example, in mountainous terrain in certain parts of the world, numerous streams may be present. Cascades and water falls in these streams can be a source of considerable power. For example, as little as 100 gal/min falling 10 ft through a pipe or 5 gal/min falling 200 ft through a pipe can provide 80 W of continuous battery-charging power.[60] Small paddle wheel generators and turbines could be used to drive high-efficiency dc generators to recharge batteries. When such sources are near an encampment, they could be utilized as continuous sources of low power.

Where more permanent encampments are established, more sophisticated systems can be utilized to produce larger amounts of power. For example, pelton wheel generators[61] have a high power-to-weight ratio and could be used where sufficient hydraulic head is available, usually a few hundred feet. The installation would be very simple requiring only a few lengths of plastic pipe in addition to the pelton wheel/generator. The pelton wheel is a simple device consisting of a disc with buckets attached to the outside rim. Water passes through a nozzle and strikes the buckets one at a time causing the disc to spin. Efficiency of converting water energy to mechanical energy is in the range of 80 to 85%. Several firms in the United States manufacture pelton wheels as well as complete "micro power systems." Some of these systems[62] perate with heads as low as 20 ft (with reduced efficiency), but may have heads as high as 600 ft. A range of power outputs from 150 W to 10 kW is available. A complete 150-W system costs approximately $800.

3.6.5 Flywheel Energy Storage

3.6.5.1 Conceptual description

Flywheels are mechanical devices that store energy kinetically in the angular momentum of a rotating body. Most commonly, flywheels take the form of rotating rings or cylinders attached to a central hub. The primary components of modern flywheel systems are the rotor, the bearings (and bearing control system), the stator, the power and control electronics, and the containment system (mechanical containment and vacuum) (see Figure 5).

Two federal organizations are the primary funding agencies for current flywheel research efforts—DARPA and the U.S. Department of Energy (DOE) through its hybrid electric vehicle (HEV) program. The National Institute of Standards and Technology (NIST) through its Advanced Technology Program and the National Aeronautics and Space Administration (NASA) through Small Business Innovation Research (SBIR) programs are also sponsoring flywheel research. In addition, the major domestic automobile manufacturers are also investing in flywheel research. Both large, stationary systems (for utility load leveling and for providing uninteruptable power supply) and smaller, portable systems (mainly for automotive use) are being developed.

The controlling relationship for energy storage in flywheels is $E = \frac{1}{2} I\omega^2$, where E is energy stored, I is the rotor moment of inertia, and ω is the angular velocity. Since energy stored is proportional to the square of the angular velocity, flywheels are spun as rapidly as possible. The centrifugal forces (and subsequent tensile stresses) on the rim limit the achievable rotational speed. Since stored energy is proportional to the square of the angular velocity and only directly proportional to the rotor mass, rotors have the highest possible tensile-strength-to-weight ratios.

3.6.5.2 Flywheel features and limitations

Flywheel energy storage systems have the potential to store relatively large amounts of energy in portable units (10 kW·h in 50 kg). A recent prediction indicates that flywheels have a near-term potential to deliver 2 kW/kg and a long-term potential of 8 kW/kg.[63] This contrasts with the much lower installed efficiency of prototype systems such as an urban bus with a specific energy of 5 W·h/kg and a specific power of 375 W/kg.[64] Recently published data show that superconducting bearings are available (on a research basis) with energy losses of <0.1%/h.[65] Also, a ceramic contact bearing 2-kW·h, 25-kW system has demonstrated bearing losses totaling 120 W for both the rotor and motor bearings.[66] Conversion losses are relatively low for flywheel with rates of power returns typically between 90 and 95%.

A major advantage of flywheel technology is its insensitivity to usage. Current flywheel systems are designed for 10-year maintenance free lifetimes (with minor maintenance at 20 years). This is not effected by the flywheel usage (even with repeated deep discharges). Also, the angular speed of a flywheel represents its state of charge unambiguously. Flywheel full charging times currently are 5–10 min.

The major limitation of flywheel technology is its relatively low level of development. Flywheels remain custom and therefore high cost items. The technology required for high-efficiency, high-power flywheels is just becoming available. Dow-United Technologies Composite Products, Inc., completed development of a polar weaving process in early 1996 which places reinforcing fibers both radially and circumferentially in rotors, thereby both increasing rotor strength and allowing the use of lower cost materials.[67,68] Bearing technology is undergoing rapid evolution as the materials become

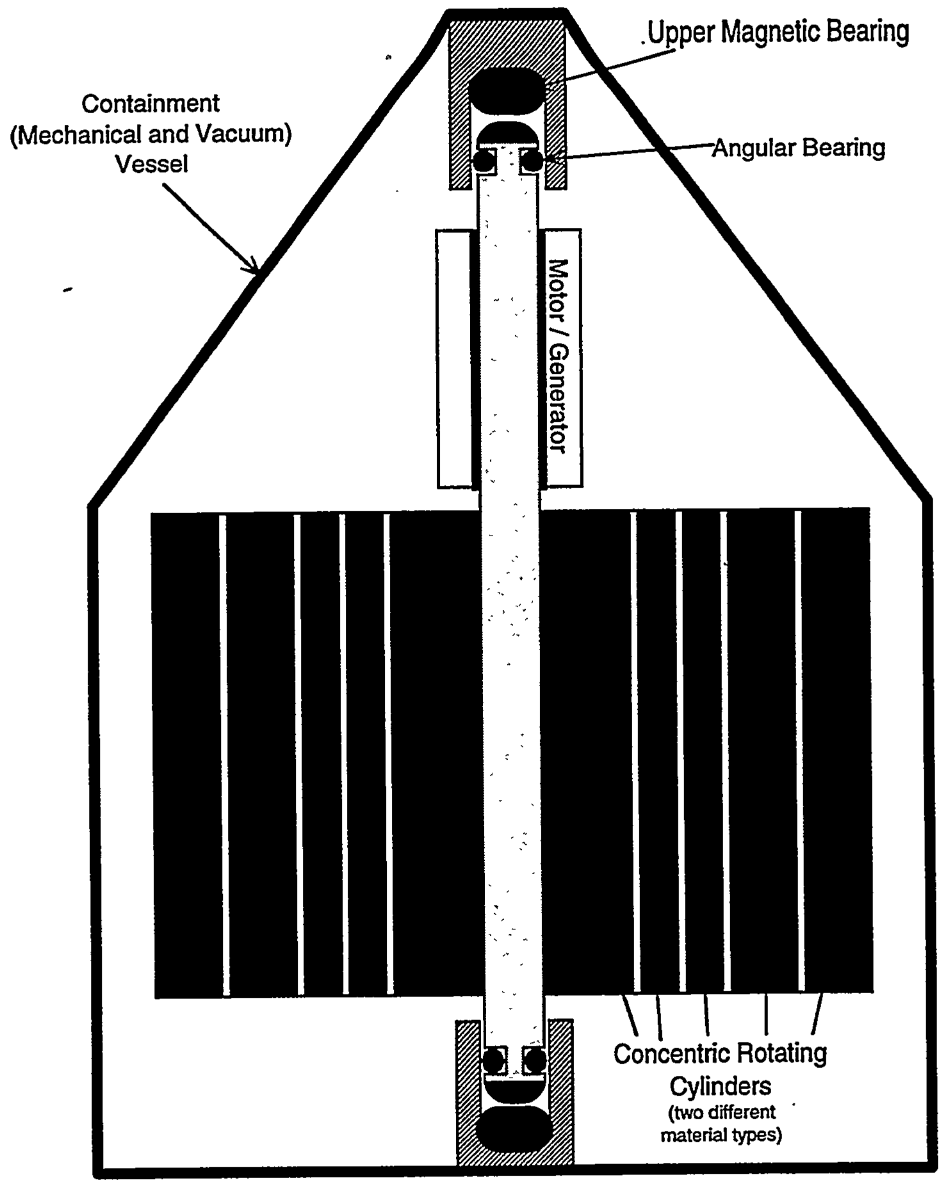

Figure 5—Typical Flywheel System

available to permit higher speed rotors. Permanent magnet bearings (often with electromagnetic assist), ceramic contact bearings, and superconducting magnetic bearings are all under active development. Electromagnetics with relatively advanced control systems are required to overcome the nonlinearities of permanent magnet bearings.

A major safety concern with portable flywheels is their performance under accident conditions. The primary function of the rotor is to store kinetic energy—its uncontrolled release is hazardous. A containment vessel that is capable of containing the rotor fragments under all credible accident scenarios is therefore required. The weight of the containment vessel is a limiting factor in portable devices. One strategy often used to contain high energy rotor fragments is to use a separate internal burst-containment cylinder that is free to rotate under angular impulse of fragments. This serves to distribute the burst load over the entire container wall, reducing the likelihood of high speed fragment ejection.[69] Another concern with portable flywheel systems is their gyroscopic nature. Without a gimbal-type mounting or a counterrotating element rotating flywheels are difficult to transport.

3.6.5.3 Five year prediction

Flywheel energy storage technology already has had some military usage. In July 1996 SatCon Technology Corp. received a $1.1 million contract from the U.S. Marine Corps to build a flywheel-based, uninterrupted-power-supply system for remote power generation stations.[70] Chrysler has been developing the "Patriot" race car that uses a flywheel (for regenerative braking and burst power) along with a constant-speed combustion engine.[71] In short, flywheel technology is currently available for specific custom missions.

What remains in doubt for flywheel technology is its mass scale application. Although several organizations are proceeding toward commercialization, it appears unlikely that flywheels will be available as a mass market portable electric power storage device within the next 5 years. Over the longer term, flywheels remain among the most promising technologies for storing energy. More than likely, within 10 years, flywheels will be commercially available, in portable systems, at consumer price levels, for storing up to 10 kW·h for a period of weeks.

3.6.6 Wind Turbines

3.6.6.1 History of Small Wind Turbines

Over 8 million windmills have been installed in the United States since the 1860s. These systems were generally used to supply from 200 to 3000 W to farms throughout the Midwest. However, most of these systems were eliminated when inexpensive grid power was extended to rural areas in the 1930s. The energy crisis of the 1970s and early 1980s provided an incentive for homeowners and farmers to install wind turbines to reduce electricity costs. Tax credits and favorable federal regulations provided additional incentives to install wind turbines. When tax incentives were eliminated in 1985 and oil prices dropped, the small wind turbine industry once again disappeared. However, the wind energy industry has grown steadily over the last 10 years, and there are now a number of companies [72] that produce and market small wind turbines.

3.6.6.2 Small wind turbines

Small wind turbines range in size from 250 W to 100 kW. These systems have rotor diameters as small as 1.14 m (45 in.). Most wind turbines are horizontal-axis propeller-type systems with a rotor (two or three blades), low -speed direct drive generator, mainframe, and a tail to align the rotor into the wind. The tail also provides overspeed protection. A wind turbine must have a clear shot at the wind to perform efficiently.[73] Air turbulence, which is highest close to the ground, reduces wind turbine performance. Therefore, turbines are normally placed on a tower at least 30 ft above any obstacles within 300 ft to provide more and smoother air flow. Towers can be hinged at their base to allow easy erection. Most turbines require an average wind speed of at least 8 mph to generate electricity. The power produced increases as the cube of wind speed. For example, the Bergey Windpower Company's Model BWC 850 system is rated at 850 W at a wind speed of 28 mph.[74] The BWC 850, weighing approximately 86 lb, cuts in at 8 mph and generates 100 W at 12 mph. Southwest Windpower Company's AIR Wind Model has a rotor diameter of 1.14 m (45 in.), capacity of 300 W, cuts in at 8 mph, and generates 100 W at 21 mph. It weighs only 13 lb. These microturbines use special power electronics packages to track the peak of the power curve for maximum efficiency.

3.6.6.3 Current small wind turbine market

There are several applications for small wind turbines that sustain a viable market for wind turbine manufacturers. Small turbines are used to supply power for military facilities; remote village electrification; irrigation, remote residences and vacation cottages, and navigational aids. Wind turbines get less expensive with increasing size. For example, a 50-W turbine costs about $8.00/W whereas a 300-W system is down to $2.50/W.

The National Renewable Energy Laboratory (NREL) has a project to extend the current market for small wind turbines in sizes from 5 to 40 kW.[75] The overall goal of this project is to help U.S. industry develop cost-effective, high-reliability small wind turbines for both domestic and international wind energy markets.

3.6.6.4 Portable wind power

It is conceivable that a small wind generator could be transported and assembled to provide power for charging batteries in a base camp location. Such application would only be practical in open territory such as desert, plains, or seashore. A specially adapted system utilizing a small, highly efficient generator, miniaturized light-weight electronics package, and telescoping tower (if required) could provide a significant power source for battery recharging. However, it is unlikely that military forces will be willing or able to utilize wind power except in special circumstances.

3.7 SOLAR

The sun can be used as both a direct and an indirect source of power. Solar power can be converted directly to electricity using photovoltaic technology. The sun can be used indirectly by plants to store energy by means of photosynthesis and as a heat source for a number of different working fluids to operate a mechanical engine using a particular thermodynamic cycle (e.g., Stirling engines). Recent research suggests that photosynthesis may be used to generate enough electric power to be sufficient to operate some microelectronic devices (see section below on biosources).. Use of the sun as a heat source for generating power for portable applications is not as effective (and will not likely be for the foreseeable future) as direct conversion methods. Consequently, the discussion of solar power sources in this report will be limited to photovoltaic technology and the potential application of biosources (photosynthesis).

Photovoltaic technology has been commercially available for nearly 30 years, but solar cells have not been packaged in a form for convenient use in a wide range of military field operations. Most of the R&D effort during this period has focused on improving the efficiency of photon conversion and decreasing the costs of manufacturing the photocells.

Solar cells obviously depend on having sunlight available in order to generate power. Commercial solar panels are now available which can supply power in remote areas for individual appliances such as water pumps, television and radio transmitters and receivers, desktop computers, telephone systems, individual street lights, and fluorescent lights in homes and small industries.

Photovoltaic cells and modules are generally quite rugged and reliable with lifetimes typically of 30 years. Balance of system components (inverters, support structures, junction boxes, control systems) represent half the cost of photovoltaic systems but account for as much as 99% of system failure and repair problems [76].

While the basic picture for photovoltaic technology has not changed much for the past two decades, there has been steady progress in the two areas that continue to receive greatest attention: photon conversion efficiency and manufacturing costs. Conversion efficiencies have generally improved by a factor of 2 or more. Cheaper methods for manufacturing solar cells have been developed which at the same time have brought increased reliability over the useful lifetimes of the cells.

DOE has been working with photovoltaic cell manufacturers and with the electric utilities for more than a decade to develop cost-effective photovoltaic power sources. Typical goals are to achieve an efficiency of 15% at a cost of $50/m^2.

3.7.1 Research and Development Activities

Goals of DOE and participating industries for the next couple of years and for the next 5 years are the same: to increase photon conversion efficiencies and to lower manufacturing costs. More efficient photon conversion can be achieved by use of multijunction cells and better design of thin-film layers to trap light. Lower manufacturing costs will be achieved by greater use of automation, reducing the number of steps in the production process, and moving from batch to continuous processing.

The status of photovoltaic technology as of early 1996 is summarized briefly next and in Table 4.

Table 4—Solar Cell Technology Overview

Solar Cell Technology	Commercial Availability	Flexible	Efficiency (maximum measured)	Efficiency (commercial units)	Energy Density (W/m^2)	Weight Range (lb)	Cost (dollars/W)
Amorphous Silicon	yes	yes	10.2	?	50-70	1-5	?
Thin-film Crystalline Silicon	?	yes	?	?	?	?	?
Polycrystalline Silicon	yes	no	18	14	130-140	3-30	?
Single Crystal Silicon	yes	no	24	?	220	15-30	7
Gallium Arsenide	?	thin-film	28	?	190	?	?
Cadmium Telluride	?	thin-film	16	6	180	?	?
Copper Indium Diselinide	?	thin-film	17.1	10	130	?	?

3.7.1.1 Amorphous silicon

The first thin-film amorphous silicon devices made more than 20 years ago had efficiencies less than 1%. By 1994, stabilized efficiencies greater than 10% had been achieved. Efficiencies as high as 13% are expected from use of cells with multijunction layers.

3.7.1.2 Polycrystalline silicon

Efficiencies of multicrystalline devices have reached nearly 18% for laboratory cells, over 15% for prototype modules, and 14% for commercial modules.

3.7.1.3 Single-Crystal silicon

Devices made of single-crystalline silicon in the laboratory have achieved measured efficiencies as high as 24%.

3.7.1.4 Cadmium telluride

Small laboratory devices have been fabricated that have efficiencies of nearly 16%, while efficiencies of commercial devices are around 6%. Interest in CdTe is due chiefly to the potential for very low-cost production of cells.

3.7.1.5 Copper Indium diselenide

Device's based on copper indium diselenide were measured in 1995 to have 17.1% efficiency. This thin-film material shows no degradation in performance after many years of outdoor exposure. However, no commercial products based on this material have yet been produced.

3.7.1.6 Gallium arsenide

Measured single-junction efficiencies now exceed 25% at 1-sun and nearly 28% under concentrated sunlight. Multijunction cell efficiencies are greater than 30% and should exceed 32% in concentrator systems.

3.7.2 Commercial Availability

Solar cell systems are commercially available in units that are portable, though not specifically designed for portability, with weights as low as 15–30 lb., with rated power range of 50–100 W (current: 3–5 A, voltage: 17–20 volts) for less than $500. Lighter-weight modules are available that deliver correspondingly less power (lower currents). Solar cell panel areas range from roughly 1 ft^2. to 3 ft by 4 ft and 1–2 in. thick. The most common material still is single- crystalline or poly-crystalline silicon.

Commercial solar cell systems appear to be well suited as sources for recharging batteries but have the drawback of being easy to detect (light reflected from flat panels and heat from infrared signature). Solar cell systems integrated with the Smart Battery technology appear to present a very attractive option (environmentally benign, no fuel requirements to operate, noiseless).

Solar cells (polycrystalline) were used to recharge batteries during Desert Storm. Two thousand book-sized kits were ordered, each capable of providing 15 W of power.[77].

Increases in efficiency achieved for solar cells, with near-term possibilities of significant further improvements using multilayer and multijunction designs, combined with reduced power requirements of newer microelectronic devices should make for an attractive match of technologies. With increased attention to microelectromechanical systems (MEMS) technology and development of MEMS applications, the desirability of using solar cells for power as an integral part of future systems is expected to grow. It is appropriate to consider now the consequences of this technology convergence in procurement planning.

3.8 ALKALI METAL THERMAL TO ELECTRIC CONVERTER

The alkali metal thermal to electric converter (AMTEC) is often referred to as the sodium heat engine. AMTECs convert heat directly into electricity using a flowing stream of liquid sodium and a solid electrode which is sodium ion permeable (see Figure 6). A heat supply and sink maintain a temperature difference of ~500°C across the two sections of the converter, thus creating a pressure gradient across the porous electrode. This causes sodium ions to flow through the electrode, thus creating an electric potential that can be used to perform work.

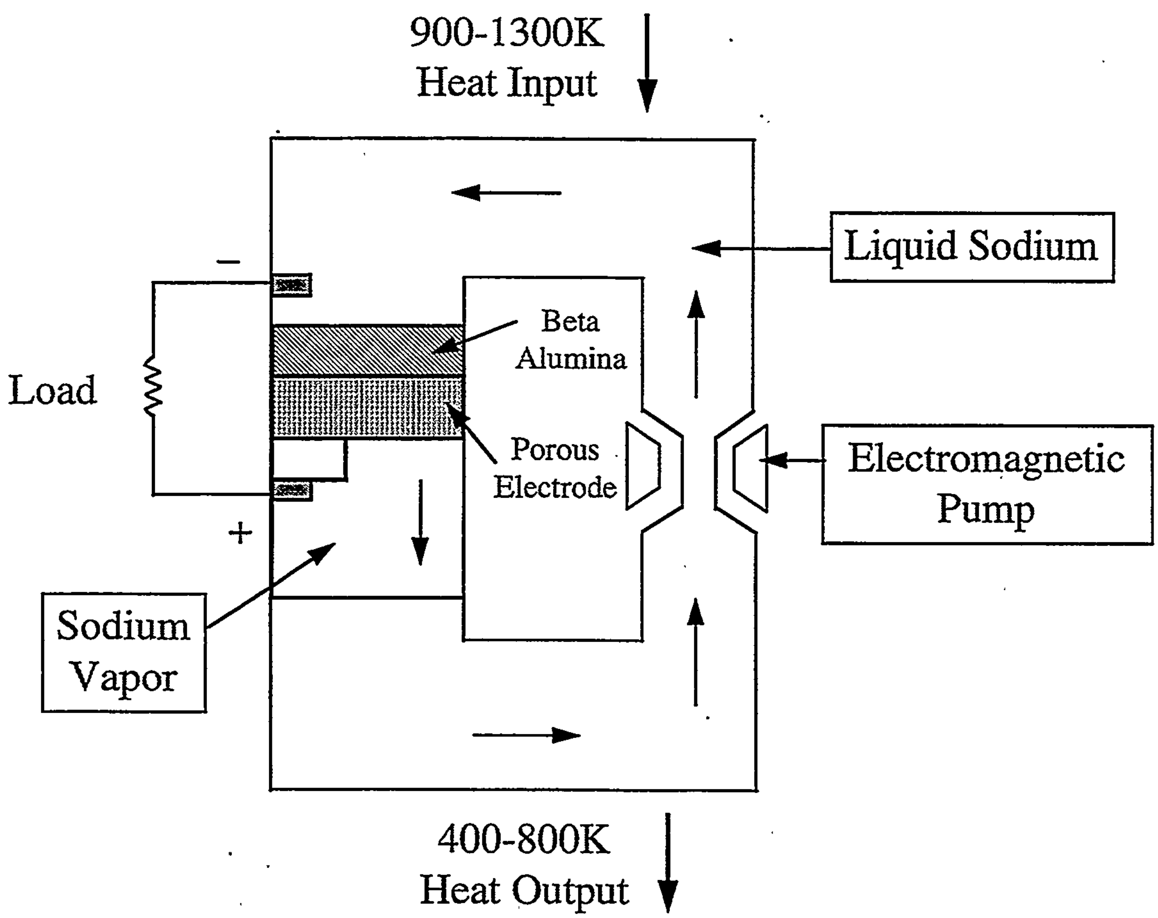

Figure 6—Alkali Metal Thermal Electric Converter

Assuming a temperature difference of ~500°C, the efficiency of AMTECs is 25–35% and the power density may be greater than 500 W/kg.[78] The principle advantages of AMTECs are (Ref. 78, p.218)

- Potentially long life.
- High power density.
- No moving parts (except flowing sodium).
- Adaptable to a variety of fuel sources.
- Beta alumina is the only unusual material.
- Low cost [$300–$500 per kW(e)].

A recent workshop[79] concluded that AMTEC technology is almost ready for application in the 10–100-W range and that industrial interest will ensure availability of converter components. However, as with all power sources that depend on high temperatures, there is a significant thermal signature associated with AMTEC deployment.

3.9 EXOTIC PORTABLE POWER SOURCES

In the course of our study, we have identified several novel methods that may supply electrical power. We have lumped discussion of these potential power sources in this section as a means of documenting their potential. Although it is unlikely that these methods will meet the needs of SOCOM in the next 5 years, we recommend that the literature be reviewed periodically to assess the state of technology advancement and application.

Novel sources identified are: (1) laser power beaming; (2) beamed electromagnetic energy; (3) tapping ambient electromagnetic radiation; (4) electromagnetic energy propagation by global transmission; (5) microfabricated cantilever piezoelectric generator; (6) nuclear radiation powered sources, including isotopic generators and small reactors; (7) Patterson cells; and (8) biosources. These novel portable sources are briefly described in the following sections.

3.9.1 Laser Power Beaming

It may be possible to supply forces in remote areas with considerable power by beaming lasers from aircraft or satellites. Friedman[80] proposes to charge batteries of satellites in geostationary orbits using high power lasers in the kilowatt range. If this proves feasible, then the reverse process may also be capable of beaming power from satellite or aircraft to ground receivers, which could convert the signal to useful energy. There are obvious safety issues to deal with as well as tracking and receiving.

3.9.2 Beamed Electromagnetic Energy

An alternative to tapping ambient electromagnetic energy is to beam a strong signal directly to a receiver. This could be accomplished by a ground-based or airborne transmitter. A pseudorandom or coded signal might be used to avoid detection by distributing the beamed energy over a predetermined set of frequencies. However, participants at a 1992 workshop[81] concluded that this technique could only work in a carefully controlled environment. Analysis of an antenna size compatible with the power level restraints for biological damage requires antenna sizes too large to be manageable. Also, the power source, operating at microwave frequencies, must have line-of-sight to the soldier to be effective.

3.9.3 Tapping Ambient Electromagnetic Radiation

Certain microelectronics devices might derive their required power from ambient electromagnetic radiation. Commercial radio stations are one of the strongest sources of such radiation. The available power may range from microwatts to tenths of a watt depending on distance and power of the transmitter. Norton[82] has proposed to develop and demonstrate an ambient electromagnetic radiation source that automatically seeks the strongest local AM carrier signal and rectifies it to produce useful power.

3.9.4 Electromagnetic Energy Propagation by Global Transmission

Another possibility for supplying portable power in the field is through global energy transmission. Electromagnetic energy may be propagated using the earth as a "single-wire" spherical transmission line, as expressed by Nikola Tesla in his 1905 U.S. patent where transmission resonances are predicted at intervals of 11.7 Hz. In particular, these transmission line modes have extremely low attenuation for frequencies below 20 kHz and "wash out" for frequencies much above 50 kHz. (These resonances are not to be confused with Schumann cavity resonances.)

These transmission line modes can be generated using a fixed, lumped circuit resonator. An array of field deployable lumped circuit, earth connected, receiving resonators allow extraction of the energy for local use. Minimum atmospheric radiation is produced, and no tall antennas are required for this transmission mode.

The feasibility of this concept has been described analytically and experimentally demonstrated.[83] Extensive theoretical literature exists on the computation of electric field strengths at very low frequencies; the most famous have been compiled by Louis W. Austin.[84]

3.9.5 Microfabricated Cantilever Piezoelectric Generator

Another method proposed for powering low-power electronic devices is based upon external motion to mechanically stimulate an electric generator.[85] Intentional or incidental vibration can excite a suspended mass attached to piezoelectric material, which, in turn, generates alternating energy. The current could be rectified and stored in a small battery or capacitor to power a low-power electronic device.

3.9.6 Radioisotopic Generators and Small Nuclear Reactors

Power systems for space missions have employed radioisotopic sources and small nuclear reactors[86] and thermoelectric materials to convert thermal energy to electrical energy. Over the past 25 years, 34 radioisotope power systems have been safely flown on 19 U.S. space missions. These systems typically use ^{238}Pu oxide pellets as the heat source, tungsten emitter (cathode), niobium collector (anode) and produce approximately 300 W. A man-portable isotope powered Stirling generator is being developed by Pacific Northwest Laboratory and Stirling Technology Company.[87] The energy source of the generator is a 60-W ^{238}Pu source developed for space applications. A free piston Stirling engine drives a linear alternator to convert the heat to power. The system weighs about 7.5 kg and produces 11 W ac power with a conversion efficiency of 18.5%. However, these radioisotope powered systems are very expensive to produce and are unlikely to be considered for military applications except for unattended long-life power supplies for remote locations.

Small nuclear reactors have also been considered for powering space missions. The United States has not deployed nuclear reactors in space, but Russia has routinely used reactors in space. The Romashka reactor with an unshielded mass of 455 kg delivers 500 W over a lifetime of 15,000 + hours. The Topaz thermionic reactor, with a mass of 320 kg, delivers 6–10 kW over a lifetime of 1100–2760 h. It is extremely unlikely that nuclear reactors will be utilized by military forces except to supply power to remote bases.

3.9.7 Patterson Power Cell

It is still uncertain whether the claims made by Clean Energy Technologies, Inc.,[88] are true that the Patterson cell (named for the inventor, J. A. Patterson), produces a heat output of 450-1300 W with an input of only 0.1-1.5 W. The Patterson cell is filled with microscopic plastic beads coated with a thin layer of palladium sandwiched between two layers of nickel. The cell is filled with ordinary water. Hydrogen atoms released by electrolysis are soaked up by the palladium and/or nickel. It is inside the metal that some kind of energy releasing mechanism is claimed to take place. The device is patented (unlike cold fusion, which is unpatentable) but is far from being understood or accepted by the scientific community. Therefore, it is unlikely that Patterson cells will be commercially available in the next 5 years.

3.9.8 Biosources

Biosources in principle can provide mechanical (e.g., wind-driven motion), chemical (e.g., combustion), and electrical (photosynthesis) power. Biosources could be used as fuel to generate heat for thermophotovoltaic or thermoelectric power generation (see previous sections on thermophotovoltaics and thermoelectrics). Discussion in this section will be limited to electrical power derived from plant material.

Nature provides an amazing abundance of electric power sources, but nearly all of these sources provide power only at very low levels. With the steady reduction in physical size and concomitant reductions in power requirements combined with increase in system integration that continues to occur with semiconductor electronics, prospects improve for possible eventual use of such low-level power sources. At the same time, growing understanding of how these natural systems operate holds the promise of finding ways to amplify natural processes under appropriate conditions (e.g., chemical treatment) so as to be able to harness these power sources.

Lee et al.[89] have studied ion and electron transport phenomena in platinized photosynthetic thylakoid membranes. Greenbaum[90] has constructed cells that were able to generate short-circuited photocurrents of a microampere by entrapped platinized chloroplasts. The work Greenbaum did was intended to demonstrate that photocurrents could be produced; he has not attempted to explore systematically the possible use of platinized chloroplasts as an electric power source. Advantages he sees with use of platinized chloroplasts are the possibility of modifying system characteristics through genetic engineering to get material with specific properties and of making use of self replicating capability of the host cells. He would expect to produce power cell material by growing algae in large farms rather than by harvesting green leafy material.

No attempt was made to align the chloroplasts, vary packing, or to measure quantum efficiency of the photosynthesis process for this system. While no data were taken on how long a power generating system would last, Greenbaum expects a period of hours to days, with the platinized chloroplasts behaving in many respects much like semiconductor materials. Output voltages would depend on the differences in energy levels involved in the photosynthesis process, typically around 1 V.

He expects it should be possible to achieve at least two orders of magnitude larger current (e.g., 100 μA) with proper optimization of parameters. If this expectation were borne out, his system of platinized chloroplasts would be capable of trickle charging batteries or ultra capacitors. He also believes that a focused effort to develop prototype power sources based on photosynthesis reactions could well achieve a demonstration prototype within 3–5 years.

Substantially more current than 1 μA will be required for bioelectric power sources to be considered a useful way to trickle charge batteries. However, currents in the range of 10–100 μA from modestly improved systems based on platinized chloroplasts may be adequate in the future to power MEMS applications.

The possibility of getting even small amounts of electric power from green leaves is appealing, especially if such a source could be employed as needed in the field. A drawback with this type of power source would be the amount of preparation, such as special treatment of leafy materials, needed in the field to build a power-producing cell. Based on laboratory experience to date, preliminary chemical processing including various solutions of platinum compounds must be used to make proper electrical contact with the photosynthetic membranes. The platinized choroplast mixture must be transferred to a filter or other substrate for mounting and assembled with appropriate hardware to construct a power-producing cell. With what is known now, it is hard to see what advantages such biosources will have. However, application of this approach for generating power has not been explored systematically, either.

Possible future uses of this technology should not be dismissed too hastily, if for no other reason because of recent advances in the areas of nanotechnology (micro/nano-sized channels for fluidics applications) and MEMS. These areas not only open up the possibility of biosources for power, but also possible options for new ways to deploy sensors and actuators coupled to microtransmitters that could transmit data over short distances.

Too little is known at present to say what the potential uses might be or what the advantages or disadvantages are for particular kinds of applications. There is value in carrying development at least to the stage of a demonstration prototype power delivering system.

4. POWER SOURCE STANDARDS

This report covers a wide range of types of portable power sources, many of which would require considerable development to bring to a level for demonstrating feasibility for use in the field. Some agreed-upon set of parameters for characterizing these sources and systematizing information about them would be useful to applications designers and end-users (especially military mission planners). A formal characterization needs to cover general areas of interest or concern such as electrical and physical properties, environmental qualification, and maintenance, handling, and disposal considerations. Table 5 gives a list of general attributes intended to promote discussion and to suggest what a standard characterization might include. No attempt has been made to be comprehensive.

Table 5—Formal Characterization of Portable Power Supplies

Category/Attribute	*Comments*
Electrical	
Energy Density	
Total Energy Content	
Power Density	
Maximum Voltage	
Maximum Current	
RF Emission Power	
Electrical Interconnects	
Physical	
Size/Shape	
Weight	
Environmental	
Acoustic Emission Power	
Mechanical Shock Tolerance	May require defining test conditions.
Electrical Shock Tolerance	May require defining test conditions.
Water Resistance	
Operating Temperature Range	
Operational	
External Energy Requirements	Applies to rechargeable systems.
Orientation	Usually need orientation independence.
Maintenance	
Testing Requirements	Will require test procedure descriptions.
Safety	May require identifying potential safety problems.
Disposal	Determined by environmental regulations.

Once specific attributes are agreed upon, then attention must be given to how to measure the attribute and how to report the results. Some parameters may require a highly specialized measurement technique. Others, such as mechanical shock tolerance, may require deciding what types of impacts batteries must be capable of withstanding; several different quantities may have to be measured to provide adequate characterization.

There are several reasons for developing standards covering portable power systems. Reliability in its many forms is a major one because of its importance to the success of military operations. Other goals include increased efficiency in use of resources, decreased design and operating costs, and better control over testing and maintenance of equipment. In the case of rechargeable batteries, the Smart Battery Specification goes a long way toward meeting these goals.

Microelectronics technology is rapidly assuming a much greater role in a warrior's resources. In addition to sophisticated communications systems, there are Global Positioning System locator devices; night vision viewers; various types of sensor systems for detecting, identifying, and locating various hazards; and specialized information systems. As the use of microelectronics expands, the options for providing power must expand. The technological complexity also increases. Greater use of standards is one way to manage and control the impacts of this increased complexity. The primary goal of the kinds of standards advocated in this report is to deal effectively with the increased complexity of the technologies used.

A standard basis for comparing the different battery technologies would be particularly useful and will be the subject of the remainder of this section.

Standards are needed for characterizing batteries and other portable electric power systems according to how well they will perform in certain applications. Until the last several years, there was no agreed-upon system for reporting performance characteristics of the ever-widening range of battery types that would allow an appropriate selection to be made relatively quickly based on the requirements of the application. Extensive testing and prototyping are still required to gain sufficient experience with candidate batteries in order to make a final satisfactory selection. This is particularly true for rechargeable batteries.

Whatever type of standard is developed will need to complement the Smart Battery Management suite of standards, which appears to cover the operation and maintenance phases of a battery life cycle very well. What is missing now is a standard approach to characterizing the performance normally expected of each type of battery. Benefits of such a standard will include greater incentives for battery manufacturers to produce batteries with consistent quality. Information is needed to address design requirements for new electronic devices, response to harsh environmental conditions, and information for planning required maintenance, handling, and disposal after the battery is put into service.

Designers of electronic devices would benefit from such a standard in being able to produce systems faster and more efficiently, without having to spend as much time in system prototyping. The standard should include current–voltage curves for different loads and load scenarios. Many types of electronic devices today can be characterized by quite distinct use patterns. Such use patterns should therefore be the basis for selecting load scenarios for use in the standard. Military electronics must already meet many standards and often are used in carefully planned and prescribed ways, providing a further historical basis for choice of scenarios to use in a standard.

What is needed is a standard, reliable way to quickly compare different portable electric power source capabilities and capacities during mission planning phases. Sufficient information in handbooks and manufacturer's product data sheets is not usually provided in the amount and kind of detail or laid out in a form that facilitates comparisons. Making useful comparisons becomes more difficult if the technologies used differ widely and no doubt lies behind the designations used for batteries as primary and secondary types of power. This section of the report attempts to address the issues that need to be covered by standards that would allow mission planners to make useful comparisons.

Development of battery standards has been driven historically by requirements for interchangeability of batteries manufactured by different vendors. These requirements were concerned with physical characteristics such as size, shape, location and configuration of terminals, and nominal voltage. Standards have also been developed for testing batteries in order to determine product quality. More than a dozen military standards exist but deal primarily with physical characteristics.

Some consumer electronics items (e.g., some hand-held calculators) as recently as the mid-1980s, powered by 9-V batteries, would not work reliably with some rechargeable NiCd 9-V batteries because these batteries did not provide the same voltage as a 9-V alkaline battery. Information booklets provided by consumer electronics did not and still do not always warn consumers of incompatibility problems such as the case of the example given here.

Widespread use of laptop computers and the need for being able to use them reliably on business trips and at important business meetings has stimulated much work in new battery technology, including further development of standards and a communications bus and protocol for monitoring and tracking the condition and recharging history of the battery.

The obvious application to SOCOM is to allow planners to decide more quickly and reliably which power sources are appropriate or necessary for a particular mission. Perhaps a combination of sources is needed. The type of standard envisioned and advocated in this report needs to address the technical capabilities of power sources in such a way that system designers and integrators are able to assemble components to produce a final system that will probably work satisfactorily. Such a standard will prove to be increasingly advantageous (likely necessary eventually) with the introduction of more specialized microelectronics support systems and especially for MEMS technology.

We suggest that SOCOM consider development of a general standard that identifies the common attributes of a portable power source that a microelectronics applications designer or a mission planner for special operations will need to know. Some of these attributes can be measured and the results reported in a straightforward way (e.g., weight, size, operating temperature range, total stored power, and energy density). Other attributes will require having to define a measurement procedure or special conditions under which the measurements must be made.

5. SUMMARY

Table 6 summarizes the overall results of our assessment of portable power sources for use by SOCOM. The table provides a comparison of portable power technologies but does not tell the whole story. Although some of the sources are presently available and have sufficient energy or power density, they should not be seriously considered at this time, either because of a lack of technical maturity or they do not meet other SOCOM requirements such as continuous power delivery, weight, size, or ruggedized for field deployment. Table 7 lists those sources which we believe meet SOCOM requirements now or within the next 5 years. Batteries will continue to be the preferred source of power for most short-interval SOCOM missions. However, it is unlikely that there will be significant improvement in battery energy density, and significant safety issues are associated with the use of high-discharge-rate lithium-based batteries. Battery technology development is proceeding rapidly in support of a growing commercial market (portable electronic devices and electric vehicles). Consequently, nonspecialized battery technology may not require additional defense funded R&D. Fuel cells and TPVs can meet most, if not all, of SOCOM power requirements, but there are other limitations such as thermal and acoustic signatures, support and training, system reliability, and infrastructure deployment for these new technologies.

Table 6—Comparison of Power Sources

Power Source	Energy Density [Wh/kg]	Power Density [W/kg]	Available* 0-2 years	Available* 3-5 years
Nonrechargeable Battery (Lithium Based)	500	50-100	x	
Rechargeable Battery (NiMH)	80	20@1.2 V 240@1.0 V	x	
Thin-Film Battery	480	0.012 W/cm^2	x	
Fuel Cell	800	700		x
Thermophotovoltaic	750 (with 1 kg of fuel)	250	x	
Thermoelectric	based on fuel supply	25	x	
Piezoelectric	?	?		>5 years
Hand-Crank Generator	455	455	x	
Engine-Driven Generator	850	12.5	x	
Stirling Engine	based on fuel supply	556	x	
Microturbine Gen + Fuel	3500	50,000		x
Flywheel	200	2000		>5 years
Solar	variable	8	x	
Water Driven	variable	?	x	
Wind	variable	2-20	x	
Patterson cell	?	?		>5 years
Radioisotope	?	1.5		>5 years
Electromagnetic	?	?		>5 years
Biosources	?	?		>5 years
AMTEC	based on fuel supply	500		x
Ultracapacitor	3.3-7.5	1400-21,000		x
Diesel Fuel	10,000		n/a	n/a

*Cost-effective for widespread deployment.

Table 7—Sources That Meet SOCOM Requirements

Power Source	Fuel	Weight	Thermal Signature	Acoustic Signature
Nonrechargeable Battery	none	varies	low	none
Rechargeable Battery	none	varies	low	none
Fuel Cell	hydrogen/ methanol	medium	medium	low
Portable Engine Generators	diesel/ gasoline	medium	high	high
Thermophotovoltaic	variety	medium	high	low

In the course of our study, we identified several sources that are commercially available but are only applicable for special missions or under the proper field conditions. Table 8 lists these sources and the conditions under which they might be used. The hand-crank generator might be considered by SOCOM as an emergency backup on all missions because of its reliability and portability (size of a fishing reel may be possible).

Table 8—Sources For Special Field Locations and Conditions

Power Source	Location	Condition	Application	Limitation
Wind Turbine	desert, plains seashore	wind>12 mph	long-term mission	variable output requires setup
Solar	desert	sunny	battery charging	variable output/daytime only
Thermoelectric	anywhere	any	high reliability	low power density/high thermal signature
Flywheel	base camp or vehicle	any	faster energy discharge	doesn't scale to small sizes
Hand-crank	anywhere	any	backup	occupies personnel
Water Turbines	mountains with flowing streams	>6 m head >1 L/s	long-term mission	requires setup

We also identified several technologies that have a high potential to meet requirements but need more R&D to adapt them for portable use. Of these sources, listed in Table 9, the most likely to meet future SOCOM needs are the proven AMTEC technology in the 3–5 year time frame and microturbines in later years. Microturbine development is in its infancy, but the technology should mature with the development of improved materials and precision microfabrication techniques.

Table 9—Potentially High Payoff Sources That Require Additional Research and Development

Power Source	Current Limitation	Years to Deployment	Payoff
Microturbines	expensive	10	very high power density;
Radioisotope	politically unpopular; safety issue; expensive	3-5	suitable for long-term mission
Patterson Cell	unproven	?	?
AMTEC	high thermal signature; proven but unfamiliar technology	3-5	variety of fuels; long life; no moving parts

Table 10 lists four sources that do not meet present SOCOM requirements primarily in the ability to provide useable amounts of power in a reasonable size package. However, all of these sources might provide built-in power for individual devices, which could improve device reliability and reduce dependence on portable power.

Table 10—Sources Unlikely to Meet Present SOCOM Requirements

Power Source	Limitation	Advantages	Status
Thin-Film Battery	output too low	reliable; rechargeable for on-chip power	ongoing R&D
Microcantilever Piezoelectric	output too low	reliable on-chip power	patent disclosure
Ambient or Beamed Electromagnetic	beamed issues: soldier safety and detection by enemy	ambient energy always available for on-chip power	white paper
Biosources	output too low		on-going R&D

6. RECOMMENDATIONS

SOCOM should continue to periodically reassess the state of the art and commercial availability of portable power sources. Of particular interest are fuel cells, TPVs, AMTEC, and microturbine

6. RECOMMENDATIONS

SOCOM should continue to periodically reassess the state of the art and commercial availability of portable power sources. Of particular interest are fuel cells, TPVs, AMTEC, and microturbine generators. SOCOM should encourage additional development of specialized power sources such as aluminum–air fuel cells for underwater propulsion applications that use seawater as the electrolyte; miniature hybrid diesel generators; high-efficiency, miniaturized hand-crank generators for emergency backup; and small water and wind turbines. Given that infrastructure costs are not too great, SOCOM should consider the use of hybrid systems to meet some special needs, for example, combining batteries with solar cells, hand-crank or other sources to provide battery recharging capability. If it has not already done so, SOCOM should adopt the use of intelligent battery technology.

It is also highly likely that power requirements will change (less power required) as electronic circuits are more highly integrated on small energy efficient chips which provide their own power from such devices as thin-film batteries or more novel approaches as tapping ambient electromagnetic energy. Power requirements may also be reduced or met through application of MEMS technology. The microturbine generator is an example of application of MEMS technology for producing power with a very small, lightweight device.

Finally, we suggest that a multitechnology conference similar to the 37th Power Sources Conference held in Cherry Hill, New Jersey, June 17–20, 1996, be organized to bring together experts in all the technologies addressed in this survey. This would provide an up-to-date assessment of available and potential portable power sources to meet SOCOM needs.

7. REFERENCES

1. Linden, David ed., *Handbook of Batteries*—2nd ed., McGraw-Hill, 1995
2. Crompton, T.R. ed., Battery Reference Book—2nd ed., Butterworth-Heinemann Ltd., 1995
3. Pistoria, G. ed., *Lithium Batteries*, Industrial Chemistry Library, Volume 5, Elsevier Science B. V., 1994
4. Munshi, M.Z.A. ed., *Handbook of Solid State Batteries & Capacitors*, World Scientific Publishing Co. Pte. Ltd., 1995
5. http://prodeng.nwscc.sea06.navy.mil/battery/p-doc/toc.htm
6. http://www.monmouth.army.mil/cecom/lrc/safety/safety1.html
7. http://www.3m.com/profile/pressbox/phase2.html
8. http://www.calstart.org/news/newsnotes/96032202.html
9. http://www.usfa.nl/lithium.html
10. http://ovonic.com/evpacks.html
11. http://home.hkstar.com/~welllink/nimh_cyl.htm
12. Swager, Anne Watson, "Smart Battery Technology: Power Management's Missing Link," Electronic Design News, March 2, 1995, pp. 47-64.
13. Duracell, Intel, "Smart Battery Data Specification," Revision 1.0, February 15, 1995, Available at http://www.intel.com/IAL/powermgm/sbovr.htm.
14. Intel, "System Management Bus Specification (SMBus)," Revision 1.0, February 15, 1995, Available at http://www.intel.com/IAL/powermgm/sbovr.htm.

15. Duracell, Intel, "Smart Battery Charger Specification," Revision 0.95a, February 15, 1995, Available at http://www.intel.com/IAL/powermgm/sbovr.htm.
16. Philips Semiconductors, "The I2C-bus and How to Use It," Available at http://www.semiconductors.philips.com/ps/philips53.html.
17. Computer Access Technology Corporation, "ACCESS.bus Technology Information Sheet," http://www.best.com/~catc/ab_tech.htm.
18. G. Pistoia (Editor), *Lithium Batteries-New Materials, Developments and Perspectives, Industrial Chemistry Library, Vol 5,* Elesevier Science B. V.,1994.
19. J. B. Bates, D. Lubben and N. J. Dudney, "Thin Film Li-Mn_2O_4 Batteries", 1995 IEEE Publication 0-7803-2459-5/95.
20. Jones, S.D., "Development and Performance of a Rechargeable Thin-Film Solid-State Microbattery", Journal of Power Sources, March 1995, p 63-67
21. Analytic Power Corporation, *FC150-1 Fuel Cell Power Supply*, advertising literature, (617) 542-6352
22. http://www.newswire.ca/releases/October1995/03/c0228.html
23. http://www.hev.doe.gov/components/hydrogen.html
24. ordesch, Karl and Günter Simader, *Fuel Cells and Their Applications*, VCH Publishers, Inc., New York, NY, 1996, p. 54
25. http://www.gate.net/~h2_ep/10kw_pem.htm
26. Personal communication with David Bloomfield of Analytic Power Corporation, September 1996, (617) 542-6352
27. http://www.metc.doe.gov/projfact/power/onsi.html
28. http://www.metc.doe.gov/research/power/fc_mcfc.html
29. http://www.metc.doe.gov/research/power/fc_descr.html
30. http://electrochem.cwru.edu/research.htm
31. Hamlen, Robert P., *Metal/Air Batteries* in Handbook of Batteries 2nd ed., David Linden (ed.), McGraw-Hill, 1995, p. 38.1
32. http://www.llnl.gov/str/pdfs/10_95.pdf
33. Gibbons, D.W. and Rudd, E.J., *The Development of Aluminum/Air Batteries for Propulsion Applications* in Proceedings Of The 28th Intersociety Energy Conversion Engineering Conference, Volume 1, 8-13 August 1993, p. 1.1091-1.1097
34. Personal communication, M. Frank Rose (334-844-5894), Space Power Institute, Auburn, AL
35. D. C. White and R. J. Schwartz, "P-I-N Structures for Controlled Spectrum Photovoltaic Converters," Proceedings of NATO AGARD Conference, Cannes, France, March 16-20, 1964, Published by Gordon & Breach Science Publishers, London, 1967, pp. 897-922.
36. Bernard L. Slater, "Vertical Multi-junction Cells for Thermophotovoltaic Conversion", *The First NREL Conference on Thermophotovoltaic Generation of Electricity*, July 24-27, 1994, p. 57.
37. G. A. Holmquist, E. M. Wong and C. H. Waldman, "Laboratory Development TPV Generator," *The Second NREL Conference on Thermophotovoltaic Generation of Electricity,* pp. 138-161, AIP Conference proceedings 358,July 1995.
38. Principal investigator, Dr. Glenn A. Holmquist (619-457-3048).
39. Personal communication, Chris DeBellis (330-829-7664) Babcock & Wilcox Alliance Research Center, Alliance, Ohio.
40. Principal investigator, Dr. Lewis M. Fraas (206-392-5237).
41. Kevin Krist, "GRI Research on Thermophotovoltaics", *The First NREL Conference on Thermophotovoltaic Generation of Electricity*", p.13, July 24-27, 1994, Copper Mountain, Colorado.
42. Prospector VIII: "TPV-An Update of DOD, Academic and Commercial Research, July 14-17, 1996 (proceedings in press).
43. M. Frank Rose, "Competing Technologies for Thermophotovoltaics", *The Second NREL Conference on Thermophotovoltaic Generation of Electricity,"* July 1995, pp. 213-220, AIP Conference Proceedings 358, 1996.
44. http://www.sbu.ac.uk/~sesd/research/research.html#thermoelectric
45. http://www.tbe.com/products/energy/telan2.html
46. Bass, Elsner and Leavitt, "The Preliminary Design of a 500 Watt Thermoelectric Generator," Proc. IECEC, pp.586-591, AIAA-94-4197-CP, August 1994.
47. Prospector IV: Small Engines and Their Applicability to the Soldier System Workshop, November, 10-11, 1992, Published by the Space Power Institute, Frank Rose, Director.

48. Personal communication, Neville Howell (423-574-3777), Oak Ridge Centers for Manufacturing Technology,Oak Ridge, Tennessee.
49. C. D. West, *Principles and Applications of Stirling Engines*, van Nostrand Reinhold Company, Inc., 1986.
50. Prospector IV: Small Engines and Their Applicability to the Soldier System Workshop, November 10-11, 1992, Space Power Institute.
51. Personal communication, Neville Howell (423-574-3777), Oak Ridge Centers for Manufacturing Technology, Oak Ridge, Tennessee.
52. R. J. Paur, "Why Are We Here Anyway?", presentation at the Prospector VIII Workshop: Thermophotovoltaics, July 14-17, 1996, contact F. Rose, Space Power Institute for proceedings.
53. http://clean.rti.org/ecg.htm
54. "A New Type of Linear Piezoelectric Stepping Motor", *IEEE Transactions on Components Packaging and Manufacturing Technology Part A*, Vol. 18, issue 2, pp 257-260, 1995.
55. *SOCOM Power Study*, unpublished report by Power Sources Division, Army Research Laboratory, September 1994.
56. High Energy Density Permanent Magnet Axial-Gap Motors, *Technology Brief, Engineering Technology Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee.*
57. Personal communication, Neville Howell (423-574-3777), Oak Ridge Centers for Manufacturing Technology, Oak Ridge Tennessee
58. Personal communication, Guido Gauzzoni (908-427-4081), CECOM Advanced Systems Directorate.
59. Personal communication, George Au (908-427-4886), CECOM Advanced Systems Directorate.
60. Micro-Hydroelectric Power, http://www.asis.com/aee/aee5.html.
61. Ron Alward, et al, U.S. Department of Energy, Idaho Operations Office.
62. Harris Hydroelectric Systems, Jade Mountain Inc.,P.O. Box 4616, Boulder CO 80306.
63. Anerdi, G., Brusaglino, G., *Technology Potential of Flywheel Storage and Application Impact on Electric Vehicles*, 12th International Electric Vehicle Symposium (EVS-12), V. 1, 1994, pp. 37-47.
64. http://www.hev.doe.gov/components/flywheels.html
65. Wei-Kan Chu, et. al., *Hybrid Superconducting Magnetic Bearing and its Frictional Energy Loss in Flywheel Applications*, Flywheel Energy Storage Workshop, October 31-November 2, 1995, Oak Ridge, TN, CONF-9510242
66. Joe Olbermann, *Flywheel Development at Unique Mobility, Inc.*, Flywheel Energy Storage Workshop, October 31-November 2, 1995, Oak Ridge, TN, CONF-9510242
67. http://pprc.pnl.gov/pprc/rpd/fedfund/doc/doc_nist/manufact.html
68. Steven Ashley, *Cheaper Composite Flywheels*, Mechanical Engineering, **118**(6), 10 June 1996, p. 10
69. http://www.hev.doe.gov/general/fly.html
70. Briefly Noted, Mechanical Engineering, 14 July 1996
71. http://www.chryslercorp.com/environment/alternative_fuels.html
72. Manufacturers of Small Wind Turbines, http://www.igc.apc.org/awea/faq/smsysist.html.
73. Michael Bergey, "A Primer on Small Wind Generators", http://www.bergey.com/primer.html.
74. BWC 850, http://www.bergey.com/850.html.
75. Personal communication, Trudy Forsyth, Manager of NREL Small Wind Turbine Project.
76. National Renewable Energy Laboratory, "Photovoltaics: the Power of Choice," January 1996.
77. Personal communication, George Au (908-427-4886), CECOM Advanced Systems Directorate.
78. M. Frank Rose, "Competing Technologies for Thermophotovoltaics", *The Second NREL Conference on Thermophotovoltaic Generation of Electricity, p. 217 July 1995, AIP Conference Proceedings 358.*
79. *Prospector VII: Small Fuel Cells for Portable Power Workshop* , October 31-November 3, 1994, Space Power Institute, Edited by M. F. Rose.
80. Friedman, H.W., " Near Term Feasibility Demonstration of Laser Power Beaming, UCRL-JC--114401, January 1994.
81. Prospector IV: Small Engines and Their Applicability to the Soldier System Workshop, November 10-12, 1992, Space Power Institute.
82. Personal Communication, Steve Norton (423-576-9965), Energy Division, Oak Ridge National Laboratory.
83. Kenneth L. Corum, James F. Corum, and J.F. Daum, "Spherical Transmission Lines and Global Propagation", 1996 International Tesla Symposium, Colorado Springs, Colorado, July 19-21, 1996.
84. L. W. Austin, "Some Quantitative Experiments in Long Distance Telegraphy", Bureau of Standards Bulletin (J. Res. NBS) Vol. 7, 1911, No. 3, October, pp 315-366.

85. Personal communication, Wayne Manges (423-574-8529), Instrumentation & Controls Division, Oak Ridge National Laboratory.
86. Personal communication, Roy Cooper (423-574-4470), Metals & Ceramics Division, Oak Ridge National Laboratory.
87. G.L.Tingey, G.C. Sorensen and B.A. Ross, PNL-SA--25194, NTIS Order Number DE95008932, January 1995.
88. http://www.cleanenergy.com/ceti/.
89. Lee, James W., Lee, Ida, and Greenbaum, Elias, "Platinization: A Novel Technique to Anchor Photosystem I Reaction Centres onto a Metal Surface at Biological Temperature and pH," Biosensors and Bioelectronics, Vol.II, No.4, 1996, Elsevier Science Ltd.,pp.375-387.
90. Greenbaum, Elias, "Electrical Contact of Molecular Components in a Submicron Biological Structure," in Molecular Electronic Devices, Carter, F.L., Siatkowski, R.E., and Wohltjen, H. (Editors), Elsevier Science Publishers, 1988, pp.575-581.

INTERNAL DISTRIBUTION

1. D. J. Adams
2. G. T. Alley
3. J. B. Bates
4. R. H. Cooper
5. B. G. Eads
6. E. C. Fox
7–11. D. N. Fry
12. T. M. Gayle
13. R. G. Gilliland
14. E. Greenbaum
15. R. a. Hess
16. B. A. Hoffheins
17. D. E. Holcomb
18. L. N. Howell
19. J. M. Jansen
20. R. A. Kisner
21. M. J. Maston
22. D. W. McDonald
23. G. N. Miller
24. J. K. Munro
25. S. J. Norton
26. L. C. Oakes
27. D. V. O'Kain
28. R. M. Schilling
29. G. K. Schulze
30. J. Sheffield
31. J. O. Stiegler
32. R. E. Uhrig
33. J. Vancoevering
34. C. D. West
35. J. D. White
36. R. F. Wood
37. Central Research Library
38. Y-12 Technical Reference Section
39. Laboratory Records-Record Copy
40. I&C Division Publications Office

EXTERNAL DISTRIBUTION

38. AMC Liaison, Attn: Mr. Russ Robinson, PSC 117, Box 165, APO AE, 09080
39. Chief, ARL-HRED, Attn: Field Element, Bldg. 333, Picatinny Arsenal, NJ 07806-5000
40. Commander, SOFT, Attn: TEOR (Zeisman), P. O. Box 70660, Ft. Bragg, NC 28307
41. Commander, USASOC, Attn: AOFI-RI-SI (Knight), Ft. Bragg, NC 28307-5200
42. Commander, USASOC, Attn: AOFI-RI-PR-SOFCIL (Raineri), Ft. Bragg, NC 28307-5200
43. DA, AMC, Attn: SMCAR-CCJ (Small), Picatinny Arsenal, NJ 07806-5000
44. Director, U.S. Army Research Laboratory, Attn: ARMSRL-WT-N (B. King), 2800 Powder Mill Road, Adelphi, MD 20783-1197
45. Army Material Command, Attn: AMC-FAST (F. Tremain), 5985 Wilson Road, Suite 100, Ft. Belvoir, VA 22060-5829
46. Commander, AMC, Attn: AMCDCG-T (Fisette), 5001 Eisenhower Avenue, Alexandria, VA 22333-0001
47. Commander, SOTF, Attn: Mitchell Pearce, P. O. Box 70660, Ft. Bragg, NC 28307
48. Commander, USASOC, Attn: AOOP-ASL (LTC Lewis), SOF Liaison Officer, Ft. Bragg, NC 28307-5200
49. Director, U.S. Army Research Laboratory, Attn: AMSRL-WT-WA (MAJ Bray), Aberdeen Proving, Grounds, MD 21005
50. Director, US Army Research Laboratory, Attn:AMSRL-HR-M (Paicopolis), Aberdeen Proving Grounds, MD 21005-5425
51. Dismounted Battle Lab, Ft. Benning, GA 31905-5007

52. HQ, CECOM, Attn: AMSEL-RD-AS-AT (Urbanik), Bldg. 200, Ft. Monmouth, NJ 07703
53. HQ, TRADOC, Attn: ATFE-GE-LO (Fischer), Ft. Monroe, VA 23651
54. OASA (RD&A), Attn: SARD-TT (Reisman), Pentagon, RM 3E480, Washington, DC 20310-0130
55. U.S. Army, NVESD, Attn: AMSEL-RD-NV-TIS (Soyka), 10221 Burbeck Road, Suite 430, Ft. Belvoir, VA 22060-5806
56. U.S. Army Soldier Systems Command, Attn: SSCNC-I (Mooney), Natick, MA 01760-5019
57. USACHPPM, Attn: MCHB-DS-HA (Gross), Aberdeen Proving Grounds, MD 21010-5422
58. HQ, 5TH SFG (A), Attn: ODA 596 (CTP Mitchell), Ft. Campbell Office, P. O. Box 627, Oak Grove, KY 42262
59. HQ, Dept. of the Army, Attn: DAMO-FDQ (MAJ McGonalle), 400 Army Pentagon, Washington, DC 20301-0460
60. HQ, U.S. Army MICOM, Attn: ARMSMI-RD-AC-CC (Fulda), Redstone Arsenal, AL 35898-5242
61. U.S. Army Infantry School, Attn: ATSH-CD, Ft. Benning, GA 31905-5007
62. U.S. Air Force Phillips Laboratory, Attn: Maj. Bagnell, 3550 Aberdeen Avenue, Kirtland AFB, NM 87117-5776
63. USACAPOC, Attn: AOCP-OP-FD (CPT Callahan), Ft. Bragg, NC 28307
64. Belvoir RD&EC, Attn: STRBE-FGE (Dr. L. Amstutz), Ft. Belvoir, VA 22060-5606
65. Commander, TRADOC, Attn: ATCD-CC, Ft. Monroe, VA 23651-5000
66. Director, U.S. Army Research Laboratory, Attn: CDR Randy Large, N33, 2000 Trident Way, Bldg. 624, San Diego, CA 92155
67. COMNAVSEASYSCOM, Attn: CWO2 Mills, PMS340Z6, 2531 Jefferson Davis Hwy, Arlington, VA 22242-5160
68. COMNAVSPECWARDEVGRU, Attn: N5, Regulus Avenue, Virginia Beach, VA 23521
69. COMSPECBOATRON ONE, Attn: Keith LeBoeuf, Code 06, 3400 Tarawa Road, San Diego, CA 92155-5176
70. Naval Surface Warfare Center, Attn: John Young, 116 Lakeview Parkway, Suite 200, Suffolk, VA 23435-2698
71. Commander, TECOM, Attn: CSTE-ECS, Park Center IV, 4501 Ford Avenue, Alexandria, VA 22302-1458
72. Electronics Technology & Devices Lab, Attn: Robert Hamlen, Fort Monmouth, NJ 07703-5000
73. Commander, NAVSPECWARGRU ONE, Attn: Frank Clark, 3632 Guadacanal Road, San Diego, CA 92155-5583
74. COMNAVSPECWARCOM, Attn: N33 (CW3 Molenaar), 2000 Trident Way, NAB Coronado, San Diego, CA 92155-5037
75. COMNAVSPEWARGRU TWO, Attn: Mr. Paradis, 1430 Helicopter Road, Norfolk, VA 23521-2944
76. Naval Special Warfare Command, Attn: QMCS Bolduc, N3334, 2000 Trident Way, Bldg. 624 San Diego, CA 92155
77. NAVSPECWARDEVGRU, Attn: Dave Rowland, N51, 1636 Regulus Avenue, Virginia Beach, VA 23461-2299
78. NSAP, Attn: John Smaldino, Bldg. 1523, Box 555300, Camp Pendelton, CA 92055-5300
79. NSWC-Dahlgren Division, Attn: JPO/STC (Levine), 17320 Dahlgren Road, Dahlgren, VA 22448-5100
80. Office of Special Technology, Attn: Erik Syvrud, 10530 Riverview Road, Bldg. 3; Ft. Washington, MD 20744

81. Commander, AFSOC, Attn: XPQT (Maj. Moon), 100 Bartley Street, Hurlburt Field, FL 32544-5723
82. TRAC-WSMR, Attn: WAA (DeHastings), WSMR, NM 88002
83. WL/MN (Wright Labs), Attn: Capt. Rob David, 101 W. Egline Blvd., Suite 258, Eglin AFB, FL 32542
84. Commander, JSOC, Attn: J5-R (MAJ Spiegel), P. O. Box 70239, Ft. Bragg, NC 29307-5200
85. NSAP, Attn: Ms. Susan Bales, Code 09N, 800 N. Quincy Street, Arlington, VA 22217
86. NSWC-Dahlgren Division, Attn: Elton Lanier, 17320 Dahlgren Road, Dahlgren, VA 22448-5100
87. AFSC/XRS, Attn: SOF TPIPT (MAJ Illig), 2275 D Street, Suite 10, Wright-Pat AFB, OH 45433-7256
88. HQ, ACC, Attn: SPXS (SMSgt Gunther), 220 Sweeney Blvd, Suite 112, Langley AFB, VA 23665-2796
89. USAF Technology LNO, Attn: Maj Keipert, CMR 456, Box 2287, APO AE, 09157
90. CO, USMC Combat Development Center, Attn: WF11CD (COL White), Quantico, VA 22134-5068
91. Commander, JSOC, Attn: J8R (Huseman), P.O. Box 70239, Ft. Bragg, NC 28307
92. DARPA, Attn: TTO (John Pennella), 3701 N. Fairfax Drive, Arlington, VA 22203-1714
93. Defense Equipment Directed Energy, Attn: Mr. Jim Paterson, British Embassy, 3100 Massachusetts Avenue, Washington, DC 20008
94. DARPA, Attn: Defense Sciences Office (L. Dubois), 3701 Fairfax Drive, Arlington, VA 22203-1714
95. OASD/SO-LIC, Attn: John Reingruber, Pentagon, RM 1A-6748, Washington, DC 20301
96. DOE Albuquerque Field Office, Attn: M. Flor, P. O. Box 5400, Albuquerque, NM 87185-5400
97. DOE Nevada Field Office, Attn: D. Shipley, P. O. Box 98518, Las Vegas, NV 89193-8518
98. DOE Richland Operations Office, Attn: D. Goranson, K8-50, P. O. Box 550, Richland, WA 99352
99. DARPA, Attn: Dick Urban, 3701 N. Fairfax Drive, Arlington, VA 22203-1714
100. Defense Evaluation Support Activity, Attn: TD/AC (MAJ Daly), 2251 Wyoming Blvd., SE, Kirtland AFB, NM 87117-5609
101. DOE, Special Technologies Program, Attn: Bob Wall; NN-30, GA-301, 1000 Independence Ave., SW, Washington, DC 20585
102. DOE, Idaho Field Office, Attn: N. Romero, 528 35th Street, Los Alamos, NM 87544
103. DOE Oak Ridge Field Office, Attn: R. Spradlen, P. O. Box 2001, Oak Ridge, TN 37831
104. Argonne National Laboratory, Attn: J. Peerenboom, 9700 S. Cass Ave., Building 900, Room P21, Argonne, IL 60439
105. Brookhaven National Laboratory, Attn: L. Forman, Building 197C, Upton, NY 11973
106. Los Alamos National Laboratory, Attn: T. Burris, NIS/IT Program Office, MS-B224 Los Alamos, NM 87545
107. Oak Ridge National Laboratory, Attn: V. Baylor, Building 9113, MS-8206, P. O. Box 2003, Oak Ridge. TN 37831-8206
108. Remote Sensing Laboratory, Attn: Bechtel Nevada (H. Bostick), P. O. Box 98521, MS RSL-9, Las Vegas, NV 89193
109. Special Technologies Laboratory, Attn: T. Lewellan, 5520 Ekwill St., Suite B, Santa, Barbara, CA 93111
110. USSOCOM, Attn: SOAC-DP (LTC Cotter), 7701 Tampa Point Blvd., MacDill AFB, FL 33621
111. DynMeridian, Attn: Thomas Brophy, 2909 Bay to Bay Blvd., Suite 200, Tampa, FL 33629-8161
112. INEL, EG&G Idaho, Inc., Attn: T. Chapman, P. O. Box 1625, MS-2805, Idaho, Falls, ID 83415

114. Pacific Northwest Lab, Attn: Battelle-PNL (J. Heaberlin), P. O. Box 999, MS-K841, Richland, WA 99352
115. Sandia National Laboratory, Attn: R. Wilson, P. O. Box 5800, MS-0767, Albuquerque, NM 87185
116. Allied Signal Inc., Attn: Federal Manu & Tech (J. Bowers, Dept. 291), P. O. Box 419159, Kansas City, MO 64141-6159
117. Wintec, Inc., Attn: Kurt Badertscher, 2907 Bay to Bay Blvd., Suite 314, Tampa, FL 33629
118. Commander, USASOC, Attn: AOMD-OP (Clayton), Ft. Bragg, NC 28307-5200
119. DOE, Idaho Field Office, Attn: R. Sheldon, 785 DOE Place, Idaho Falls, ID 83402
120. Director, U.S. Army Research Laboratory, Attn: AMSRL-EP-PA (H. Christopher), Fort Monmouth, New Jersey 07703-5601
121. T. L. Forsyth, NTTC/2, National Renewable Energy Laboratory, Golden, CO 80401
122. S. Gilman, U.S. Army Research Laboratory, Ft. Monmouth, NJ 07703
123. R. J. Paur, ARO, P. O. Box 12211, Research Triangle Park, NC 27709-2211
124. M. F. Rose, Space Power Institute, 231 Leach Center, Auburn University, Auburn, AL 36849
125. Assistant Manager for Energy Research and Development, DOE-ORO, P.O. Box 2001, Oak Ridge, TN 37831-8600
126. Ron Moore, The RM Group, Inc., 12024 Broadwood Drive, Knoxville, TN 37922
127. David Norton, Houston Advanced Research Center, 4800 Research Forest Drive, The Woodlands, TX 77381
128. M. M. Sevik, Carderock Division, Naval Surface Warfare Center, Code 70, Bethesda, MD 20084-5000
129. Ernesto Suarez, Pratt & Whitney, P. O. Box 109600, Mail Stop 716-87, West Palm Beach, FL 33410-9600

130–131. Office of Scientific and Technical Information, U.S. Department of Energy, P.O. Box 62, Oak Ridge, TN 37831