

ARMY RESEARCH LABORATORY



**A Survey of Power Source Options for a Compact Battery
Charger for Soldier Applications**

by S. Gilman, D. Chu, B. Geil, B. Morgan, and T. Podlesak

ARL-TR-4693

December 2008

NOTICES

Disclaimers

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.

Army Research Laboratory

Adelphi, MD 20783-1197

ARL-TR-4693

December 2008

A Survey of Power Source Options for a Compact Battery Charger for Soldier Applications

S. Gilman, D. Chu, B. Geil, B. Morgan, and T. Podlesak
Sensors and Electron Devices Directorate, ARL

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY) December 2008		2. REPORT TYPE Final		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE A Survey of Power Source Options for a Compact Battery Charger for Soldier Applications				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) S. Gilman, D. Chu, B. Geil, B. Morgan, and T. Podlesak				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory Sensors and Electron Devices Directorate, ATTN: AMSRD-ARL-SE-D 2800 Powder Mill Road Adelphi, MD 20783-1197				8. PERFORMING ORGANIZATION REPORT NUMBER ARL-TR-4693	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT This report was inspired by a request from Mr. Scott Feldman of the Army Natick Soldier Research Development and Engineering Center (NSRDEC) for a survey of technologies that might enable the development of a militarized 250 W battery charger, preferably JP-8-fueled, within the next few years. While the short-term prospects are limited, a number of technologies are likely to bear fruit in the longer term. This report reflects the status of the various technologies considered in November 2007.					
15. SUBJECT TERMS battery charger, small engines, fuel cells, thermoelectric, thermophotovoltaics					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 24	19a. NAME OF RESPONSIBLE PERSON Sol Gilman
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (Include area code) (301) 394-0339

Contents

Acknowledgment	iv
1. Introduction	1
2. Small Engines	1
2.1 AC to DC Converters for Use with Small Engine Generators	1
2.2 Internal Combustion Engines	1
2.3 External Combustion Engines	3
3. Fuel Cells	4
3.1 General: Types of Fuel Cell Systems	4
3.2 Polymer Electrolyte Membrane (PEM) Fuel Cells	5
3.2.1 Hydride-Fueled Hydrogen Fuel Cell Systems	5
3.2.2 Reformed Methanol Fuel Cell Systems	6
3.2.3 Direct Methanol Fuel Cell Systems	6
3.2.4 Hydrogen Fuel Cell Systems using a Polybenzimidazole (PBI) Membrane	7
3.3 Solid Oxide Fuel Cells (SOFC)	7
4. Thermophotovoltaics (TPV)	9
5. Thermoelectrics	10
6. Summary	11
7. Conclusions	13
8. References	14
Acronyms	16
Distribution List	18

Acknowledgment

We gratefully acknowledge support and encouragement of this study by Mr. Scott Feldman, Army Natick Soldier Research Development and Engineering Center (NSRDEC). We also acknowledge helpful discussions with Ms. Selma Matthews, Army Communications-Electronics Research Development and Engineering Center (CERDEC), and Mr. Christopher Bolton, PE Mobile Electric Power.

1. Introduction

Typical Soldier power requirements are at the level of tens of watts of average power for missions that can last from 1 (present) to 3 (future) days. The Army's policy, going back almost to the dawn of wireless communication and extending to relatively recent times, has been to rely on primary batteries to supply those power needs for combat and "realistic training" scenarios and to rely on rechargeable batteries mainly as a cost-savings measure for "classroom" training. Historically, the main factors that limited the use of rechargeables was the much lower specific energies afforded by aqueous rechargeable chemistries, mainly nickel cadmium (Ni/Cd) (compared to aqueous magnesium/manganese dioxide (Mg/MnO₂) and more recently, by nonaqueous lithium sulfur dioxide (Li/SO₂) and lithium-manganese dioxide (Li/MnO₂) chemistries. The emergence of high performance Li-ion batteries with specific energies rivaling that of present primaries is removing one obstacle to using rechargeables for combat where there is proximity to a power grid or vehicle. The remaining obstacle to using rechargeables in "non-tethered" combat conditions is the absence in the Army's inventory of a suitable compact power source that will fill the gap between the 10–100 W range corresponding to more traditional Soldier power and the multikilowatt range corresponding to auxiliary power units (APUs) and vehicles. The ideal power source would utilize the Army's strategic fuel (JP-8) and would be lightweight, low signature, and long-lasting with a reasonable replacement cost.

2. Small Engines

2.1 AC to DC Converters for Use with Small Engine Generators

Battery chargers designed to use an AC source are already readily available both for civilian and military applications and will not be discussed separately in this report.

2.2 Internal Combustion Engines

With over 100 years of development, internal combustion engines are the most developed power systems and have the advantage of being able to operate on hydrocarbon fuels. They provide higher specific energies than competing technologies. Many internal combustion engines may be roughly classified on the basis of their use of the "Otto cycle" with a volatile fuel (usually gasoline/low molecular weight hydrocarbons, sometimes methanol) or the "Diesel cycle" with a nonvolatile fuel (usually diesel/high molecular weight hydrocarbons with a chain length of 16 or greater), although the line between the two cycles is blurring and "combined" cycles are becoming more common. Otto cycle engines use the force created when an atomized mixture of fuel and air is ignited using a spark plug in the reaction

chamber. The force is delivered to the external work, either through the movement of a piston or the rotation of the reaction chamber (i.e., in Wankel engines). In conventional diesel engines, the fuel is introduced into the reaction chamber after the air charge has been highly compressed. This compression causes heating of the air, which in turn causes the fuel to ignite when it is introduced into the cylinder. Because of the higher compression ratios and the method of combustion used, diesel engines require heavier construction and create a higher level of noise and vibration than comparable gasoline engines. Internal combustion engines have the advantage of a higher power density than any competing technology. With an enthalpic heat content equivalent to 13,200 Wh/kg, even 10% efficiency results in a fuel specific energy over 1300 Wh/kg, which is better than any presently available competing technology. Issues to be addressed in developing improved engines include noise, vibration, need for maintenance, thermal signature, and engine life. Advances in acoustic noise control may drastically reduce current engine acoustic signatures. Simple, non-dissipative muffler designs exist that may reduce the level of emitted noise to a level acceptable to military applications. Active suppression of vibration, both in the exhaust system and the engine in general, can reduce the noise signature even further.

If the Army's preference for jet fuel is waived, a small gasoline engine could serve for a near-term solution. As an example, the Honda EU1000i generator (*1*) (list price \$789.95) has the built-in capability of providing only 96 W of DC power; however, it provides 900 W of AC power at 120 V, which is equivalent to an average DC power of 636 W. Assuming an AC to DC conversion efficiency of 90%, approximately 570 W is available for DC battery charging. The Honda generator provides a fuel specific energy of 2300 Wh/kg at full rated load (based on claimed running time vs. fuel volume), weighs 14.5 kg, and is relatively vibration-free and quiet (noise level of ~59 dB at 7 m and 53 dB at 7 m at full and ¼ load, respectively). Redesign for half the power is possible, but would not lead to a proportional decrease in weight.

Considering the advantages of some available gasoline engines, it may be worthwhile to explore the possibility of using diesel fuel reformat for the fuel now that a number of research and development (R&D) organizations are involved in developing miniature fuel reformers to use with solid oxide fuel cells.

“Model airplane engines” are commonly fueled with a mixture of methanol and nitromethane. They can be viewed as a derivative of both the Diesel and Otto cycles, involving higher pressures than the former and a glow plug, rather than a spark plug, for ignition. It appears possible to modify the sturdier of these engines to use diesel fuel. This might be accomplished through raising head pressure, making some parts sturdier, increasing engine speed, and improving atomization of the fuel. D-Star Engineering (2, 3), in particular, has reported success in modifying such engines. A 450 W 2-stroke engine with linear dimensions smaller than 6 in. reportedly provided a fuel specific energy of approximately

2800 Wh/kg using a mixture of JP-8 and 6% 2-stroke oil with a dry weight in the range of 10 kg. D-Star has projected that they can achieve a more silent and durable 4-stroke 250 W diesel generator within a few years.

A key issue in acquiring good performance in small diesel engines is achieving droplet diameters on the order of 5 to 10 μm to achieve clean combustion. Atomizing fuel to this level is difficult and current methods require large pressures (60 to 22,000 psi) and correspondingly large amounts of power to obtain these pressures. Research is being done at the U.S. Army Research Laboratory (ARL) and other organizations to develop high efficiency, low power atomizers that provide the flow rates required by sub 1000 W generators and could, therefore, contribute to the successful development of a small battery charger using a diesel engine. Current plans are to demonstrate high flow rate atomizers (>1 L/hr) by the end of 2008. More effective atomization may also give the engine multi-fuel capability. Although JP-8 is and shall remain the fuel of choice, due to its energy density and ubiquity, being able to burn other fuels is extremely valuable from a military logistics perspective. Available gasoline, cooking kerosene, diesel fuel, heating oil, various alcohols, and edible oils may be burned in an internal combustion engine provided a specified, uniform fuel droplet diameter is produced. Droplet size is a function of fuel viscosity, so if such a system could automatically sense what was put in its fuel tank and adjust the atomization accordingly, virtually any flammable liquid could be used as a fuel.

Research on linear engines, enabled by developments in power control and linear electrical machines, was begun by the early 1990s at West Virginia University (4), Sandia National Labs, the University of Regina, and most recently, Stanford University. Compared with existing internal combustion engines, the new design eliminates conversion of the piston's linear motion into rotary motion prior to conversion of the mechanical energy to electrical energy in a linear alternator. This minimizes the use of moving parts, reduces vibration, and also introduces the possibility of certain thermodynamic advantages that can result in significant efficiency and reliability gains. Aerodyne (3) projects that a 300 W diesel-fueled system could provide a fuel specific energy greater than 1500 Wh/kg. The linear motion is highly dependent on spring action and identification of a long-lasting material for that component is one of the technical issues.

2.3 External Combustion Engines

The Stirling engine was invented in 1816 and has, in the past, been developed for refrigeration, heat pumps, and more recently, space applications using radioisotopes. The Stirling is defined as a closed-cycle regenerative heat engine with a gaseous working fluid. "Closed-cycle" means the working fluid (usually hydrogen or helium) is permanently contained within the sealed engine system that usually incorporates a power and a displacer piston. "Regenerative" refers to the use of an internal heat exchanger called a regenerator, which increases the engine's thermal efficiency. Because combustion is conducted

externally, a variety of fuels can be used. Also, there are fewer moving parts than in internal combustion engines and no possibility of those parts being contaminated by fuel or exhaust. There are two versions of the Stirling: the kinematic Stirling involves rotary mechanical linkage to an alternator, and the free piston Stirling engine (FPSE) transfers its power to a linear generator without mechanical linkages and is more likely to result in a power source that is relatively quiet and maintenance-free (5). However, the FPSE requires a significant subsystem to control piston displacement. Several companies, including Sunpower, Infinia, and TIAX, have been involved in developing Stirling engines for Department of Defense (DoD) applications. In particular, TIAX has reported (5) characteristics of a 600 W FPSE developed under contract with the Communications Electronics Research and Development Center (CERDEC). Fuel efficiency was reported to be in the 16–22% range, which implies a good specific energy for the present application. However, power densities were in the range of 15–24 W/kg due to the need to operate the engine at high pressures and temperatures, necessitating heavy pressure vessels, which highlights an area needing improvement in Stirlings for this application. Development of a practical militarized Stirling for the present application is expected to require more than the next few years to complete.

3. Fuel Cells

3.1 General: Types of Fuel Cell Systems

Fuel cells operate by directly extracting electrons from the fuel and directly inserting electrons into oxygen at catalytic surfaces. Hence, the basic energy production process involves no moving parts, raising expectations of silent, vibration-free operation combined with a long system life. However, the need for ancillaries to handle fuel and air delivery, provide cooling, and process the raw fuel tends to impinge on performance expectations to a greater or lesser extent depending on the type of fuel cell chemistry selected, which in turn depends largely on the type of fuel selected.

Fuel cells are classified primarily by the kind of electrolyte they employ. This determines the kind of chemical reactions that take place in the cell, the kind of catalysts required, the temperature range in which the cell operates, the fuel required, and other factors. These characteristics, in turn, affect the applications for which these cells are most suitable. There are several types of fuel cells currently under development, each with its own advantages, disadvantages, and potential applications. A few of the most promising types include the following:

- Alkaline
- Molten carbonate

- Phosphoric acid
- Polymer electrolyte membrane (PEM)
- Solid oxide

Alkaline fuel cells require pure oxygen as the cathodic reactant and lend themselves well to space applications but not to land applications, where reliance is on the use of atmospheric oxygen. Molten carbonate and phosphoric acid fuel cells use hot corrosive liquid electrolytes and are best applied to stationary units using impure hydrogen as the fuel. Therefore, the first three “types” of fuel cells will not be given further consideration in this report.

The best possibilities for achieving a fuel cell-powered 250 W battery charger appear to be those using PEM and solid oxide fuel cell technologies.

3.2 Polymer Electrolyte Membrane (PEM) Fuel Cells

The first PEM fuel cell, based on a phenol/formaldehyde resin membrane, was invented at General Electric in the late 1950s (6). There are two versions of this technology that have emerged over the last three decades. Development of PEM fuel cells using DuPont’s NAFION membranes began at General Electric and Ballard Industries in the early 1980s. NAFION is a fluoropolymer with chemically bonded sulfonic acid groups. When hydrated, the sulfonic acid groups support ionic conduction via the movement of protons in the polymer. Because water is needed in the conduction process, NAFION membranes cannot operate at temperatures approaching the boiling point of water (actually, below 70 °C). Catalysis of the anodic oxidation of fuels is difficult at these relatively low temperatures. The result is that only pure hydrogen is oxidized efficiently in a NAFION-PEM fuel cell. Methanol can also be oxidized in “direct methanol fuel cells” (DMFCs) but with the loss of approximately 1/3 of the intrinsic energy. If we rule out the use of bottled hydrogen, the most-developed approaches for using NAFION-PEM technology for the present application are the following:

1. Use of pure hydrogen produced on demand by a chemical reaction of a hydride with water.
2. Use of impure hydrogen produced by a thermal decomposition of methanol, followed by purification by the diffusion through a palladium (or Pd alloy) membrane
3. Direct oxidation of methanol in a DMFC fuel cell

3.2.1 Hydride-Fueled Hydrogen Fuel Cell Systems

Regarding possibility (1) above, so far, the most developed technology using NAFION-PEMs with chemical hydrides is that developed by the Millennium Cell Co. (7, 8). This involves passing an alkaline solution of sodium borohydride over a supported ruthenium catalyst. Protonex (9) has reported characteristics of a 30 W system that incorporates

replaceable hydride cartridges. The hydrated “P2” cartridges provide a specific energy of 425 Wh/kg at a cost of \$800 for 3 cartridges. Considered as “fuel,” this is a relatively low specific energy and relatively high cost compared with alternatives using bulk methanol or hydrocarbon fuels. The approach may lend itself better to lower wattages than that required for the present application.

3.2.2 Reformed Methanol Fuel Cell Systems

Regarding possibility (2) in section 3.2, this approach to a 250 W power supply has already been pursued by Idatech (3, 8) and Protonex (3, 9, 10). Protonex’s VALTA M250 system (10) weighs 25 kg (dry) and provides 714 Wh/kg of methanol based on the stated (10) consumption rate of 400 ml/h of 60/40 methanol mix at a 250 W output. While this is less than half of the specific energy of fuel utilization in engines, the projected noise level is 50 dB at 1 m, which far exceeds expectations for engines in the area of silent operation. Under the Office of the Secretary Defense (OSD) Quick Reaction Fund Program administered by the Army Research Office, Protonex has extended its “VALTA” technology to the development of a 250 W battery charger system. Complete prototype systems are already undergoing evaluation (April 2008). The Protonex and Idatech systems use a Pd membrane filter to prevent PEM catalyst poisoning by the ~1% output of carbon monoxide (CO) from the reformation process. Field evaluations of the prototype systems will allow determination of whether issues of system complexity have been adequately overcome.

3.2.3 Direct Methanol Fuel Cell Systems

Regarding possibility (3) from section 3.2, this would be based on DMFC technology that has been developed in the United States and Germany. In the United States, the DMFC technology has received funding from the Defense Advanced Research Projects Agency (DARPA), the Army, and other U.S. Government agencies over the last decade. Army programs have usually been oriented toward Soldier applications requiring only tens of watts. DMFCs based on NAFION use membrane/electrode assemblies (MEAs) with anode designs and a different (i.e., platinum /ruthenium (Pt/Ru)) alloy in place of a carbon-supported platinum) anodic electrocatalyst that is better suited to use with the liquid methanol/water mixtures than those suitable to use with gaseous hydrogen. MEA life and reliability may be poorer than when hydrogen is the fuel, but may be acceptable for lower power applications. NAFION-DMFCs designed for power levels in the range of 50 W or less have been found to provide specific energies in the range of 1200 Wh/kg based on the weight of fuel only. For higher wattages, including the present 250 W application, thermal and water management may present a serious problem. This is the result of the relatively high overvoltages experienced at both the anode and cathode, together with ohmic contributions, resulting in an energy conversion efficiency of approximately one-third in a cell that must be maintained at

temperatures of less than 80 °C. For this reason, and based on its unproven service life, the NAFION-PEM DMFC does not appear to be a preferred approach to achieving a 250 W battery charger where system weight is an important consideration.

3.2.4 Hydrogen Fuel Cell Systems using a Polybenzimidazole (PBI) Membrane

Phosphoric acid fuel cells were mentioned previously and eliminated as possible technology for this application because they use a hot and highly corrosive electrolyte. Three decades ago, Prof. Wainright and co-workers at Case Western Reserve University introduced a variation of phosphoric acid fuel cells that involved a gel made with phosphoric acid and the polymer PBI. (10). Operating at 170 °C, this type of fuel cell was tolerant of impurities that could be encountered when using impure hydrogen as the fuel, but was still subject to corrosion problems because of the imperfect immobilization of the phosphoric acid electrolyte. More recently, scientists at Rensselaer Polytechnic Institute (RPI) have developed an improved version of the PBI membrane using a sol-gel process that reportedly provides long service with little or no electrolyte leaching. RPI's original industrial partners were the Plug Power Co. and PEMEAS Fuel Cell Technology. RPI's technology is incorporated in the Ultracell Co.'s "XX25 Micro-Fuel Cell" developed for CERDEC (11). While the specific energy for a 72-h mission based on the weight of the entire system including fuel has been reported at the modest level of 375 Wh/kg (3, 11), the specific energy based on the weight of the methanol/water mixture has been reported as 755 Wh/kg (12). That value could serve as a guide for what may be achieved for fuel use in a scaled up version. The electrocatalysts at both the anode and cathode are much more tolerant of impurities than are the corresponding electrocatalysts in the NAFION-based systems discussed in section 3.2.1. This would tend to eliminate anticipated problems related to methanol-based impurities and the effect of poisons (e.g., CO and hydrocarbons) in battlefield air. Hence, this could be good choice of technology for scale up for the present application, but near-term availability of a militarized 250 W version is not anticipated.

3.3 Solid Oxide Fuel Cells (SOFC)

SOFC technology offers, in principle, the best possibility for using JP-8 in an electrochemical power source that is relatively quiet, vibration-free, and fuel-efficient. Research on SOFCs began at General Electric and Westinghouse in the early 1960s. U.S. Government support of that technology has been largely through the Department of Energy (for large stationary systems) and more recently through DARPA and certain DoD agencies. SOFCs are based on the use of yttria-stabilized zirconia as the electrolyte. Primarily because of the low ionic conductivity of that electrolyte at lower temperatures, SOFCs operate in the 800–1000 °C temperature range, which means using carbonaceous fuels is a greater possibility. However, SOFCs have a problem creating a cell structure that bonds the dissimilar ceramic materials that must be used for the catalyzed anode, cathode, and electrolyte of the individual cell and has a composite structure that can survive many heating

and cooling cycles. The latter problem is severe for a small power, portable application such as is being considered here. It is less severe for stationary applications where the SOFC system may be kept hot and running indefinitely once put into operation.

Much has been accomplished during the last decade toward achieving the goal of lower power, portable SOFCs, particularly in the areas of improved electrode materials and new (e.g., tubular) cell designs. Highly relevant to the present application is a contract recently awarded by the Office of Naval Research (ONR) to Protonex. Protonex recently acquired Mesoscopic Devices, a developer of its SOFC technology. Protonex is planning, this year, to commercialize a 75 W SOFC system that can operate on propane. The contract with ONR has as its goal precisely a solution to the needs of the present application (i.e., a 250 W battery charger that is fueled by JP-8). The key to success in this program is, reportedly, the development of a tubular cell structure that will use an anode, cathode, and electrolyte based on a new perovskite ceramic oxide-conducting material. Use of a similar material for the entire cell structure is expected to overcome the problems accompanying thermal cycling and the use of the perovskite anode is expected to allow the use of JP-8 without prior desulfurization. Protonex projects a system with a dry weight of 6 kg, providing almost 3000 Wh/kg of JP-8 and the capability to survive hundreds of thermal cycles. With additional significant Army funding, the Protonex program may result in a laboratory prototype system within several years.

Another encouraging result, which may eventually simplify the development of JP-8-fueled SOFCs, has been reported by Cell-Tech Power. Cell-Tech has developed a liquid tin anode that may eliminate the need for both reformation of the JP-8 hydrocarbons (to a mixture of easily oxidized hydrogen and carbon monoxide) and removal of the organosulfides that would otherwise attack the cell current collectors. The Cell-Tech effort has been funded by DARPA, the Natick Soldier Research Development and Engineering Center (NSRDEC), and CERDEC and also features a tubular design that is especially suitable for lower power cells. An obstacle still to be overcome at Cell-Tech is the low power density (about one-third) compared to more conventional SOFC formulations.

In spite of the promising advances in recent years, the successful development of a militarized SOFC for a battery charger does not seem likely in the next several years. It may be noted that Nanodynamics and Adaptive Materials, Inc., is also pursuing propane-fueled SOFC systems, and Nanodynamics has recently initiated testing of a 50 W system on “clean” (zero-sulfur) synthetic diesel and has proposed a path forward to the 250 W level.

4. Thermophotovoltaics (TPV)

A complete TPV system typically includes five component sections:

1. *Heat source* – This can include the combustion of any hydrocarbon fuel, including JP-8 in a burner.
2. *Emitter* – This focuses the heat into the infrared spectrum, which the TPV cell is optimized to convert with best efficiency.
3. *Filter* – This is placed between the emitter and TPV cell and serves to reflect any non-utilizable energy back into the source, resulting in increased efficiency.
4. *TPV cell* – This converts the infrared spectrum energy into electricity, using the same principles as a standard solar cell with visible light spectrum energy. Common cell materials include silicon (Si) or gallium antimonide (GaSb).
5. *Electronic interfaces* – This is circuitry for storing the energy in batteries or directing it to a load, and controlling systems to allow for selection between these options.

Army interest in TPV began in the early 1960s at Fort Monmouth, NJ (13). Kittle and Guazone (13) created the first documented prototypes, with efficiencies below 1%. In the 1970s and 1980s, efficiencies were increased from efforts at the Electric Power Research Institute in Palo Alto, CA, and the Gas Research Institute in Chicago, IL. Results were still well below the 10–15% required for useful conversion devices. The increases came through the use of selective emitters (rare-earth oxides), alternative converters (Si, GaSb, indium gallium arsenide (InGaAs)). In the last 10 years, additional technologies in selective filtering using photonic bandgap materials have helped increase system efficiency by returning low energy photons back to the emitter. The Army Research Office sponsored research on TPV at Auburn University in the late 1990s (14). Results of that program were discouraging relative to obtaining practical system efficiencies for Army applications.

Prototype TPV systems have generally provided <15% fuel to electricity efficiency, resulting in a very large thermal signature. TPV becomes more attractive when the unconverted heat can be used for other purposes (e.g., heating living space). This is accomplished in a commercial system manufactured by Jx Crystals, Inc., to provide heating and low power for maritime applications. Research to improve the efficiency of TPV systems is ongoing, but TPV does not appear to be an acceptable option for the current application in the near future.

5. Thermoelectrics

The thermoelectric (TE) effect was originally discovered by German physicist Thomas Seebeck in 1821 when he noted that a metal bar created and maintained a potential difference between its two ends when a temperature difference was applied across it. As a result, the Seebeck coefficient became a measure of how much voltage is produced for a unit temperature difference of 1 °C. In 1834, John Peltier discovered that the reverse is also true, where a flowing current in a metal or semiconductor creates a temperature gradient across the material. These two effects have been widely utilized over the past ~200 years to make a variety of devices for either power generation or cooling applications. Such direct energy conversion exhibits high reliability (no moving parts), silent operation, and compatibility with a variety of heat sources/sinks—including potential JP-8 burners.

Thermoelectric generators are subject to both Carnot cycle and materials limitations. Thermoelectric materials are typically evaluated by their Figure-of-Merit (ZT), which measures how efficiently thermal energy is transferred into electrical energy at a particular temperature. In practice, a high ZT is achieved by maximizing the Seebeck coefficient and electrical conductivity, while simultaneously suppressing the thermal conductivity (thereby forcing heat to preferentially conduct from hot to cold using electrons/holes rather than phonons). By the 1950s, materials with $ZT=1$ demonstrated ~5% efficient heat conversion; however, the performance of bulk materials essentially stalled around $ZT=1$ until the last 20 years or so.

With the advent of microfabrication and thin film technology, TE material research has vaulted beyond the $ZT=1$ threshold using numerous micro- and nano-structuring techniques. At the forefront of this research, Venkatasubramanian (15) at RTI International has reported $ZT>2.4$ using bismuth telluride (Bi_2Te_3)-based superlattice structures to reduce thermal conductivity while maintaining high electrical conductivity. Modules fabricated with this technology have produced ~15 W at $\Delta T=160$ °C, delivering 6% of input thermal power to an electrical load. When these thin films are coupled with bulk technology for higher temperatures (so-called segmented devices), efficiencies of ~15% have been demonstrated in a laboratory setting ($\Delta T\sim 700$ °C).

The most efficient materials, thin film Bi_2Te_3 and lead telluride (PbTe)-based superlattices, can be expensive to manufacture and difficult to package. Hybrid systems combining thin film and bulk technologies offer the most promise in the near future, but system level concerns regarding thermal management of large ΔT 's must be addressed further to produce a militarized system.

Some companies currently offer TE modules. RTI International (team led by Dr. Rama Venkatasubramanian) has demonstrated a 15 W TE and a lower power burner/TE combination to CERDEC. They reported a power density greater than 50 W/cm^3 and a specific power of 100 W/g (based on the weight of the thermocouple) at the Power Micro-Electro-Mechanical Systems (MEMS) 2006 conference. Much work needs to be done in thermal management, burners, and module integration before a militarized system can be realized. Due to these issues, this technology does not look promising for a 2010 delivery but might be available within the next five years.

Global Thermoelectric is currently producing commercial systems that are designed for continuous use in very hostile environments. They operate on butane, propane, natural gas, or diesel fuel and are designed for remote areas that require power. Since they are so ruggedly designed, they are too large and heavy for this application. The 60 W, 24 V system weighs 45 kg and a 500 W, 24 V system weighs 182 kg. This company does have an engineering group and can do custom work, so they might be capable of reducing the size and weight of these systems. Also, Teledyne Energy Systems (TES) developed and built 32 prototype systems for CERDEC in the mid-1980s. These were 120 W 28 VDC nominal systems that were very close to being “fieldable;” the system dry weight was 18 kg.

6. Summary

- The nearest-term possibility for achieving the goal of a 250 W battery charger fueled by JP-8 with reasonable weight and reliability requires using an engine as the primary power source. Achievement of a militarized version of such a battery charger by the summer of 2010 seems doubtful.
- If “containerized” gasoline can be considered as the fuel for the present application, the Honda 1000i is the most conservative choice for short-term possibility for realizing a reasonable system dry weight, low fuel weight (corresponding to a fuel specific energy of $\sim 2300 \text{ Wh/kg}$), reasonably long service life ($>100 \text{ h}$), relatively low noise ($<60 \text{ dB}$ at 7 m), reliable manufacturing base, and low cost. While its AC power level is more than adequate to power an external AC to DC battery charger, “militarization” of this commercially available unit might include modification of the present built-in DC circuit to increase its power level, thus avoiding external AC to DC conversion and corresponding weight savings. Also, it is possible that integration of the fuel line with a JP-8 fuel reformer may be accomplished within several years of accelerated R&D, with a fallback to the present gasoline usage.

- A second possibility for near-term realization of a suitable engine for prime power is the development of a 4-stroke diesel engine through an accelerated R&D effort. Recent advances in fuel atomization and bearing technology could result in a system with moderate noise (<70 dB at 7m) and light weight. Reliability and service life may be issues. Other types (e.g., linear engines) might also be considered. Based on past experience, a militarized system of this type would not be achieved within 2.5 years.
- A third possibility for realization of a suitable engine for prime power is development of a small Stirling engine. A Stirling engine could be expected to operate on JP-8 fuel, and provide the longest service life and lowest noise levels. However, the system dry weight can be expected to remain high and the specific energy (based on fuel consumption) can be expected to remain low (less than ~1500 Wh/kg), compared with the Honda 1000i gasoline engine, well past the summer of 2010.
- Past the year 2010, a TE generator could provide a good combination of JP-8-fueling with low noise, good reliability and service life, and reasonable weight. Fuel efficiency would have to be increased to ~10% compared with the present ~5% level. With 90% of the available fuel energy exhausted as heat, the thermal signature would still be large.
- Use of a SOFC for prime power holds the most promise for providing near-silent operation and high fuel utilization of JP-8; however, it does not appear likely that the reliability, robustness, and high weight issues can be overcome in the short term.
- If using JP-8 as the fuel is dropped as a key requirement, fuel cells that operate at relatively low internal temperatures may be considered for the primary source. They offer the possibility of near-silent operation and long service life. Presently, the most advanced technology for this purpose appears to be a methanol-fueled system that converts methanol to hydrogen, purifies the hydrogen, and uses a NAFION/PEM membrane for the electrolyte. Specific energy based on the weight of methanol/water fuel mixture can be expected to be less than 1000 Wh/kg (or <1/4 that of a gasoline engine) based on present technology. Field testing of prototype systems (Protonex) in the near future may be expected to reveal whether issues of life, reliability, and resistance to contamination have been adequately addressed.
- If methanol is accepted as the fuel, an alternative to the Protonex system mentioned previously is one using reformed methanol and a PBI membrane. This offers the advantage of not requiring a Pd diffusion membrane, and the likelihood of greater simplicity and resistance to contamination by atmospheric impurities than the Protonex NAFION-based fuel cell system. However, development of such a system has proceeded to only the 25 W level (at Ultracell); hence, a militarized version of this technology for the present application would probably require longer than 2.5 years for achievement.

- TPV energy conversion offers the possibility for using JP-8 as the fuel and providing near-silent operation; however, the problems of very low fuel utilization efficiency and corresponding high heat signature preclude its consideration at this time. Promising new materials are appearing for this purpose and could result in success in the long term.
-

7. Conclusions

This report explored several candidate technologies for a 250 W charger system. Only two possibilities appear likely for pre-production “militarized” systems by the summer of 2010, and neither meets the “JP-8-fueled” requirement. The first possibility is the commercially available Honda 1000i gasoline engine, which might be modified somewhat for suitability for this application. The second possibility is the methanol-fueled system now being constructed for this precise application, which could be available as a militarized pre-production prototype by the summer of 2010 if evaluations scheduled for the next few months provide positive results. The methanol/water mixtures required for this latter system present a lower hazard than gasoline; however, the energy density based on the fuel will remain low. Past 2010, a number of possibilities exist for a system utilizing JP-8 as the fuel. Heat engines are likely to succeed first, followed by fuel cells and TE generators.

It is unlikely that any one primary source will combine all of the desired physical, performance, and economic characteristics for this application. The user’s priorities for those characteristics would be extremely useful in planning future R&D programs.

8. References

1. Honda Power Equipment. <http://www.hondapowerequipment.com/> (accessed May 2008).
2. D-STAR Engineering. <http://www.dstarengineering.com/> (accessed May 2008).
3. ARO Workshop on Soldier Power Systems, University of Maryland, February 20–21, 2008.
4. Cawthorne, W. R.; Famouri, P.; Chen, J.; Clark, N. N.; McDaniel, T. I.; Atkinson, R. J.; Nandkumar, S.; Atkinson, C. M.; Petreanu, S. Development of a Linear Alternator–Engine for Hybrid Electric Vehicle Applications. *IEEE Transactions on Vehicular Technology* **November 1999**, 48, 6.
5. Targoff, J.; Chertok, J.; Mc Taggart, P.; Owens, P.; Carobne, P. 250-3000 Watt Suilent Clean Power with TIAX Free Piston Stirling Engine McroPower Platform. *Proceedings of the 42nd Power Sources Conference*, June 12–14, 2006, p 539.
6. Grubb, W. T.; Niedrach, L. W. *J. Electrochem. Soc.* **1960**, 107, 131.
7. Conti, J. P. Recharging. *IET Power Engineer* **August/September 2006**, 39.
8. Millennium Cell. <http://www.millenniumcell.com/>(accessed May 2008)
9. Osenar, P.; Humiston, J. Advancements in Chemical Hydride-Based Fuel Cell Systems for Portable Military Applications. *Proceedings of the 42nd Power Sources Conference*, June 2006, p 408.
10. Wainright, J. S.; Wang, J. T.; Wang, D.; Savonell, R. F.; Litt, M. Acid Doped Polybenzimidazoles: A New Polymer Electrolyte. *J. Electrochem Soc.* **1995**, 142 (7), 121–123.
11. UltraCell. <http://www.ultracellpower.com> (accessed May 2008).
10. IdaTech. <http://www.idatech.com/> (accessed May 2008).
11. Protonex. <http://www.protonex.com/> (accessed May 2008).
12. Fuel Cell Markets.
http://www.fuelcellmarkets.com/fuel_cell_markets/products_and_services/2,1,1,17.html
(accessed May 2008).
13. Herschakowski; Kittl, E. Design considerations for a photovoltaic conversion system using concentrators. *Proceedings of the 15th Annual Power Sources Conference*, May 9–11 1961, pp 120–122

14. Adair, P. L.; Chen, Z.; Rose, F. TPV Power Generation prototype using composite selective emitters. *Third NREL Conference on Thermophotovoltaic Generation of Electricity*, Colorado Springs, CO, May 1997.
15. Venkatasubramanian, R; Siivola, E.; Colpitts, T.; et al. Thin-film thermoelectric devices with high room-temperature figures of merit. *NATURE* **2001**, *413* (6856), 597–602.

Acronyms

APUs	auxiliary power units
ARL	U.S. Army Research Laboratory
Bi ₂ Te ₃	bismuth telluride
Cd	cadmium
CECOM	Communications Electronics Command
CERDEC	Communications-Electronics Research Development and Engineering Center
DARPA	Defense Advanced Research Projects Agency
DMFCs	direct methanol fuel cells
DoD	Department of Defense
FPSE	free piston Stirling engine
GaSb	gallium antimonide
InGaAs	indium gallium arsenide
Li	lithium
Li/MnO ₂	lithium-manganese dioxide
MEAs	membrane/electrode assemblies
MEMS	Micro Electro-Mechanical Systems
Mg	magnesium
MnO ₂	manganese dioxide
Ni	nickel
NSRDEC	Natick Soldier Research Development and Engineering Center
ONR	Office of Naval Research
OSD	Office of the Secretary Defense
PBI	polybenzimidazole
PbTe	lead telluride

Pd	palladium
PEM	polymer electrolyte membrane
Pt	platinum
R&D	research and development
RDECOM	Research Development and Engineering Command
RPI	Rensselaer Polytechnic Institute
Ru	ruthenium
Si	silicon
SO ₂	sulfur dioxide
SOFC	solid oxide fuel cell
TE	thermoelectric
TES	Teledyne Energy Systems
TPV	thermophotovoltaics
ZT	Figure-of-Merit

NO. OF COPIES	ORGANIZATION	NO. OF COPIES	ORGANIZATION
1 ELEC	ADMNSTR DEFNS TECHL INFO CTR ATTN DTIC OCP 8725 JOHN J KINGMAN RD STE 0944 FT BELVOIR VA 22060-6218	1	US GOVERNMENT PRINT OFF DEPOSITORY RECEIVING SECTION ATTN MAIL STOP IDAD J TATE 732 NORTH CAPITOL ST NW WASHINGTON DC 20402
1	DARPA ATTN IXO S WELBY 3701 N FAIRFAX DR ARLINGTON VA 22203-1714	1	US ARMY RSRCH LAB ATTN AMSRD ARL CI OK TP TECHL LIB T LANDFRIED BLDG 4600 ABERDEEN PROVING GROUND MD 21005-5066
1 CD	OFC OF THE SECY OF DEFNS ATTN ODDRE (R&AT) THE PENTAGON WASHINGTON DC 20301-3080	1	DIRECTOR US ARMY RSRCH LAB ATTN AMSRD ARL RO EV W D BACH PO BOX 12211 RESEARCH TRIANGLE PARK NC 27709
1	US ARMY RSRCH DEV AND ENGRG CMND ARMAMENT RSRCH DEV AND ENGRG CTR ARMAMENT ENGRG AND TECHNLGY CTR ATTN AMSRD AAR AEF T J MATTS BLDG 305 ABERDEEN PROVING GROUND MD 21005-5001	8	US ARMY RSRCH LAB ATTN AMSRD ARL CI OK PE TECHL PUB ATTN AMSRD ARL CI OK TL TECHL LIB ATTN AMSRD ARL SE D S GILMAN ATTN AMSRD ARL SE D C D CHU ATTN AMSRD ARL SE DP B GEIL ATTN AMSRD ARL SE D B MORGAN ATTN AMSRD ARL SE DE T PODLESAK ATTN IMNE ALC IMS MAIL & RECORDS MGMT ADELPHI MD 20783-1197
1	PM TIMS, PROFILER (MMS-P) AN/TMQ-52 ATTN B GRIFFIES BUILDING 563 FT MONMOUTH NJ 07703		
1	US ARMY INFO SYS ENGRG CMND ATTN AMSEL IE TD F JENIA FT HUACHUCA AZ 85613-5300		
1	COMMANDER US ARMY RDECOM ATTN AMSRD AMR W C MCCORKLE 5400 FOWLER RD REDSTONE ARSENAL AL 35898-5000		
			TOTAL: 18 (1 ELEC, 1 CD, 16 HCS)