Diesel Fuel-to-Electric Energy Conversion Using Compact, Portable, Stirling Engine-Based Systems

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Abstract

U.S. soldiers in the field require a reliable and efficient logistics supply chain to deliver critical materials including ammunition, spare parts, fuel, and, ever increasingly, batteries. Batteries presently serve as the predominant power source in soldier-portable devices. Hundreds of thousands of batteries of various types must be delivered to, and removed from, the field each month. This represents an enormous financial and logistics burden for the U.S. military.

The DARPA Palm Power program challenged developers to deliver viable battery alternatives which convert the widely-available, energy-dense liquid fuel, JP8 (military diesel) into usable electric power. The team including Sunpower, Inc., Yale University and Precision Combustion, Inc. (PCI) have developed a wearable, JP8-fueled, 35 W_e free-piston Stirling engine (FPSE)-based soldier power source with funding support from DARPA Palm Power. The unit exhibits 21% gross fuel-to-electric conversion efficiency.

With design optimization, the system will possess a mass of 1.7 kg (excluding fuel tank), net efficiency of 18% and energy density of 870 W-hr/kg, a value one order of magnitude greater than standard military batteries. An integrated system was successfully demonstrated in November 2006.

Sunpower, joined by Radiance Technologies, Auburn University, and Precision Combustion, Inc., is also participating in the development of a JP8-fueled, soldier-portable power source. The nearly-silent system has an output of 130 W_e net (160 W_e gross) electric power to be used by external devices or for recharging batteries. A prototype propane-fueled version of this system, developed by the team under a recent U.S. Army-funded contract, was successfully demonstrated in August 2006. The ongoing follow-on effort will demonstrate a low-mass, JP8-fueled system in Fall 2007.

The paper will describe the details and development status of these two military power source programs. Planned efforts to advance the system performance and ruggedness in preparation for field trials will be discussed.

1. Introduction

1.1 DARPA Palm Power Wearable Power Source

Upon joining the Palm Power program in June 2004, the team of Sunpower, Inc., Yale University, and Precision Combustion, Inc. began the development of a JP8-fueled power source in two phases. In March 2005 at the end of Phase One, the team successfully demonstrated a breadboard version of the system which included all of the functional system components in a non-optimized, non-integrated package. During Phase Two of the program the team developed a compact integrated system which was tested in the laboratory under a subset of representative field conditions in June 2006. Final integration of all system components occurred in September 2006. The final demonstration occurred in November 2006 (Figure 1).

Figure 1 Palm Power system demonstration in November 2006.

The system is composed of the key components shown in Figure 2. The free-piston Stirling engine converts the heat accepted from the JP8 burner into electric output power. A vibration absorber attached to the FPSE eliminates system casing motion caused by the oscillation of internal engine components. The cooling fan forces air through the FPSE heat rejector fins. The cooling air continues flowing past the burner where it mixes with the burner exhaust before exiting the system. A controller supervises the operation of the FPSE, burner and all other system auxiliary components.

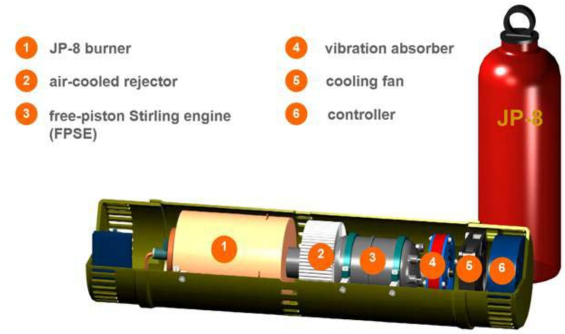

Figure 2 Integrated Palm Power system components

The power source developed by Sunpower, Yale University, and Precision Combustion has already met the primary challenge of the DARPA Palm Power program – conversion of JP8 to electric power in a small system.

1.2 U.S. Army 160 W_e Portable Power Source Based upon the early success demonstrated by the 35 W_e DARPA Palm Power system, the Army funded the development of a net output 130 W_e system to recharge batteries in the field using JP8 fuel. Sunpower, joined by Radiance Technologies, Auburn University, and PCI, began work on the program in March 2005. The system was successfully demonstrated using propane fuel to charge AA batteries in Fall 2006 (Figure 3).

Figure 3 Battery Charger system demonstration

Sunpower provided two non-hermetically sealed 80 W_e FPSE units. PCI developed and delivered two propane burners. Auburn University developed the system controls. Radiance designed and built BOP components and directed the overall integration of the system.

A follow-on effort is currently underway to demonstrate a JP8-fueled version of the system in Fall 2007. The system will contain two hermetically sealed 80 W_e engines and an integrated controller which provides non-dissipative control of the engine/ system output power.

2. Engines

2.1 Background With NASA funding, Sunpower has developed a family of 35 W_e and 80 W_e FPSE units for possible use as a power source during deep space missions. This application requires the FPSE convertor to be efficient, compact, low-mass and reliable with a 14 year projected operating life. In 2004 the EE-35 unit was NASA launch vibration qualified, having operated successfully while subjected to over 20 g's random acceleration. The development of the core EE-35 and EE-80 FPSE designs is now complete.

The FPSE is an external combustion machine whose operation does not fundamentally depend on the type of fuel used to provide heat. In the space application the FPSE unit will efficiently convert heat accepted from a radioisotope heat source into electrical power for use by the spacecraft. However, in a ground-based application the FPSE could also be adapted to accept heat from a variety of sources, including gaseous and liquid fuel burners or solar concentrators.

2.2 EE-35 FPSE Sunpower adapted the proven 35 W_e "EE-35" FPSE design for the DARPA Palm Power application. No changes to the internal components of the engine were necessary. The only changes made were to the external acceptor, external rejector and engine pressure vessel.

The standard EE-35 FPSE has a water-cooled heat rejector. An air-cooled engine heat rejector was designed and applied to the system. A new acceptor was designed specifically to provide optimal coupling with the JP8 burner. (Figure 4).

Figure 4 Hermetically-sealed 35 W_e engine, showing external acceptor and air-cooled rejector

Sunpower has built and tested more than fourteen EE-35 FPSE units with a laboratory pressure vessel. The removable laboratory vessel contains bolted flanges and o-ring seals and was designed to allow flexibility for in-lab testing. The hermetically-sealed pressure vessel features all-welded joints and prevents the loss of the FPSE helium charge gas. The sealed pressure vessel also makes the unit immune to environmental contamination (water, dirt, sand, etc.). The introduction of the hermetically-sealed pressure vessel enabled a reduction of the mass of the FPSE from approximately 1350 g to approximately 650 g.

The peak steady-state electrical power output of the EE-35 engine is 42.5 W_e. Therefore, the current specific power of the hermetically-sealed FPSE is approximately 65 W/kg. With further optimization of the pressure vessel design an engine mass of 440 g is achievable (i.e. engine specific power greater than 90 W/kg).

2.3 EE-80/ ASC-0 FPSE Under the Army Phase I Battery Charger program, Sunpower modified two non-hermetic 80 W_e "EE-80" FPSE units. The basic unit featured bolted flanges, o-ring seals, detachable FLDTs, water cooling and an electrically heated head. The subsequent evolution of the EE-80 design, known as the "Advanced Stirling Convertor" or "ASC-0" unit featured reduced engine mass and was hermetically-sealed. Sunpower has achieved 38% heat-to-electric conversion efficiency with the ASC-0 unit. Under the Army Phase II Battery Charger program, Sunpower adapted two ASC-0 FPSE units (Figure 5) to include an air cooled rejector and engine/ burner interface acceptor.

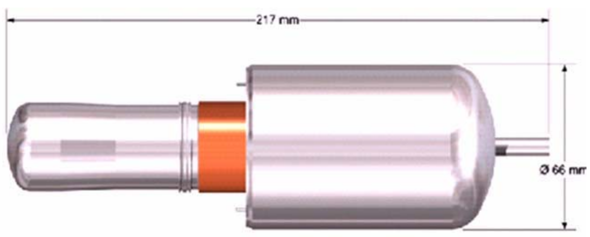

Figure 5 – ASC-0 hermetically-sealed 80 W_e engine

In the Army Battery Charger system, two ASC-0 units will be mounted in an opposed configuration reduce net casing vibration while avoiding the need for additional vibration absorbers (Figure 6).

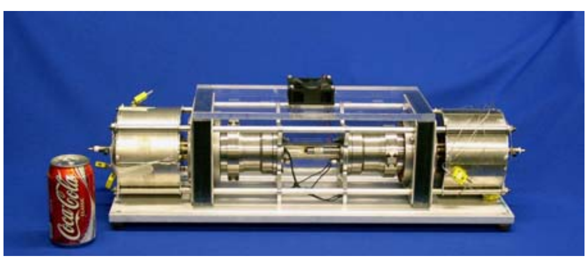
Figure 6 Opposed-configuration engines and burners

3. Controller

The system controller is responsible for performing several functions, including:

(a) Monitoring/ supporting user interface
(b) Monitoring system and load status
(c) Supporting BOP components
(d) Supervising/ controlling engine operation
(e) Supervising/ controlling burner operation

For both power source programs, the original plan was to create an integrated system controller on a single board. However, for development schedule reasons the engine, burner, and balance of plant control approaches were pursued in parallel, resulting in separate engine and system controller boards (Figure 7). The system controller board governs the operation of the burner air and fuel pumps, fuel electrospray, catalyst pre-heater, and engine cooling fan, and it also provides temperature monitoring. The Palm Power system user interface consists of two status LEDs and two small push buttons (ON/OFF). An internal serial port connector allows optional system status monitoring.


Figure 7 Palm Power engine and system controller

The Palm Power system is activated by a single press of the ON button. The controller next energizes the catalyst pre-heater element for approximately three minutes. With the catalyst at the proper temperature for JP8 fuel auto-ignition, the controller next energizes the fuel pump, fuel electrospray, and burner air pump. The engine head temperature rises quickly toward the nominal operating point of 650 °C [1, 2]. Meanwhile, the FPSE has begun to operate and produce electric power.

The basic engine/ burner control strategy is as follows:

(f) Vary engine power output to match load demand
(g) Vary the heat input from the burner to the engine to maintain constant engine acceptor temperature

The electric power produced by the engine is proportional to the square of the piston amplitude. The "non-dissipative" engine controller quickly matches the engine output power to the load requirement by varying the amplitude of the piston. As the engine power output varies, the fuel flow rate into the system is adjusted accordingly. Since the FPSE efficiency is relatively unchanged over a wide range of output power, the non-dissipative controller approach yields the very high overall system efficiencies regardless of load demand.

In contrast, a "dissipative" controller requires the engine to output full power regardless of load power requirements. The dissipative controller discards the excess power produced by the engine as the load demand decreases into a dump resistor. Since the engine is always operating at full power, the fuel flow rate into the system is always at a maximum regardless of load demand. As a result, the system only achieves maximum efficiency at full power output.

The non-dissipative engine controller maintains constant frequency operation of the FPSE. Especially in the case of the Palm Power system constant frequency operation is important to ensure optimum performance from the vibration absorber attached to the engine. The engine controller also provides a constant DC voltage output to the load regardless of load demand. The engine controller has demonstrated 90% efficient operation (input power from FPSE-to-DC voltage output).

All the above engine/ system controller functions have been demonstrated individually by the team within the DARPA Palm Power funded project and separately with single/ opposed 80 W_e FPSE units. The controller components which provide these individual functions are now being refined and integrated into a single "system controller." This system controller will be demonstrated as part of the fully integrated Army Battery Charger system in Summer 2007.

4. System Integration and Performance

4.1 DARPA Palm Power The system package is the structure connecting, surrounding, and protecting the system components. The team planned to integrate the system components with the package in two stages. In the first integration stage the "partially integrated system" included the FPSE, JP8 burner, cooling fan, air-cooled heat rejector, and vibration absorber all within an aluminum tube. JP8 fuel was delivered to the system via a tube connected to the fuel pump and external JP8 fuel tank. The system controller was not located within the package during this stage. In the second integration stage a "fully integrated system" will contain all of the components shown in Figure 1 within a single package. The partially integrated system was successfully demonstrated in March 2006 [3]. The fully integrated system was demonstrated in November 2006.

Brief testing of the partially integrated system has demonstrated successful startup at 0 to 45 °C and operation in ambient temperatures from -19 to +45 °C (reference NATO STANAG 2895). The system has demonstrated multi-fuel capabilities and may be operated using other fuels including propane or butane. The power source is nearly silent with an acoustic signature of 55 dB at 3 meters. The system thermal signature is very low with an exhaust temperature only slightly higher than the temperature of the soldier's body. The power source is "instantly rechargeable" by the addition of JP8 to the fuel tank.

With additional system mass-optimization, the system is projected to achieve a dry mass of 1.7 kg (2.9 kg when fueled for a 72 hour mission), (Figure 8). Table 1 shows the total mass and volume associated with delivery of 35 W_e for 72 hours using the JP8-fueled Palm Power system versus standard military batteries (BA-5590s). The Palm Power system allows an 80% reduction in system mass.

Table 1 Equivalent Energy Basis Comparison

JP-8 Fueled System (wet)	BA-5590 Batteries
2.9 kg (6lb)	15 kg (32lb)
4.2 L (1.1 gal)	13.2 L (3.5 gal)

Figure 8 Mass-optimized Palm Power system

4.2 Army Battery Charger/ Power Source The BOP design and integration of the Phase I and II Battery Charger system was led by Radiance Technologies. The Phase II system shares key features in common with the DARPA Palm Power system:

(a) Engine controller approach
(b) Burner controller approach
(c) JP8 fuel management approach
(d) Engine air-cooling approach

The Phase I Battery Charger system has a mass of approximately 22 kg. The Phase II system has a projected mass of less than 10 kg. A proposed follow-on program for the Phase II Battery Charger program will result in an increased technology readiness level (TRL) without increasing system mass.

7. Conclusions

The systems have demonstrated successful conversion of JP8 fuel into electrical power with 21% gross fuel-to-electric conversion efficiency. The systems are very quiet with low vibration. The systems contains low-mass, recuperated, catalytic, electrospray burners with multi-fuel capabilities. The low-mass, hermetically-sealed FPSE unit is proven and requires no further development work. Possible applications of the units include multi-fuel remote power generation and portable/ wearable power systems.

References

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