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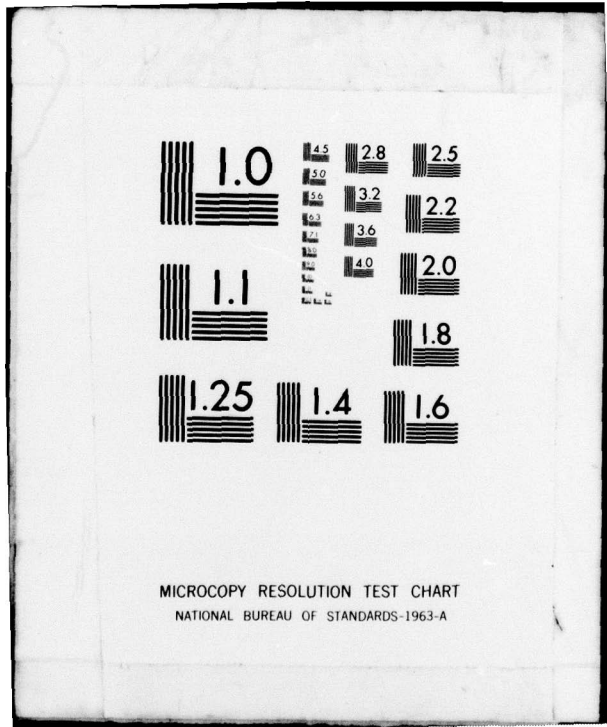
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RESEARCH AND DEVELOPMENT TECHNICAL REPORT

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MILITARIZED THERMOELECTRIC POWER SOURCES

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ELECTRONICS TECHNOLOGY & DEVICES LABORATORY

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MILITARIZED THERMOELECTRIC POWER SOURCES

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ABSTRACT

Thermoelectric power sources are being developed to provide multifuel, silent, maintenance free tactical power generators for forward area applications.

Recent technology improvements, state of development, and performance characteristics of the 100-Watt and 500-Watt Thermoelectric Power Sources are presented.

INVESTIGATIONS CONDUCTED at the US Army Electronics Technology and Devices Laboratory (ERADCOM) on the use of thermoelectric energy conversion for power generation have shown the potential to fabricate power sources covering the range of output power from 50 milliwatts to 1500 watts. Models of lightweight, liquid hydrocarbon fueled thermoelectric power sources have been fabricated in 100 watt, 500 watt, and 1100 watt sizes. The 500-Watt and 100-Watt models are at a more advanced state of development and have been tested extensively. The 500-Watt Thermoelectric Power Source is intended to replace troublesome gasoline engine-driven generator sets which are noisy, unreliable, and require frequent maintenance. The 100-Watt Thermoelectric Power Source is planned to fill a need for small, lightweight, silent energy sources for tactical applications.

The 500-Watt Thermoelectric Power Source has completed feasibility tests to determine its performance reliability for military applications over a wide range of environmental conditions. These tests were conducted under field conditions by soldiers representative of those who will operate and maintain the equipment when it is issued to the Army for field use. The unit successfully powered a variety of communication and electronic equipments demonstrating the feasibility of using a thermoelectric generator as a source of power for military equipment. During these tests some deficiencies were uncovered, namely, improper operation with diesel fuel oil (DF-2), accumulation of carbon in critical parts of the burner system when operated at low temperature (-30°C), and formation of fuel vapor in the fuel line during operation at high ambient temperature (40°C) causing sputtering, flame out, and unstable combustion conditions. These deficiencies compromise the multifuel capability, the low maintenance goal, and the safe operation of the unit.

This paper presents the results of a study conducted to resolve these problems, and describes the means devised to correct deficiencies. A technique for increasing the overall efficiency of the thermoelectric power source, by preheating the primary air for combustion, is also described with test results included.

THERMOELECTRIC POWER SOURCES DESCRIPTION

The configuration of the 500-Watt Thermoelectric Power Source is shown in Figure 1.

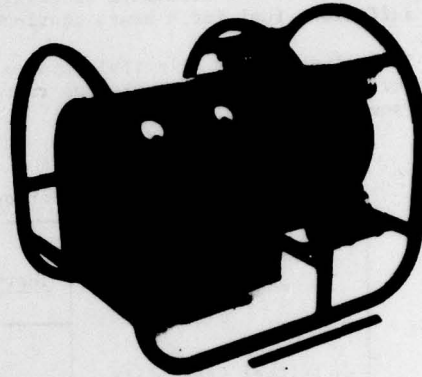


Fig. 1 - 500-Watt Thermoelectric Power Source

The cylindrically shaped thermoelectric converter, which constitutes the heaviest component of the unit, is horizontally mounted to lower the barycenter of the power source for mechanical stability. It is surrounded by the tubular shroud on the right side of the unit. The section on the left encases the cooling fan, fuel pump, and burner tube, which constitutes the initial part of the burner system, and the instrument and control panel. A moisture-proof drawer, on the bottom of the unit, contains the electronic components which are readily accessible for maintenance.

Figure 2 shows the 100-Watt Thermoelectric Power Source in its early development configuration.



Fig. 2 - 100-Watt Thermoelectric Power Source

The supporting structure of this unit is now being ruggedized to withstand rough handling normally associated with field use. Its final configuration will be similar, except for size, to that of the 300-Watt Thermoelectric Power Source. The 100-Watt Thermoelectric Power Source is being designed as a manportable unit to directly power communication-electronic equipment in forward areas and to sustain equipment operation during extended missions. A self-contained fuel tank which comprises the bottom section of the structure is designed to contain sufficient fuel for 8 hours continuous operation.

Table 1 shows the principal physical and performance characteristics of the two thermoelectric power sources.

shell of the converter features a spine-type cooling fin array. The converter is cooled on the outside by forcing ambient air across the heat dissipating fins. The annular region between the combustion chamber and the cold shell contains the thermopile. End bells are welded to both ends of the converter and provide a hermetically-sealed container for the lead-telluride (PbTe) couples. The container is backfilled with argon gas.

The PbTe couples are arranged in 32 rows parallel to the cylindrical axis of the combustion chamber. At the operating hot junction and cold junction temperatures of 565°C and 162°C, respectively, each couple develops a load voltage of 0.11 Vdc. Two hundred fifty six couples, connected in series electrically, produce a nominal 28 Vdc

Table 1 - Physical and Performance Characteristics of Thermoelectric Power Sources

	<u>100 Watt</u> <u>Thermoelectric Power Source</u>	<u>500 Watt</u> <u>Thermoelectric Power Source</u>
<u>Multifuel Capability</u>	Gasoline, Diesel, Kerosene, JP-4, JP-5	
<u>Acoustic Noise</u>	Inaudible beyond 30 m	Inaudible beyond 100 m
<u>Efficiency</u>	370 watthours/kg of fuel (2.8 percent)	400 watthours/kg of fuel (3.0 percent)
<u>Operator Simplicity</u>	Single switch activation (remote or local)	
<u>Voltage Output</u>	28 Vdc nominal (25-32 Vdc range) Regulation \pm 1% (No-Load to Full-Load) Ripple (Peak to Peak) \pm 1%	
<u>MTBF</u>	2000 hours	
<u>Operational Temperature Range</u>	-31.7°C (-25°F) to +51.7°C (+125°F)	
<u>Operational Altitude Range</u>	Sea Level to 1500 m	
<u>Outside Dimensions</u>	37 cm long, 20 cm wide 36 cm high	48 cm long, 63 cm wide 33 cm high
<u>Weight</u>	13 kg (30 pounds)	30 kg (66 pounds)

The same basic functions and subsystems characterize both units. The cross-sectional view of the 300-Watt Thermoelectric Power Source, presented in Figure 3, identifies and locates the major components.

Both units have the same thermoelectric converter configuration (Figure 4) with the combustion chamber constituting an integral part of the converter inside cylindrical structure. The outside

for the system of the 300-Watt Thermoelectric Power Source. (1)* The electrical gross power produced by the thermoelectric converter amounts to 640 watts.

*Numbers in parentheses designate References at end of paper.

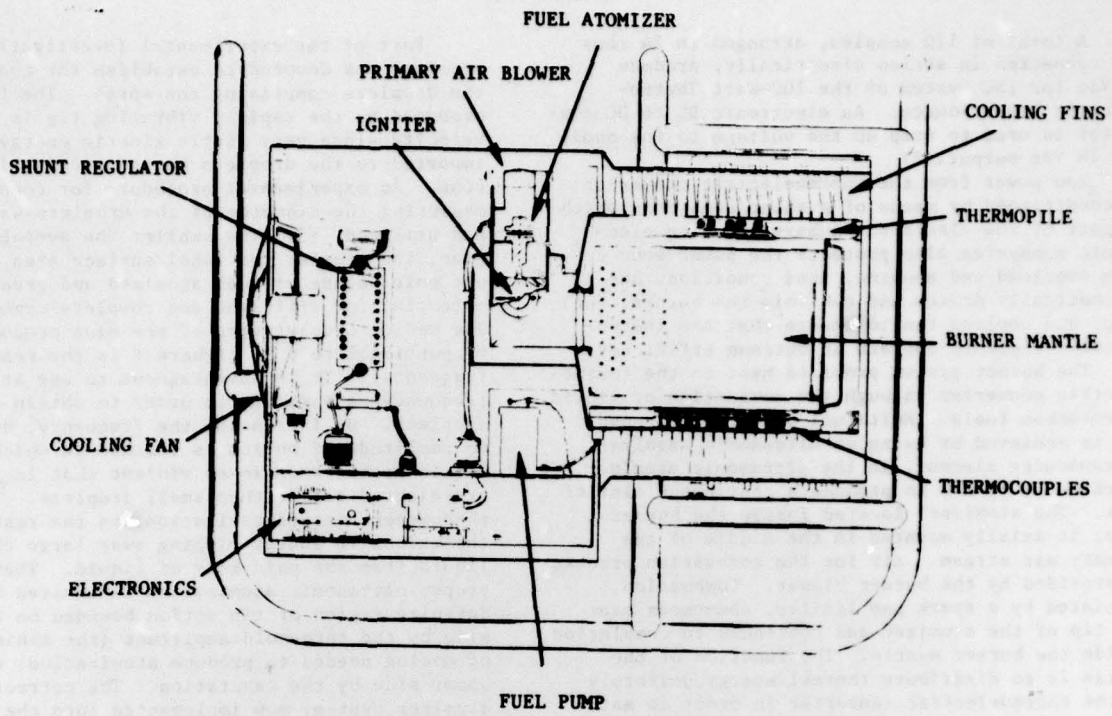
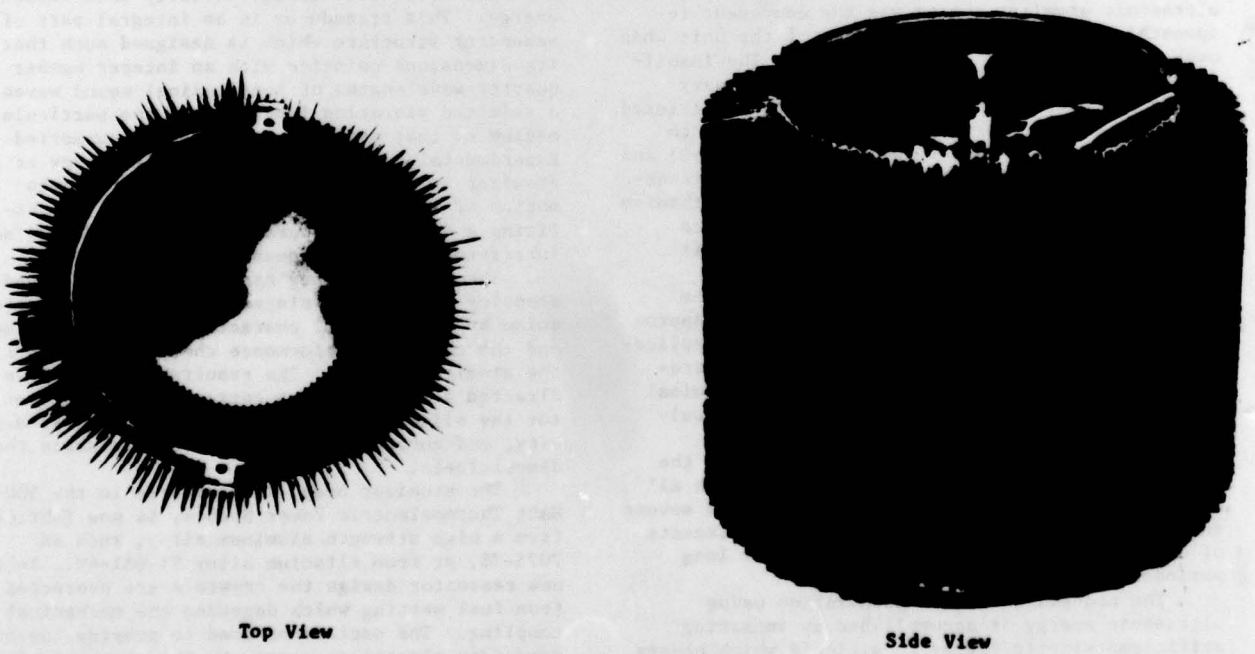


Fig. 3 - Cross-sectional View of the 500-Watt Thermoelectric Power Source



Top View

Side View

Fig. 4 - Thermoelectric Converter

A total of 120 couples, arranged in 24 rows and connected in series electrically, produce 12 Vdc for the system of the 100-Watt Thermoelectric Power Source. An electronic DC to DC converter is used to step up the voltage to the nominal 28 Vdc output. (2)

Raw power from the thermoelectric converter is conditioned by means of a shunt regulator which is part of the electronic subsystem. The electronic subsystem also protects the power source from overload and abnormal load conditions and automatically drives and controls the burner, fuel pump, and cooling fan to ensure that the thermoelectric elements operate at optimum efficiency.

The burner system provides heat to the thermoelectric converter through the combustion of liquid hydrocarbon fuels. Multifuel operational capability is achieved by using an ultrasonic atomizer. A transducer element, in the ultrasonic atomizer, vibrates at 75 kHz to produce a continuous mist of fuel. The atomizer, located inside the burner tube, is axially mounted in the middle of the primary air stream. Air for the combustion process is provided by the burner blower. Combustion, initiated by a spark gap igniter, commences near the tip of the atomizer and continues to completion inside the burner mantle. The function of the mantle is to distribute thermal energy uniformly to the thermoelectric converter in order to maintain uniform hot junction temperature at all of the couples.

DISCUSSION

The analysis of the deficiencies of the 500-Watt Thermoelectric Power Source indicated that the ultrasonic atomizer system was the component responsible for the poor performance of the unit when operated with diesel fuel oil (DF-2). The inability of this system to properly condition heavy liquid hydrocarbon fuels for combustion, restricted operation of the thermoelectric power source to lighter fuels such as jet fuels (JP-4 and JP-5) and gasoline. To correct this problem, a basic investigation was conducted on the atomization mechanism and on the characterization of the performance limits of the atomizer system utilized in this power source.

The use of ultrasonic atomization for the conditioning of liquid fuel is particularly appropriate for the thermoelectric power source application. With this technique, operational requirements of low and variable firing rate and minimal power consumption can be achieved simultaneously more effectively than with any other type of atomization technique. It is necessary that the fuel conditioning device operate readily with all types of liquid hydrocarbon fuels, withstand severe environmental stresses, and meet the requirements of unattended and reliable operation over long periods of time.

The process of liquid atomization using ultrasonic energy is accomplished by imparting sufficient kinetic energy to a liquid which covers a rapidly vibrating metallic surface. The kinetic forces generated by the vibrating surface cause the liquid to break up into minute droplets which are ejected from the surface.

Part of the experimental investigation on the atomizer was devoted to establish the character of the droplets comprising the spray. The fine mist produced by the rapidly vibrating tip is low in velocity since very little kinetic energy is imparted to the droplets by the atomization process. An experimental procedure for counting and measuring the diameter of the droplets was devised and utilized. (3) The smaller the average droplet size, the greater the total surface area exposed per unit volume of fuel atomized and greater the potential for efficient and complete combustion. The median droplet size of the mist produced is proportional to $f^{-2/3}$ (where f is the resonator frequency). It is advantageous to use as high a frequency as possible in order to obtain small droplets. By increasing the frequency, however, an amplitude of motion is reached in which the liquid disturbance is so violent that large drops are ejected rather than small droplets. This phenomenon, termed cavitation, is the result of the excessive energy ripping away large chunks of liquid from the main body of liquid. Therefore, proper ultrasonic atomization is limited to a definite region of tip motion bounded on the lower side by the threshold amplitude (the minimum amount of motion needed to produce atomization) and on the upper side by the cavitation. The corrected atomizer system, now implemented into the 500-Watt Thermoelectric Power Source, operates within these limits.

The motion of the vibrating surface is initiated by an electromechanical transducer (a lead zirconate titanate piezoelectric crystal) which converts electrical energy directly into mechanical energy. This transducer is an integral part of a resonator structure which is designed such that its dimensions coincide with an integer number of quarter-wavelengths of longitudinal sound waves at a selected vibrating frequency in the particular medium so that standing-waves can be supported. Experimental verification of the efficiency of an atomizer in converting electrical energy into motion of the atomizer tip was obtained by utilizing a diagnosis apparatus employing Michelson interferometric techniques.

The atomizer study has provided a good understanding of the role played in the atomizing mechanism by the physical characteristics of the fuel and the complete performance characterization of the atomizer design. The results obtained have directed atomizer design corrections to account for the slightly higher values of viscosity, density, and surface tension which characterize the diesel fuels.

The atomizer body, incorporated in the 500-Watt Thermoelectric Power Source, is now fabricated from a high strength aluminum alloy, such as 7075-T6, or from titanium alloy Ti-6Al-4V. In the new resonator design the crystals are protected from fuel wetting which degrades the mechanical coupling. The oscillator used to provide the high frequency electrical energy to the atomizer was also redesigned to match the electrical and operating characteristics of the atomizer horn, and to minimize the AC input power level required.

Winter testing of the 500-Watt Thermoelectric Power Source equipped with the newly designed atomizer system has demonstrated that operation with DF-2 can be achieved at temperatures down to 0°C. This unit had already successfully performed with DF-1, JP-4, and gasoline, at temperatures down to -31°C. Although the experimental investigation was conducted on an atomizer system sized for the 500-Watt Thermoelectric Power Source, the results are quite general and are being implemented into the system of the 100-Watt Thermoelectric Power Source.

The voltage to the fuel pump is controlled by an electronic circuit which regulates the rate of fuel flow as a function of temperature, output voltage, and current of the thermoelectric converter.

The start-up sequence of the unit utilized in the feasibility tests is designed to provide, during the first few minutes of operation, a rate of fuel well in excess of the normal rate. This minimizes the time required for the system to reach operational readiness. With all fuels, except DF-2, the excess initial flow causes a moderate smoky condition. When starting with DF-2 a degenerative condition can occur. The initial smoke is observed to be very thick and contains a large amount of solid particulate. In several situations (during tests run in low temperature environment), this heavy smoke causes the partial clogging of some of the holes in the mantle creating higher impedance for the combustion gases and air starvation. This critical condition, together with a reduced evaporation rate of the excess fuel mixed with air at low temperature, causes heavy carbon buildup in critical parts of the burner with consequent system failure. A solution to this problem was achieved by an electronic control circuit which reduces the present fuel pump voltage and primary air at startup. The electronic control then gradually increases fuel rate and combustion air as a function of the increasing output voltage level of the thermopile. When the thermopile output voltage reaches a determined value (18 Volts), the normal fuel control takes over. Circuitry employing this basic control concept has been fabricated and successfully tested. The design of this control logic will be optimized to provide the best compromise for an automatic air/fuel ratio control for all the operational fuels. A study is in progress to utilize the same logic control to gradually increase the voltage to the cooling fan during the first few minutes of operation. Because the cooling fan is the auxiliary component requiring the highest power (75 watts), this will reduce the demand from the ancillary power source (usually a battery) used to start the unit.

During feasibility tests run in a high temperature environment (+50°C), and with the fuel container 15-20 feet away from the unit, the performance of the 500-Watt Thermoelectric Power Source was adversely affected by formation of fuel vapor in the fuel line. This vapor causes sputtering, unstable combustion, and occasional flame-out. To correct this problem a vapor separator was devised which vents trapped air bubbles or fuel vapor present in the fuel line. The separator is comprised of a small chamber, inserted between

the fuel pump and the atomizer, in which a float element actuates a vent valve mounted in the top wall of the chamber. During normal operation, the float keeps the valve opening sealed. Accumulation of vapor or air in the chamber causes a displacement of fuel from the upper section of the chamber. The resultant downward movement of the float opens the vent valve exhausting the vapor or air. This separator prevents spilling of fuel from the vent opening, thereby eliminating hazard conditions.

In addition to correction of the deficiencies evidenced by the feasibility tests, means of upgrading the basic subsystems of the 500-Watt Thermoelectric Power Source to improve overall efficiency were investigated. (4) Efficiency improvement is of major significance to the Army for better utilization of fossil fuel in essential combat missions and in support of energy conservation requirements. The combustion products, which leave the unit at 700°C, contain considerable heat at a relatively high temperature. A large percentage of this heat can be recovered through preheating the primary air for combustion. An air-to-air heat exchanger was devised and fabricated for this purpose. The heat exchanger, which is assembled at the exit of the combustion chamber, was designed for minimum size without introducing excessive impedance in the line of primary air for combustion. It has demonstrated the capability of preheating ambient air up to a temperature of 500°C. The output of the air-to-air heat exchanger is channeled to the burner through a duct on the outside of the unit. Since preheated air enters the combustion chamber at an elevated temperature (450°C to 500°C), a considerably lower fuel flow rate is needed to maintain the combustion chamber at the operational temperature required by the thermoelectric converter. Figure 5 shows a heat exchanger, assembled on a 500-Watt Thermoelectric Power Source, with related hardware to recycle the preheated air.

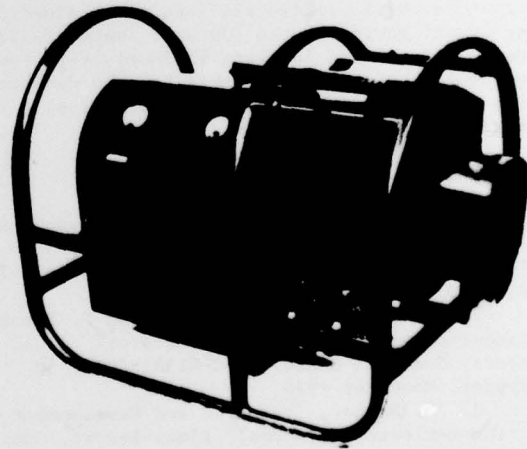


Fig. 5 - 500-Watt Thermoelectric Power Source With Heat Exchanger

This unit has been tested with JP-4, gasoline, and DF-2. Reduction of fuel consumption in the 25-27 percent range, obtained with all the unit's operational fuels, has been demonstrated (5) and is considered significant. The corresponding overall

efficiency has increased 33 to 37 percent. Additional gain in fuel saving is anticipated when heat losses, present in the configuration of this prototype heat exchanger, are eliminated. Tests indicate that other improvements in the operation of the 500-Watt Thermoelectric Power Source are obtained by utilizing the heat exchanger section at the exit of the combustion chamber. The exhaust gas temperature is lowered (from 700°C to 240°C), which significantly reduces the infrared signature detection of the unit, and combustion noise is muffled, which lowers the acoustic noise profile of this power source.

CONCLUSIONS

Development effort on critical subsystems of the 500-Watt Thermoelectric Power Source corrected operational deficiencies evidenced during the feasibility tests. The improved overall performance of this multifuel, silent, low maintenance power source improves its potential as a replacement for troublesome gasoline engine-driven generator sets which are noisy, unreliable, and require frequent maintenance.

The experimental study on the burner system of the thermoelectric power source has demonstrated the practicality of recovering a significant part of the heat exhausted with the combusted gases. Fuel reduction of 25 percent has been demonstrated with corresponding 33 percent increase in overall efficiency. In addition to these improvements in the burner system performance, the utilization of a heat exchanger at the exit of the combustion chamber considerably reduces the unit's infrared signature detection and muffles the combustion noise lowering the acoustic noise profile of this power source.

The 100-Watt Thermoelectric Power Source, now being reconfigured in a ruggedized supporting structure, will utilize the results obtained from the investigation of the 500-Watt Thermoelectric Power Source. The 100-Watt Thermoelectric Power Source technology is available for the development of small lightweight silent energy sources for tactical applications.

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