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RADIOISOTOPE THERMOELECTRIC GENERATOR STUDY

ARMY ELECTRONICS COMMAND
FORT MONMOUTH, NEW JERSEY

OCTOBER 1976

Research and Development Technical Report

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RADIOISOTOPE THERMOELECTRIC GENERATOR STUDY

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Electronics Technology and Devices Laboratory

October 1976

ECOM

US ARMY ELECTRONICS COMMAND FORT MONMOUTH, NEW JERSEY 07703

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A 55 mW, Plutonium-238 Fueled, Radioisotope Thermoelectric Generator was developed and extensively tested for performance evaluation. The utilization of the Radioisotope Thermoelectric Generator in a hybrid configuration with a sealed nickel-cadmium battery was successfully obtained and characterized over a wide range of ambient temperatures. Results have demonstrated that the hybrid configuration is feasible for powering a pulsed load with a 75:1 duty cycle.

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RADIOISOTOPE THERMOELECTRIC GENERATOR STUDY

INTRODUCTION

Power source requirements for worldwide military applications include a need for low level power (milliwatts average power) under conditions of unattended, extended periods of time. The energy content needed in such applications and the requirement for continuous, trouble-free operation led to the investigation of the military potential of radioisotope thermoelectric power sources, with specific interest in a hybrid configuration using a sealed nickel-cadmium battery.

By using the nuclear particle emission energy of radioactive decay, the radioisotope thermoelectric generator (RTG) has the highest stored energy density of any other power source. However, the power output is low being related to the emission half-life of the isotope.[1] Attainment of inherently good device power regulation requires a relatively long life isotope. Plutonium-238 (Pu-238), an 86-year half-life alpha (short range) emitter, has become available in practical quantities. It offers a very low emission hazard and, when properly encapsulated in a sintered oxide fuel form, provides an almost ideal isotopic heat source which is safe to use under all anticipated extremes of heat and shock.

RADIOISOTOPE THERMOELECTRIC GENERATOR DESCRIPTION

A Pu-238 fueled thermoelectric generator, incorporating the state-of-the-art technology of pacemaker power sources, was developed for this investigation by Nuclear Battery Corporation (Contract DAAB07-75-M-4080). This unit, which delivers a constant 55 mW(e) output in a nominal +25°C ambient temperature environment, features a cylindrical configuration (Figure 1) with the following physical characteristics - diameter 2.2 cm, length 7 cm, and weight 135 grams. It can be handled readily from both thermal and radiation standpoints, having a maximum external temperature of 46°C in a 25°C ambient and a surface dose rate of 100 mrem/h.

The energy source of the RTG is a 3.18 gram Pu-238 in the chemical form of plutonium dioxide (PuO_2). The specific sintered, dense pellet employed in this unit has been enriched in the isotope oxygen-16 reducing the (α,n) reactions taking place and thereby giving a lower radiation dose level. The PuO_2 pellet is first contained in a small can fabricated from Hastelloy C-276, a high strength superalloy possessing a melting point of 1300°C. This container, which has a head thickness twice that of the cylindrical wall to equilibrate stresses from the gradual helium buildup attendant with alpha particle decay, is subsequently placed in another superalloy can. It is felt that the use of PuO_2 and its double encapsulation provides an energy source for the RTG which is safe against all credible incidents.

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[1] T. S. Bustard, "Isotope Miniature Power System (IMPS)," Proc. 25th Power Sources Symposium, pp. 114-117 (1972).

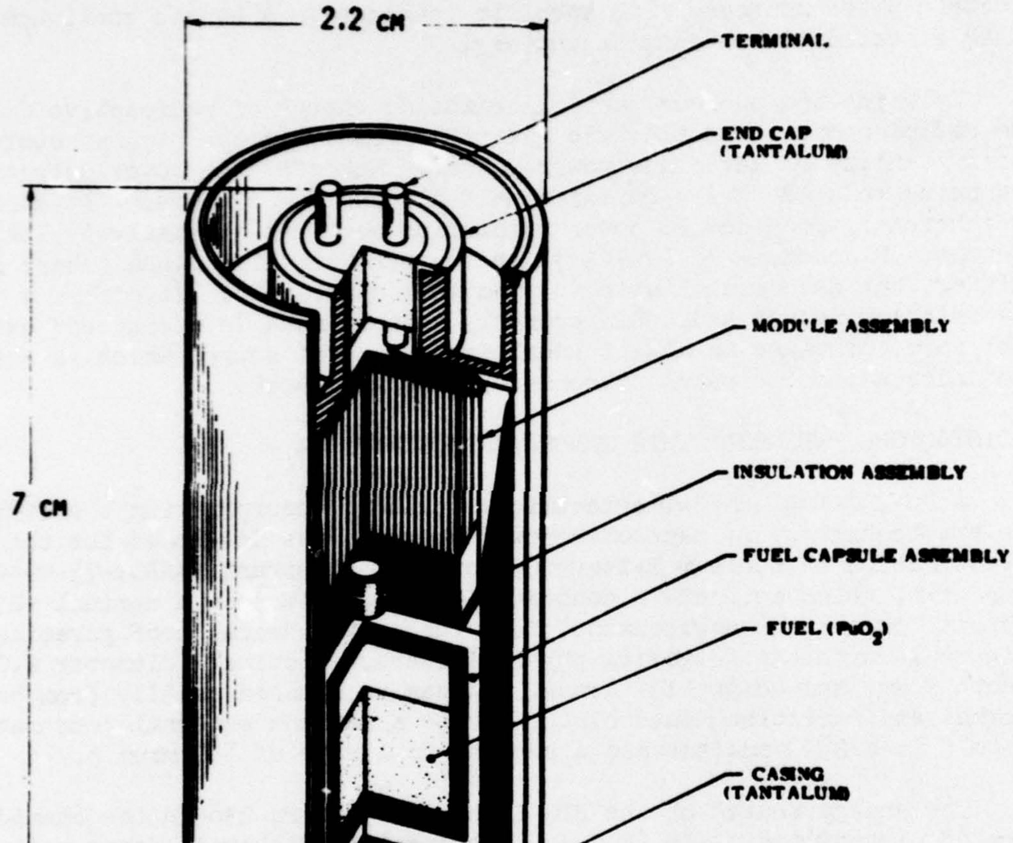

Figure 1. Diagram of Radioisotope Thermoelectric Generator

Should inadvertent fire or burial occur involving the RTG, there would be no hazardous release of plutonium. Further, the source has the capability of withstanding terminal velocity impact or the shock from high-powered bullets.

The energy converter for the RTG is a bismuth telluride type thermopile. The thermopile was originally fabricated with two identical, mechanically separated and electrically paralleled modules. This two-module thermopile was incorporated in the first RTG which was accidentally dropped, from about 8 inches, on a work bench surface. After the drop, no output voltage could be measured. The RTG had been designed in a configuration expected to withstand a 1500 g force shock. An analysis of the drop, using a mock simulator, showed that the RTG could have been subjected to a shock force between 500 to 1200 g, with a 1/2 rise time as short as 0.2 ms in the latter case. Therefore, the defective RTG was returned to Nuclear Battery Corporation where it was established that a crack had occurred in one of the thermoelectric material legs. It was also found that a slight difference existed between the lengths of the two modules. The thermopile is supported, on both hot and cold sides, by two anodized aluminum plates. These plates allow for attaching the energy source to the thermopile and for attaching the thermopile to the casing. The connection between the two plates is made by screw-in studs. The difference in length of the two modules resulted in different mechanical pressure being exerted, by the retaining plates, on the two modules of the thermopile. As a result, the shorter module was not properly secured and mechanically supported, which explained why it could have experienced a rupture even if subjected to a relatively low force shock. A second thermopile, made of only one module, was then fabricated. It consisted of a 14 by 14 array of thermoelectric elements (98 thermocouples), each measuring 508 microns by 584 microns by 1.27 cm in length. The N and P thermoelement electrical connections consist of small metallic strips firmly attached across electrical insulators which physically separate the elements. This thermopile, which has been successfully subjected to a 1500 g force shock test and is considered capable of withstanding mechanical shocks in the 2000-3000 g force range, is incorporated in the actual RTG configuration.

Bismuth telluride has been demonstrated to operate reliably and in a stable manner for very long periods of time at temperatures as high as +240°C (+464°F). Within this specific unit, the maximum temperature operation of this semiconductor material is around +182°C (+360°F) in a 25°C ambient temperature environment. Operating at this level of temperature is favorable for extremely long life for the RTG.

The thermal insulation for the RTG consists of multiple layers of shiny metal foil separated by zirconia spacers. Twenty layers of zirconia coated stainless steel are utilized in an insulating package which, when operated in hard vacuum, exhibits an effective thermal conductivity of an order of magnitude less than the best fibrous insulation available.

The casing material of the RTG is pure tantalum which has a melting point of 3035°C (5495°F). The casing is welded in such a manner so as to insure vacuum integrity and hermetic sealing. The only penetrations in the casing are two small ceramic-to-metal seals which provide the electrical output terminals. The tantalum provides a third, sturdy container barrier against any possible release of Pu-238. Its sole weakness is the electrical header which is recessed to prevent damage in the event of an accident.

RADIOISOTOPE THERMOELECTRIC GENERATOR CHARACTERIZATION

The RTG was subjected to extensive performance characterization in accordance with the method for handling radioactive sources. Digital instrumentation, which measured the background radiation level, was continuously monitored and wipe tests were performed every three months during the entire duration of this investigation. The RTG was locked up in a see-through cabinet, Figure 2, with feed throughs to allow access to power leads and temperature sensors. Three iron-constantan thermocouples were attached to the RTG tantalum case to monitor the surface temperature. A mapping of the steady state electrical characteristics of the unit obtained in a nominal +25°C ambient temperature environment is presented in Figure 3. Under these conditions, the unit produces 32 mA when short circuited and 6.95 volts when open circuited. The maximum power point is 55 mW and is obtained at 3.5 volts and 15.7 mA which corresponds to a load impedance of 220 ohms. The 3.18 gram Pu-238 energy source of the RTG delivers 1.8 thermal watts. Therefore, the RTG efficiency (η), at +25°C ambient temperature, is calculated to be

$$\eta = \frac{55 \text{ mW}}{1.8 \text{ W}} = 3.1\%$$

Figure 4 presents the characterization of the electrical properties of the RTG obtained over an ambient temperature (T_A) range from -43°C (-45°F) (with RTG maximum power output of 73 mW) to +49°C (+121°F) (with RTG maximum power output of 46 mW). At this time of the investigation, the RTG characterization was limited to +49°C ambient temperature, with case temperature of approximately +78°C (+172°F). Configurational and material considerations suggested not to exceed +80°C (+175°F) RTG surface temperature (T_{RTG}) during long operational periods.

HYBRID CONFIGURATION INVESTIGATION

After the RTG performance characterization was completed, this power source was utilized, together with chemical batteries, in a hybrid configuration study. The batteries selected for this mode of operation consisted of sealed quick-charge nickel-cadmium cells (G.E., 1.2 volt, 130 mAh).

The hybrid configuration is required to satisfy the wide range of dynamic loading for a typical unattended sensor application.

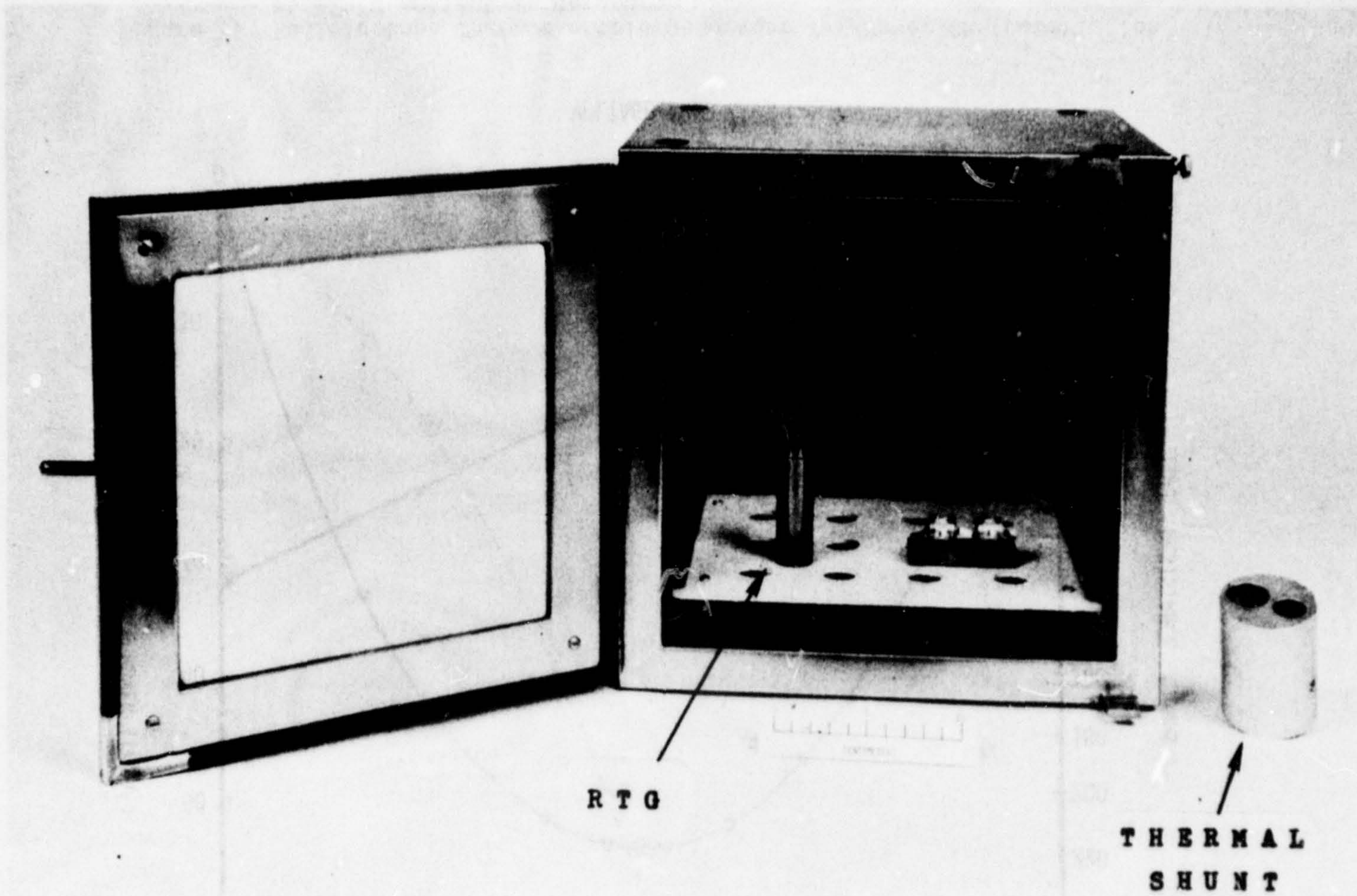

Figure 2. Radioisotope Thermoelectric Generator Inside the See-Through Cabinet

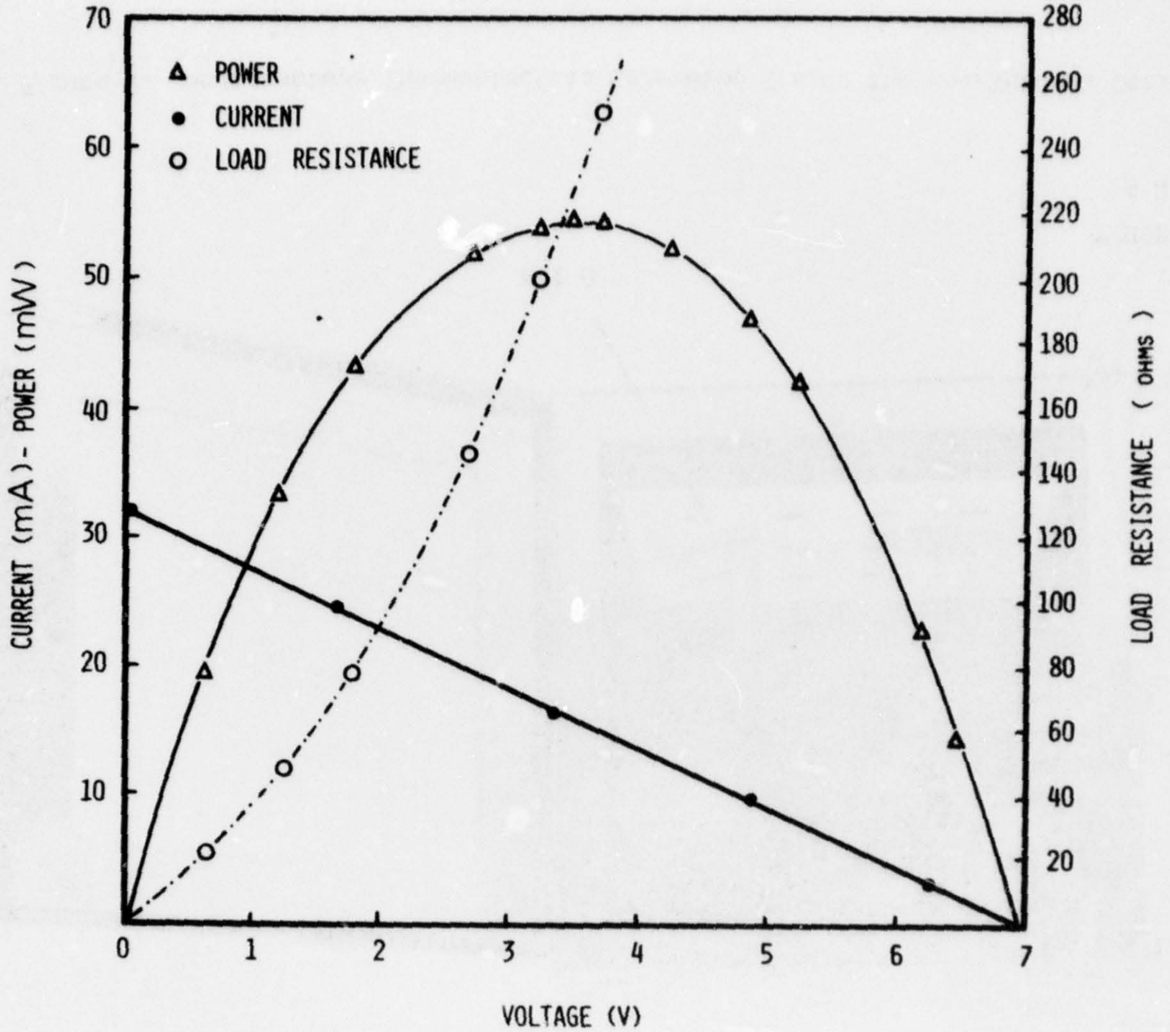

Figure 3. Radioisotope Thermoelectric Generator V-I/Power Characteristics at +25°C Ambient Temperature

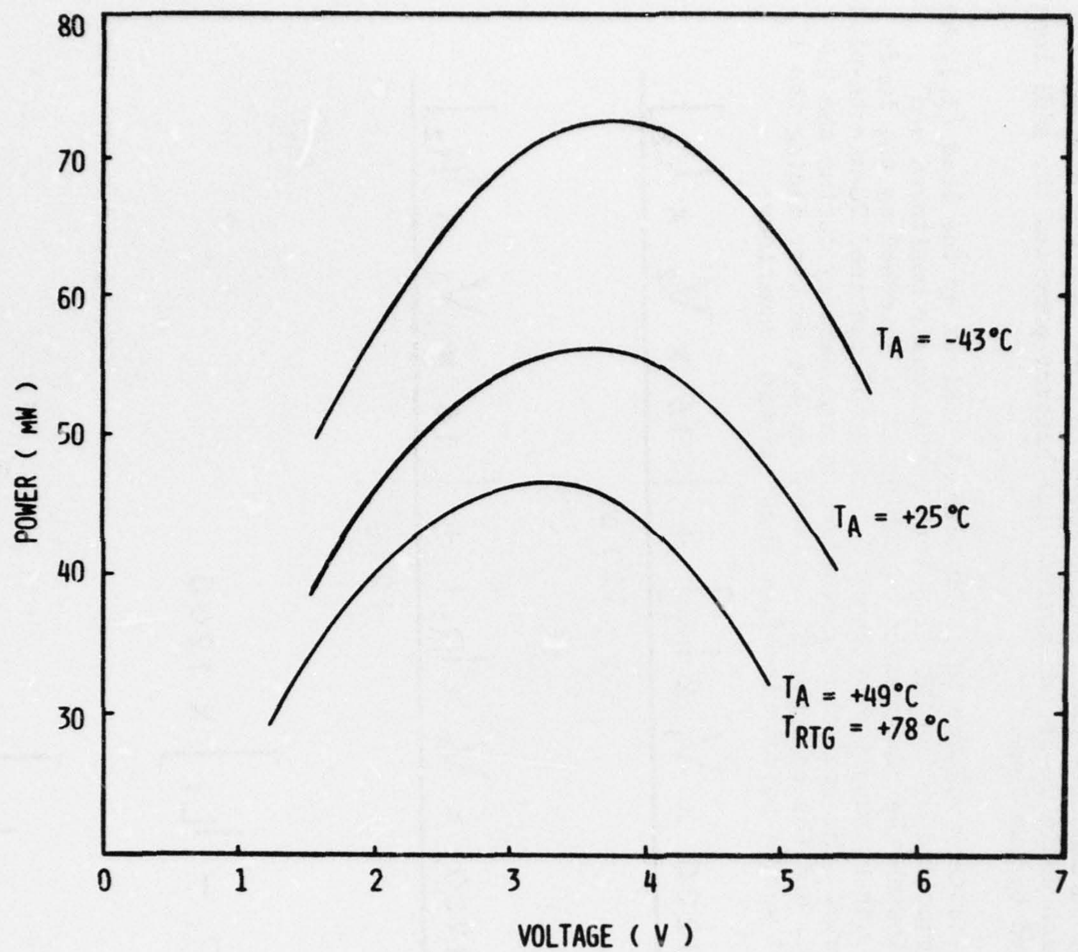

Figure 4. Radioisotope Thermoelectric Generator Voltage-Power Characteristics

A block diagram of the experimental apparatus is shown in Figure 5. Two series connected nickel-cadmium cells were paralleled to the RTG to utilize the RTG at approximately 2.8 volts, 52 mW output, in a +25°C ambient temperature environment. For clarification purposes, two cells connected in series will represent the battery in the hybrid configuration. Superimposed to a constant 280 ohm resistive load (R_c), a second load of approximately 3-4 ohms (R_i) was intermittently connected every twenty minutes for a duration of sixteen seconds. Figure 6 shows the constant load power drain, between 22 and 35 mW, depending on the output voltage of the RTG which ranged from 2.4 volts at +49°C to 3.1 volts at -43°C ambient temperature. The intermittently connected load took between 1.3 and 1.8 watts, with the voltage ranging between 2.3 and 2.5 volts. During the 20-minute period, the RTG supplies power to both load and battery. During the high drain 16-second period, the battery provides the additional power required by the load.

The RTG-battery voltage (V), the current drained by the load (I_L), and the current supplied by the RTG (I_R) were continuously monitored and recorded, allowing the computation of the power P_L absorbed by the loads and of the power P_R supplied by the RTG during the combined 20-minute-plus-16-second cycle. The coulombs C_1 received by the battery during the 20-minute period, and the coulombs C_2 delivered by the battery during the 16-second period were also computed from the following equations:

$$P_L = \frac{[1200 \times V_1 \times I_{L1}] + [16 \times V_2 \times I_{L2}]}{1216}$$

$$P_R = \frac{[1200 \times V_1 \times I_{R1}] + [16 \times V_2 \times I_{R2}]}{1216}$$

$$C_1 = [I_{R1} - I_{L1}] \times 1200$$

$$C_2 = [I_{L2} - I_{R2}] \times 16$$

The subscripts 1 and 2 refer to the 20-minute period and to the 16-second period, respectively.

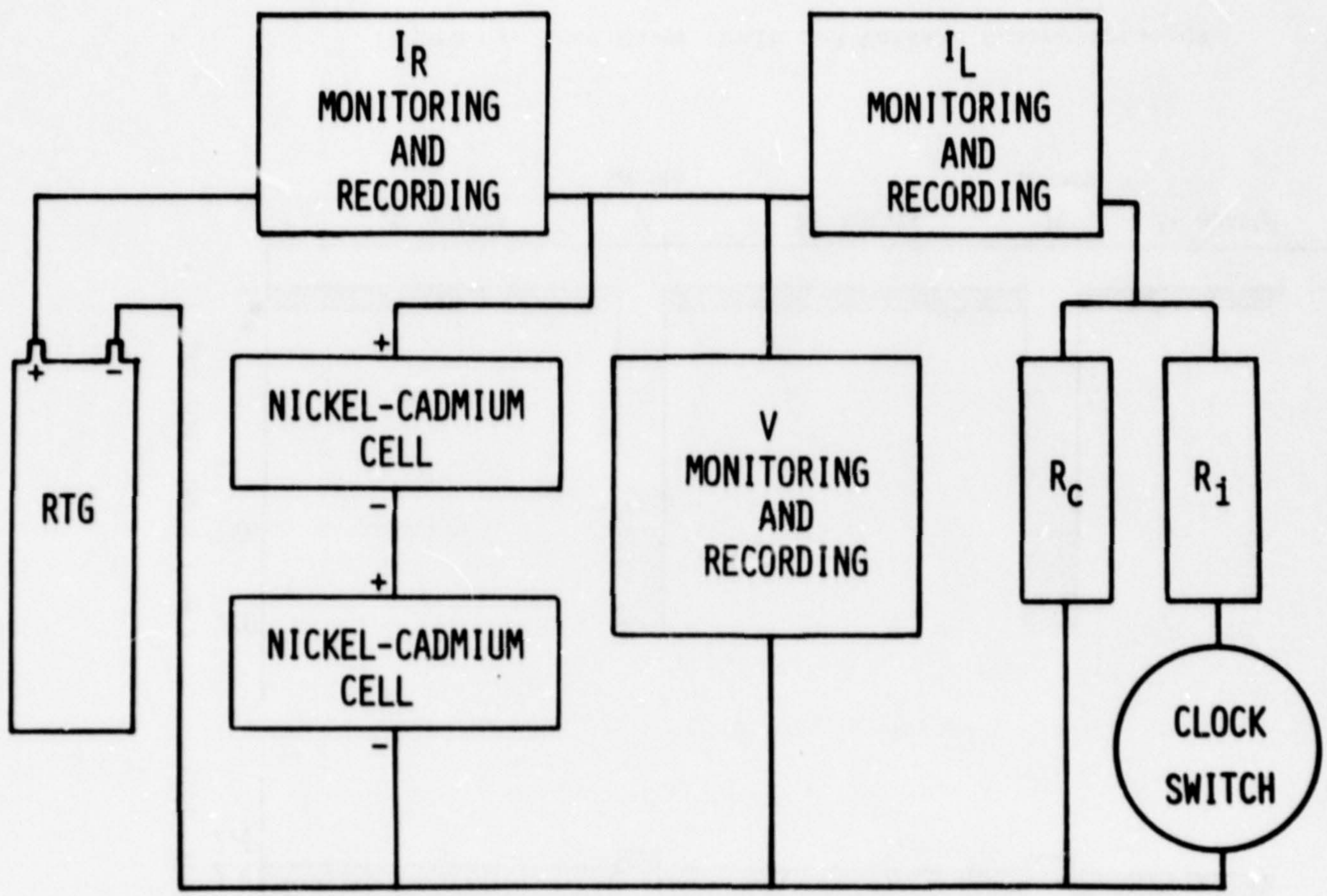

Figure 5. Block Diagram of the Experimental Apparatus for the Hybrid Configuration Study

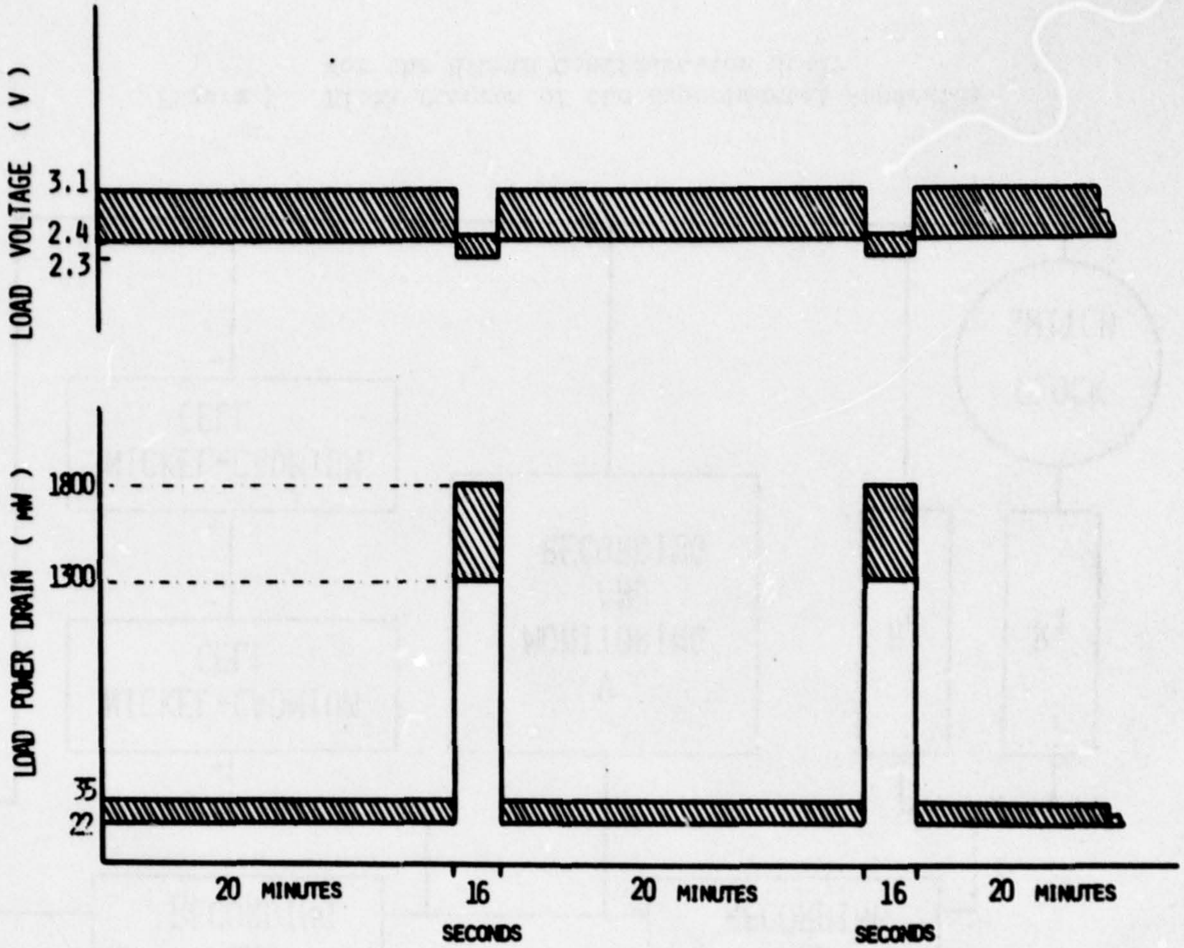

Figure 6. Load Power Drain and Voltage Characteristics

At every ambient temperature investigated, performance evaluation of the hybrid configuration was based on a three-week continuous operation test. Prior to each test a discharge curve of the two series-connected cells was obtained. At the end of the three-week testing period, with the recorded voltage and current characteristics still presenting the same initial values, a second battery discharge curve was obtained for comparative purposes.

Minor variations in the recorded values of the voltage and current delivered by the battery during the high drain period were experienced as a function of the ambient temperature. However, for each test performed at ambient temperatures ranging from +49°C (+121°F) down to -28°C (-20°F), the results showed a continuous holding of the hybrid-configuration performance at the end of every three-week testing period; this indicated a steady state condition of the battery charge state.

A reduction of the current delivered by the battery during the 16-second high drain period was experienced during the test at -32°C (-25.6°F) ambient temperature. After only a few hours of operation at this temperature, the high drain current value recorded presented a drastic change from the original 750 mA value down to the 300-350 mA value. By increasing the resistive load value or by reducing the high drain period duration, attempts were made to maintain the operational capability of the hybrid configuration at -32°C ambient temperature. However, only a few days of continuous operation could be achieved. The reduced charge acceptance of the nickel-cadmium battery at this low ambient temperature did not allow sufficient recharge during the 20-minute period. Therefore, it was realized that to extend the investigation to environmental temperatures below -28°C, some means would be needed to maintain the nickel-cadmium battery at a temperature above the ambient value. A thermal shunt was then conceived to recover waste heat from the RTG and divert it to the battery. An aluminum support, in a 5 cm diameter cylindrical configuration and provided with appropriate longitudinal cavities to lodge the RTG and the battery, was then fabricated and utilized for the completion of this investigation. Figure 7 is a cross-sectional view of this device which was also shown, in its actual configuration, in Figure 1. The thermal shunt, which maintains the battery case at a temperature approximately 18°C (33°F) higher than the ambient temperature, permitted successful performance of the hybrid configuration down to -43°C (-45°F) ambient temperature. The results are summarized in Table 1. In order to sustain the combined power drain in the temperature range investigated, the RTG must have a power capability 5 - 26% (Column 4) higher than the average power taken by the two loads.

The utilization of the thermal shunt has also resulted in more effective RTG waste heat sinking. This permitted the testing of the hybrid configuration and the RTG performance characterization at environmental temperatures in excess of +49°C (+120°F). At +62°C (+145°F) ambient temperature, the RTG surface temperature (T_{RTG}) was measured to be at +75°C (+167°F), 5°C lower than the recommended operational temperature limit. Three RTG output power characteristics obtained with the thermal shunt are presented in Figure 8, as a function of the ambient temperature, T_A. For comparison purposes, an RTG power characteristic obtained without the thermal shunt, at an ambient temperature of +49°C (+121°F), is also presented in Figure 8.

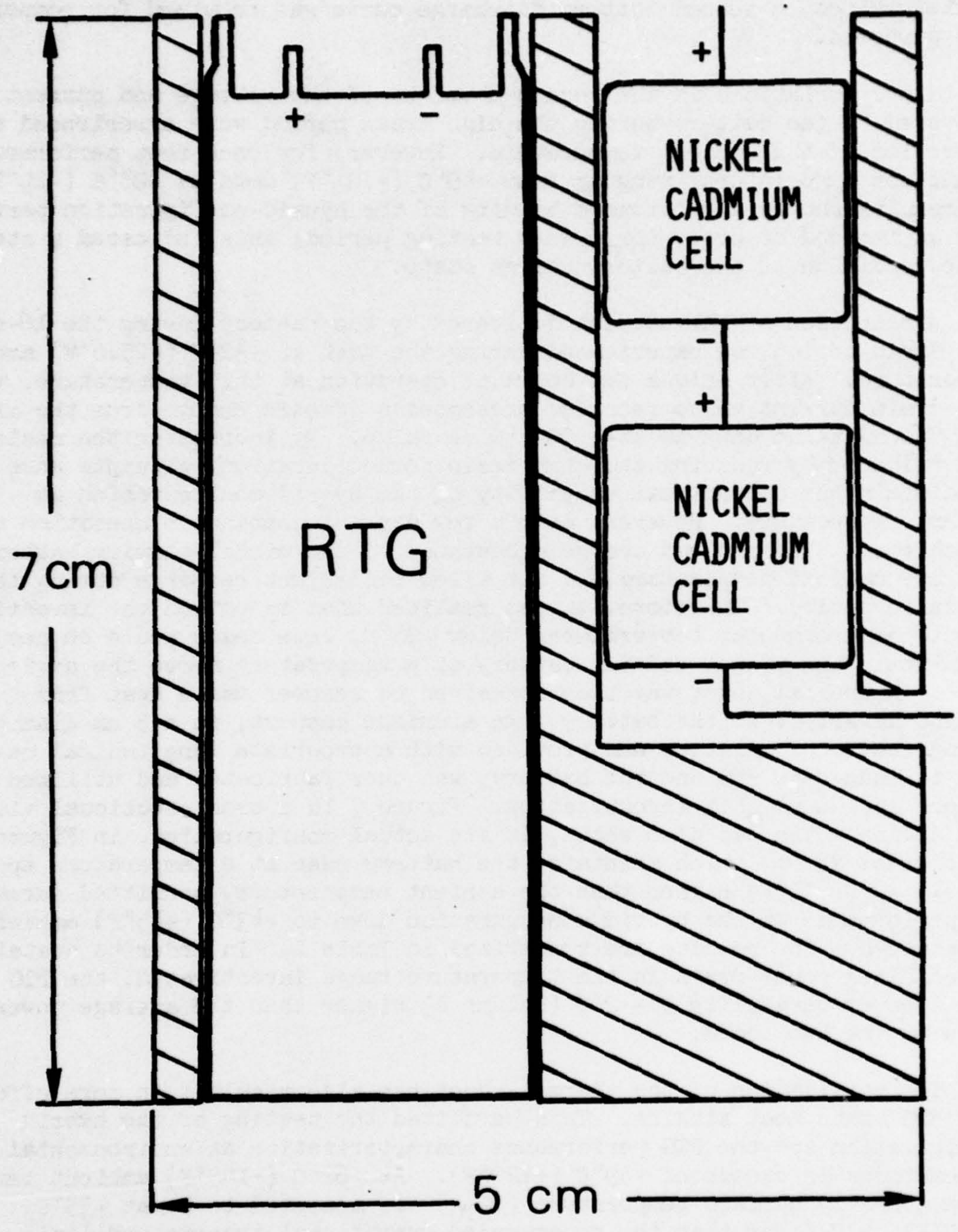

Figure 7. Cross-Sectional View of the Thermal Shunt Arrangement

Table 1. Radioisotope Thermoelectric Generator-Chemical Battery Hybrid-Configuration Performance

Ambient Temperature °C	Ambient Temperature °F	P_R mW	P_L mW	$\frac{P_R - P_L}{P_L}$ %	C_1 A·s	C_2 A·s
-43	-45	69.5	55	26	12.2	9.6
-35	-32	71.2	59.1	20	14.5	11.8
-1	30	60.2	56.4	7	11.7	11.1
25	78	52	49.2	5	10.6	10.0
37	100	45.5	42.3	7	10.1	9.5
62	145	44.6	41.6	7	9.2	8.4

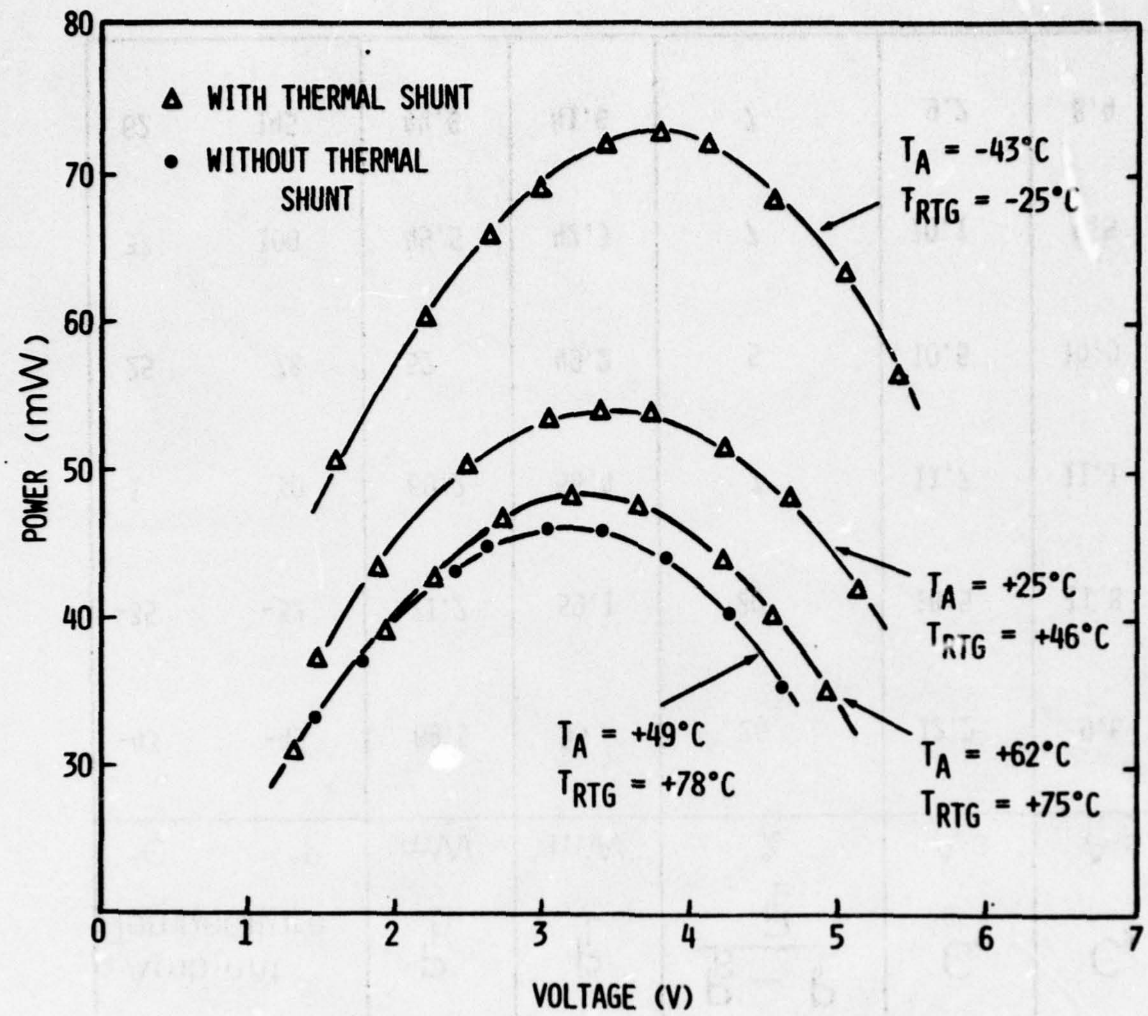

Figure 8. Radioisotope Thermoelectric Generator Voltage-Power Characteristics with the Thermal Shunt

CONCLUSIONS

The development of a 55 mW Plutonium-238 Fueled Radioisotope Thermoelectric Generator has resulted in a power source characterized by a conversion efficiency in excess of 3 percent. This indicates minimal parasitic heat losses and good utilization of the Bismuth Telluride thermoelectric material.

The RTG performance in a hybrid configuration using a sealed nickel-cadmium battery was successfully characterized in a wide range of ambient temperatures. The results obtained demonstrated that the RTG hybrid configuration is feasible for powering a pulsed load with a 75:1 duty cycle. In conjunction with other inherent characteristics of long life, trouble-free operation, this capability makes the RTG-hybrid power source a candidate to satisfy requirements that demand unattended extended periods of operation.

The thermal shunt utilization should be further explored to optimize size and performance. During this investigation, its feasibility to establish the practical possibility of such an approach was demonstrated and has unquestionably indicated the advantages obtainable by recovering and utilizing the RTG rejected heat.