22
5-19-82

I-3269 ① 4/23/82

SANDIA REPORT SAND81-1759 • Unlimited Release

Printed March 1982

19 cups to
NLS

Long-Life Power Sources for Continuous and Repetitive Loads

Thomas J. Young

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

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

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof or any of their contractors or subcontractors.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed copy: A03
Microfiche copy: A01

SAND--81-1759

SAND81-1759
Unlimited Release
Printed February 1982

DE82 014617

LONG-LIFE POWER SOURCES FOR CONTINUOUS
AND REPETITIVE LOADS

T. J. Young
Division 2527
Sandia National Laboratories
Albuquerque, NM 87185

NOTICE

This report contains information of a preliminary nature and was prepared primarily for internal use at the originating installation. It is subject to revision or correction and therefore does not represent a final report. It is passed to the recipient in confidence and should not be abstracted or further disclosed without the approval of the originating installation or USDOE Technical Information Center, Oak Ridge, TN 37830.

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Abstract

Long life electrical power sources compatible with continuous and repetitive pulse loads are of increasing interest for Sandia systems. Both primary chemical batteries and radioisotopic thermoelectric generators (RTG) are capable of supplying power for long periods of time. However, each has its particular advantages and disadvantages and neither alone may represent a good match to the system constraints. The purpose of this report is to provide some insight into the power, volume, and cost trade-offs between either of these sources alone and between hybrids consisting of RTGs with primary batteries, secondary batteries, or capacitors. These trade-offs suggest that the hybrid power sources may have significant volume and cost advantages for many applications.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Intentionally left blank

Table of Contents

	<u>Page</u>
Introduction.	7
Calculation Method.	7
Discussion.	15
Conclusions	24
References.	28

Figures

1. Volume Comparison for Continuous Loads.	13
2. Volume Sensitivity to Continuous Power Level.	17
3. Volume Sensitivity to Pulse Power Level	18
4. Volume Sensitivity to Pulse Duration.	19
5. Volume Sensitivity to Time Between Pulses	20
6. Volume Sensitivity to Energy Density.	22
7. Cost Comparison for Continuous Loads.	25
8. Cost Sensitivity to Pulse Power Level	26

Intentionally left blank

Introduction

There is increasing interest in systems which require electrical power sources that are in continuous use or which may be required to provide power several times. The two most common such weapon power sources are radioisotopic thermoelectric generators (RTG) and primary chemical batteries. Questions frequently arise concerning which type of power source is best suited to a particular application, particularly since Sandia RTGs use ^{238}Pu to provide the isotopic decay energy and chemical batteries currently are limited life components. The purpose of this report is to provide some insight into the electrical power (or energy) trade-offs with volume and cost for these components and explore possible combinations which may be more advantageous than either alone. The results reported here are based on idealized RTGs and batteries and are likely to require adjustment for specific applications. However, the calculations should be generally indicative of the nature of the trade-offs.

Calculation Method

Two sources of electrical energy, RTGs and primary chemical batteries, were considered for this study. They were chosen because they are well established as capable of producing electrical energy for long periods of time and because there is in-house expertise relating to their design and use at Sandia. Primary batteries store chemical energy which is converted into electrical energy during

use. Therefore, since there is a fixed amount of the appropriate chemical ingredients stored at beginning-of-life (BOL), these electrical sources tend to produce a fixed amount of energy, somewhat independent of electrical load. By contrast, an RTG produces electrical energy by conversion of thermal energy generated by nuclear decay. Since with long-lived isotopes the nuclear decay occurs at a nearly constant rate, an RTG more nearly represents a constant power source which is not strongly influenced by the total energy involved (until a substantial quantity of the nuclear material has decayed). This characterization of chemical batteries as energy-limited sources and RTGs as power-limited sources is an important distinction in considering appropriate applications of each. It means that chemical batteries will tend to be advantageous when pulse electrical loads are needed or when large amounts of energy are not required (i.e., short life), and RTGs are better suited to long life, relatively constant load applications.

These different characteristics of chemical batteries and RTGs also suggest that combinations of both may be advantageous where continuous as well as pulse loads are imposed. An RTG could be used to supply a continuous load and a primary chemical battery could supply the pulse load. Or, a secondary chemical battery (rechargeable) might supply the pulse load with an RTG charging the secondary battery as well as meeting the continuous requirement. Of course, for small pulse loads, a capacitor might also replace the secondary battery.

The calculations described in this report consider five possible alternatives:

1. RTG only
2. Primary battery only
3. RTG plus primary battery
4. RTG plus secondary battery
5. RTG plus capacitor

The total volume required for each of these alternatives is calculated as a function of various continuous and pulse loads. The calculations assume some nominal characteristics for all components and, although they are thought to represent current technology, neglect a number of effects (temperature, shock, discharge rates for chemical batteries, etc.) which could be significant in determining total volume for a given application. The volume of each component was estimated as follows:

RTG--For the purposes of this exercise, a "minimum volume" RTG design was assumed. Such a design provides a specified electrical power output in the smallest volume possible (given the properties of the materials involved) but does not necessarily provide a minimum plutonia content. It was selected for these calculations because it provides a unique relationship between electrical power and volume and was, therefore, convenient for comparing power source alternatives. At the higher power levels, plutonia content could be reduced by increasing volume, but the extent of such trade-offs

would be a function of the required design constraints. The "minimum volume" RTG size was approximated by

$$V_{\text{RTG}} = 40 + 378P^{0.85}$$

where

$$V_{\text{RTG}} = \text{RTG volume (cm}^3\text{)}$$

$$P = \text{total electrical power (watts)}$$

which is an empirical relationship based on current Sandia technology.

Figure 1 shows this power-volume function and the associated plutonium content (watts) at selected points along the curve. A power-volume curve in which the plutonia content is fixed at 4.5 watts (thermal) is also shown for comparison purposes. Since the size of an RTG is only a weak function of design life (within limits), operational life is not an explicit part of the calculation.

Primary Battery--The primary chemical battery selected for this comparison was the Li/SO₂ cell. It was selected because it represents the most efficient currently available technology (at Sandia). Although the available energy from these cells is a strong function of temperature and discharge rate,¹ a nominal energy density of 1500 joules/cm³ representative of D cells was assumed. The volume associated with this battery was calculated by

$$V_{PRI} = 3.16 \times 10^7 \frac{LP}{D}$$

where

$$V_{PRI} = \text{volume (cm}^3\text{)}$$

L = design life (years)

P = average electrical power (watts)

D = energy density (joules/cm³)

= 1500 joules/cm³ for Li/SO₂

Since this battery is a chemical energy storage device, design life is an important factor. The power-volume curve for this battery (5-year life) is also shown in Figure 1 for comparison.

Storage Devices--Two methods of temporarily storing electrical energy were considered. In one case, a secondary chemical battery (Ni-Cd) was assumed, and in the other case, a capacitor. For the Ni-Cd cell, a usable storage density of 150 joules/cm³ was assumed. As was the case with the Li/SO₂ cell, the available energy density is a function of several variables (temperature, depth of the charge/discharge cycle, etc.). With capacitor storage, it was assumed that either tantalum electrolytic² or ceramic³ capacitors could store approximately 0.003 joules/cm³ of which only 0.001 joules/cm³ would be usable.

When charging or discharging either of these storage media, it was assumed that the load was a pulse of power, P_p , and duration, t_p , and that the time period between load applications, t_D , was available to recharge. It was also assumed that the recharge efficiency was 50 percent. The average power required from an RTG to maintain a given pulse load is then

$$P_{AVE} = \frac{2 P_p t_p}{t_D}$$

and the storage volume

$$V_S = \frac{P_p t_p}{D_x}$$

where D_x is the usable storage density.

Power Source Combinations--The volumes of the various combinations were therefore calculated by:

1. RTG Only

$$V = 40 + 378(P_C + P_p)^{0.85}$$

2. Primary Battery Only

$$V = 3.16 \times 10^7 \frac{L}{D_p} \left(P_C + P_p \frac{t_p}{t_D} \right)$$

Figure 1. Volume Comparison for Continuous Loads

3. RTG Plus Primary Battery

$$V = 40 + 378P_C^{0.85} + 3.16 \times 10^7 \frac{LP_P t_P}{D_P t_D}$$

4. RTG Plus Secondary Battery

$$V = 40 + 378 \left(P_C + \frac{2P_P t_P}{t_D} \right)^{0.85} + \frac{P_P t_P}{D_S}$$

5. RTG Plus Capacitor

$$V = 40 + 378 \left(P_C + \frac{2P_P t_P}{t_D} \right)^{0.85} + \frac{P_P t_P}{D_C}$$

where

P_C = continuous power (watts)

P_P = pulse load power (watts)

t_P = pulse duration (sec)

t_D = time between applying pulse loads (sec)

L = system design life (years)

D_P = primary battery energy density (1500 joules/cm³)

D_s = secondary battery energy density (150 joules/cm³)

D_c = capacitor usable energy density (10^{-3} joules/cm³)

V = volume (cm³)

Discussion

If a constant load is to be supplied by a power source, temporary storage devices are of no value. The power-volume characteristics of RTGs and primary batteries are shown in Figure 1. The battery volume shown is for a 5-year life. Greater battery life would increase the required volume in direct proportion to the increased life, assuming no change in energy density (although some increase in energy density could be expected with increased volume). The figure shows that for continuous power levels greater than 1 mW, an RTG holds a decided volume advantage, and that below $\sim 400 \mu\text{W}$, the primary battery is superior. Longer application life would tend to favor an RTG while with shorter life, the battery becomes more desirable. It can also be seen that significant trade-offs can be made between volume and plutonia content during RTG design.

Examination of the volume equations for the various power source combinations shows that they have different sensitivities to the load parameters. These sensitivities to P_C , P_P , t_P , and t_D are shown in

Figures 2-5. Each parameter was individually varied about nominal conditions of

$$P_C = 0.01 \text{ watt}$$

$$P_P = 1.0 \text{ watt}$$

$$t_P = 0.1 \text{ sec}$$

$$t_D = 10^3 \text{ sec}$$

and a 5-year life. The relative merits of each power source are strongly dependent on the imposed load conditions. However, the results shown in these figures allow several observations to be made.

At very low average power levels, a primary battery is the most volume efficient. Above approximately 1 mW, an RTG alone would be desirable if the pulse power level is less than the continuous power level. However, the most important message from these calculations is that RTG/battery (or capacitor) hybrids offer significant volume advantages for many load situations. This is a consistent theme throughout Figures 2-5. The RTG/secondary battery hybrid is often the best combination, although the RTG/primary battery is equally good in many cases.

Figure 2. Volume Sensitivity to Continuous Power Level

Figure 3. Volume Sensitivity to Pulse Power Level

Figure 4. Volume Sensitivity to Pulse Duration

Figure 5. Volume Sensitivity to Time Between Pulses

The usable energy density is also an important parameter in determining battery and capacitor volume. This factor represents the energy which could be delivered to a load without a large ($\sim 20\%$) decrease in voltage. It is the only difference between the RTG/secondary battery and the RTG/capacitor calculations. Figure 6 shows the sensitivities to this parameter for the "nominal" load (solid line) and a load with a much larger pulse (dashed line). In this larger pulse, P_p and t_p are increased to 10 watts and 10 seconds. With the conditions assumed for the calculations in this report ($D_p = 1500 \text{ J/cm}^3$; $D_s = 150 \text{ J/cm}^3$; $D_c = 10^{-3} \text{ J/cm}^3$), there is not much volume difference between the RTG/primary battery and the RTG/secondary battery hybrids under the nominal load conditions, but with the greater pulse, the difference becomes large. Similarly, the sensitivity to capacitor energy density increases with pulse energy.

There are several other factors which affect the desirability of the various power sources. One of the most obvious is the hazard associated with plutonia-fueled RTGs. The ^{238}Pu isotope is a serious biological (and political) hazard, and great care must be taken to assure its containment. In some applications, it would be desirable to incur a volume penalty in order to avoid these radiological hazards.

Figure 6. Volume Sensitivity to Energy Density

Reliability is another consideration which may influence power source decisions. At the present time, the available data base favors RTGs over the Li/SO₂ battery. As additional data become available, this situation may change for the shorter life applications (≤ 5 years) but will probably continue for the immediate future for applications greater than 5 years. Secondary batteries are probably less reliable.

A third factor which must be considered is cost. Although cost is even more difficult to estimate than volume, the following direct cost relationships were assumed for comparison purposes:

1. RTG

$$\text{Direct Cost} = \$6.6 \times 10^3 (P_C + P_P)^{0.3}$$

$$\text{Minimum Cost} = \$2000$$

2. Primary and Secondary Chemical Batteries

$$\text{Direct Cost} = \$1.4/\text{cm}^3$$

$$\text{Minimum Cost} = \$50$$

3. Capacitor

$$\text{Direct Cost} = \$45/\text{cm}^3$$

$$\text{Minimum Cost} = \$25$$

The RTG cost estimate does not include PuO₂ cost because it is not normally included in direct costs. However, it is a cost to the government and may be large for high power RTGs. Figure 7 shows the

estimated direct costs for an RTG or primary battery when there is no pulse load. It indicates that primary batteries would be cost effective below 10-20 mW. Thus comparing with Figure 2, we see that (1) below 0.4 mW, primary batteries are desirable for both cost and volume, (2) between 0.4 and 20 mW, there is a cost/volume trade-off to be made, and (3) above ~ 20 mW, an RTG is favored in both respects. The dependence of the cost on pulse power for the "nominal" load is shown in Figure 8. In this case, costs have the same general relationships as volume (see Figure 3) with the exception that a primary battery alone shows a cost advantage over the other options. Aside from this exception (which would require a large volume), the RTG/secondary battery hybrid seems to have a cost as well as volume advantage. If secondary battery lifetimes > 10 years were available, the RTG/secondary battery would be less costly than any of the other options, including primary battery alone.

Conclusions

The calculations described in this report are intended to give some insight into possible schemes for providing long-term power to electrical loads which may be described as continuous loads and/or repetitive pulses. Because of the nature of the comparisons, broad generalizations are difficult to make, but it is clear that hybrid combinations of RTG and primary or secondary batteries (especially secondary batteries) may be attractive when repetitive pulse loads are applied.

Figure 7. Cost Comparison for Continuous Loads

Figure 8. Cost Sensitivity to Pulse Power Level

Volume calculations for the RTG and primary battery (Li/SO₂) are based on current Sandia design technology as is the capacitor volume. Sandia has little involvement with secondary batteries, so the estimates are based on commercial hardware. These volumes could vary considerably depending on environmental design constraints (temperature range, mechanical shock, etc.). Improvements are possible in chemical systems⁴ as well as RTG efficiency and are being pursued by the design groups. It is also worth noting that capacitors with energy densities of the order of 1 joule/cm³ (10⁻³ assumed in figures) are now being advertised commercially. These are liquid electrolyte capacitors, in many ways similar to batteries, which may prove useful for hybrid power source applications. However, little is known about their life, reliability, etc., characteristics. If these characteristics were acceptable, capacitor storage would be much more desirable. In fact, Figure 6 indicates that it would be competitive with secondary battery storage for the nominal conditions assumed in this exercise.

In addition to continued development of RTGs and primary batteries, further work in the following areas would appear to be worthwhile:

1. Design studies of complete hybrid power supplies, including interfacing electronics, to better determine size, efficiency, etc.
2. Development of Sandia expertise in secondary batteries to better understand design limitations.

3. Evaluation of the new high-energy density capacitors.

These activities should help provide a sound technology base from which to support the long-lived, continuously operating power source requirements being considered for future applications.

References

1. S. C. Levy, Private Communication.
2. C. Carlson, Private Communication.
3. C. A. Hall, Private Communication.
4. R. K. Quinn, Private Communication.

TJY:cmg:5836A:01/21/82X