angles; a repetition of the analysis presented here at nozzle vector angles up to 15° would be required to explore this potential.

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Cost-Effective Radioisotope Thermoelectric Generator Designs Involving Cm-244 and Pu-238 Heat Sources

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This paper represents a comparative analysis of some of the technical considerations surrounding the use of Cm-244 and Pu-238 heat sources in radioisotope thermoelectric generators (RTGs). The principal considerations include radiological shielding, ground handling, and generator performance characteristics. The paper also describes a novel approach to RTG design and qualification which would facilitate the use of Cm-244 heat sources. This approach, which involves hermetically sealed bellows-encapsulated thermoelectric elements, also features the potential for increased generator output power stability and reliability and lower converter costs accruing from the advantages of a standardised approach to generator design, fabrication, and qualification.

Introduction

THE application of radioisotope thermoelectric generators (RTGs) to space electrical power requirements has been successfully demonstrated during the past five years with notable successes in the Apollo program (SNAP 27), the Nimbus III RTG Experiment (SNAP 19), and the ongoing Pioneer mission to Jupiter (SNAP 19). For these and similar missions, considerable attention has been focused on maximizing specific power [w (e)/kg] and minimizing degradation in output electrical power while maximizing energy conversion efficiency thereby minimizing thermal inventory. Consequently, the cost effectiveness of the RTG designs selected for previous extraterrestrial missions has generally been given less emphasis in an attempt to maximize the over-all RTG performance. However, the trend towards increasing numbers of military satellites (e.g., reconnaissance satellites) as well as remote terrestrial applications has prompted the reconsideration of RTG designs with a view towards bringing RTG performance into balance with RTG cost effectiveness.

The present paper describes the results of a study directed at identifying potentially cost-effective RTG designs involving Cm-244 and Pu-238 heat sources. The generator concept which evolved from this study involves hermetically sealed, bellows-encapsulated thermoelectric elements. This approach features the potential for greatly increased generator output power stability and reliability. The proposed RTG concept also provides for ease of heat-source replacement as well as generator repair in the event of premature failure of any of the individual thermoelectric couples. More significantly, this standardized approach lends itself to cost-effective methods of manufacture and assembly of RTG components and over-all systems.

A recent study[1,2] of availability, cost, and application of the Cm-244 radioisotope in RTG power systems enumerated the advantages of using this fuel in place of the presently used Pu-238 radioisotope fuel. It was concluded in the referenced study that curium will be available in large quantities in the form of reactor waste products—possibly beyond any foreseen demand for radioisotopic heat sources. The study also discussed the various alternatives for the recovery of curium from existing sources as well as suggesting several short-term and long-term options for increasing projected curium availability. The study concluded that production quantities of curium can be obtained at costs between \$20 and \$100 per thermal watt (w_{th}).

The reference study[2] also discussed the application of Cm-244 radioisotopic heat sources to the Multi-Hundred Watt (MHW) program. This study revealed that the total program costs (which include such cost elements as fuel, heat source fabrication, converter, ground support equipment, ground handling and acceptance tests, and management and radiological safety tests) for the Cm-244 RTGs was lower by a factor of 1.8 for the MHW converter. According to the study, the need for biological shielding increases the costs associated with fueling, testing, and transport of Cm-244 heat sources. This characteristic of Cm-244, together with its relatively short half life (18 yr as compared with 89 yr for Pu-238) presents some problems in its utilization

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in RTG's. Several of these problems are discussed below in the context of a comparison of RTGs involving Cm-244 and Pu-238 radioisotopic heat sources.

Design Considerations for RTGs Involving Pu-238 and Cm-244

A comparison of the principal biological shielding requirements for Cm-244 and Pu-238 radioisotopic heat sources is summarized in Table 1. The major source of radiation for both radioisotopic heat sources is neutrons and account for approximately 95–98% of the total radiation doses emanating from Cm-244 and Pu-238, respectively. The balance of the radiation doses is primarily gamma-ray emanations.

The neutron source strength is approximately 45 times greater for Cm_2O_3 (4.4×10^6 neutrons/sec-w). Consequently, for a given fuel-form geometry, a significant amount of neutron shielding (see Table 1) will be required for a Cm-244 powered generator in order to reduce the dose to the same level as an unshielded Pu-238 powered generator. For example, as indicated in Item 6 of Table 1, 40 cm of water or 73 cm of moist soil would be the shielding required to equalize the dose for the two fuel forms. Since certain of the detectors used in present and planned spacecraft have a low tolerance for radiation, any attempt to use Cm-244 heat sources will require a substantial shielding analysis. The shielding study is complicated by the fact that the weight penalties imposed by shielding requirements will require that the over-all design of a spacecraft configuration take the shielding requirement into consideration. For example, many of the more sensitive instrument packages have a total neutron dose limit of 10^4 rad. In the case of a five-year mission (4.37×10^4 hr), this upper limit on the total dose translates to a dose rate of less than 0.23 rad/hr. To achieve such a low rate with Cm-244 heat sources requires substantial separation between source and instrument packages (i.e., geometrical attenuation) and/or substantial shielding thicknesses.

Table 1 Comparison of biological shielding requirements for Cm-244 and Pu-238 radioisotopic heat sources

Parameter	Cm-244	Pu-238
1) Fuel form	Cm_2O_3	PuO_2
2) Half life, yr	18	89.6
3) Specific power, w_{th}/g	2.67	0.55
4) Power density, w_{th}/cc	25.7	3.5
5) Dose rates for unshielded source, in mrem/hr:		
1 Kw_{th} at 1 m	3360	82
1 Kw_{th} at 3 m	366	9
1 Kw_{th} at 10 m	34	1
2 Kw_{th} at 1 m	6710	164
2 Kw_{th} at 3 m	741	18
2 Kw_{th} at 10 m	67	2
10 Kw_{th} at 1 m	33200	810
10 Kw_{th} at 3 m	3610	88
10 Kw_{th} at 10 m	330	8
6) Thickness of slab shield required to reduce dose by factor of 40 for selected materials, in cm:		
H_2O	40	...
Be	31	...
LiH	26	...
Soil (100 percent saturated)	73	...
Soil (dry)	96	...
7) Distance in air to reduce dose to 2.5 mrem/hr and 40 mrem/hr for selected thermal inventories, in meters:		
1 Kw_{th} at 2.5 mrem/hr	25	6
1 Kw_{th} at 40 mrem/hr	6	1
2 Kw_{th} at 2.5 mrem/hr	36	8
2 Kw_{th} at 40 mrem/hr	9	2
10 Kw_{th} at 2.5 mrem/hr	113	18
10 Kw_{th} at 40 mrem/hr	28	5

Table 2 Summary of component weights for unitized bellows RTG concept

Power output, BOL	30 watts (th)
Thermoelectric materials	2N and 2P PbTe
Hot and cold electrodes	W and Fe
Hot junction	800 K
Cold junction	500 K
Fin-root temperature	494 K
Power output/couple	0.310 watts(e)
Conversion efficiency of generator, BOL[a]	4.6
Number of couples	Approximately 100 (200 elements)
Element diameter × length	0.914 cm × 1.2 cm
Unit component weights (per element):	
Thermoelements	6.4 g
Shoes[b] (Fe, W)	1.1 g
Bellows (Inconel 718)	1.0 g
Hot platen (Ni)	0.7 g
Heat-sink extension (magnesium HM21A-T8)	0.9 g
Radiator fin (magnesium HM21A-T8)	5.5 g
Subtotal weight	15.6 g/element
Thermoelectric converter weight (200 × 15.6 g/element)	3120 g
Thermal insulation weight (Min-K)	300 g
Generator shell weight	950 g
Heat source weight[c] [652 w(th)]	4940 g
Total RTG weight (excluding power conditioning)	9.31 kg
Specific power, BOL	3.22 watts(e)/kg

[a] Includes 14% heat loss through bellows plus 7% heat loss through thermal insulation and heat source support.
[b] 25 mil (0.127 cm) Fe, and W shoes.
[c] Based on specific power of 132 w(th)/kg for SNAP 27 (integral heat source) RTG.

In the case of terrestrial applications, the Cm-244 looks more attractive since submersion in water or burial in earth at modest distances (see Table 2) will provide biologically safe levels of radiation at the surface. However, RTGs fueled with Cm-244 and operating above ground (in air) will require 25–100 meters separation between personnel and the RTG, depending on dura-

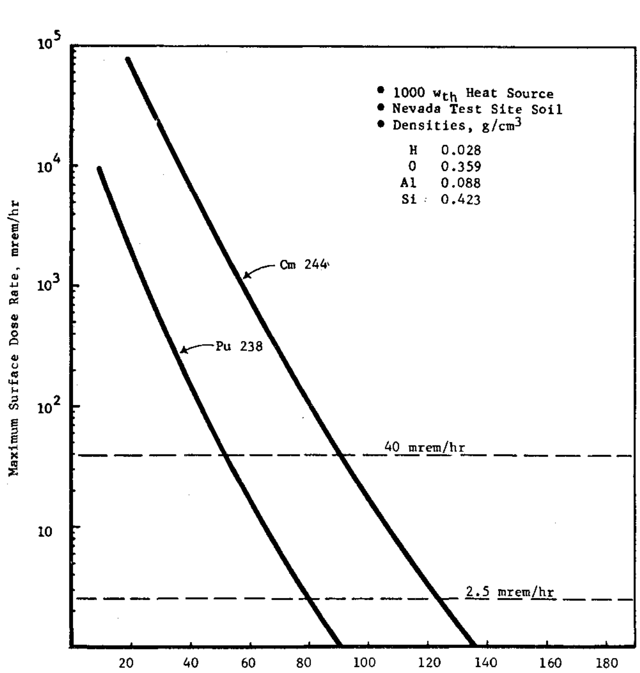

Fig. 1 Comparison of surface dose rates for buried Cm-244 and Pu-238 heat sources.

tion of exposure. A comparison of the relative depths of burial in soil is presented in Fig. 1 for both Cm_2O_3 and PuO_2.

Ground-Handling Considerations

On the basis of the foregoing shielding considerations, it is clear that special handling requirements would be needed for curium-fueled RTGs. Specially designed shipped containers would be needed to transport and store either the heat source or the total RTG unit. Likewise, shielded work areas with manipulator assemblies would be necessary for insertion or removal of the heat source. The insertion or removal of the heat source from RTGs requiring special jigging (as in the case of certain spring-loaded converter configurations) would further complicate the handling problem. Likewise, once the RTG has been fueled, any attempt to make repairs on the RTG, inspect hermetic seals, or conduct any other type of acceptance testing would be greatly complicated due to the need for remote handling.

As an example of comparative handling costs, the General Electric/Space Division study[2] concluded that RTGs of the MHW design would incur 40% higher ground-handling costs if Cm-244 were used in place of Pu-238.

RTG Performance Considerations

The operating characteristics of RTGs are strongly influenced by the choice of fuel due to the effects of radioisotope decay. For example, consider an RTG involving PbTe thermoelements operating at cold-junction and hot-junction temperatures of 500 and 800 K, respectively, and designed for a 5-yr mission. As shown in Fig. 2, at the end of 5 yr, the curium fueled RTG undergoes a decrease in thermal input power per couple of approximately 20% (due to radioisotope decay), which is reflected in a drop in output power per couple of approximately 28%, and a drop in the hot-junction temperature from 800 K (BOL‡) to 747 K (EOL‡).

In contrast, during a similar period, the plutonium-fueled RTG undergoes a decrease in the thermal input power per couple up only 3.5% which is reflected in a drop in output power per couple of approximately 8 per cent, and a drop in the hot-junction temperature from 800 K (BOL) to 788 K (EOL).

Another important consideration with respect to fuel selection is the indirect effect of temperature decrease on pressure-contacted junctions. For example, under normal operating conditions, pressure-contacted junctions involving PbTe or PbSnTe thermoelements must be operated above 750 K in order to maintain acceptably low levels of junction resistance. The example summarized in Fig. 2 indicates that the hot-junction temperature of the RTG may approach this threshold temperature. There is also a constraint on the BOL hot-junction temperature due to principally evaporative erosion and creep flow of the thermoelements.

Hence, the selection of the operating temperatures of curium-fueled RTGs must consider the effect of the decrease in the hot-junction temperature on the pressure-contacted junction resistance. In addition, it was shown above that the curium-fueled RTG cannot use the available thermal power as efficiently as its plutonium-fueled counter part. Despite these disadvantages and the additional biological shielding requirements, the potential cost benefits suggest that the use of Cm-244 (as a cost-effective substitute for Pu-238) should be studied thoroughly for each specific application of interest. Likewise, the present claims that Cm-244 can be produced for one-eighth to one-tenth the cost of Pu-238 should be reviewed in light of recent studies[3] that indicate that, in production quantities, Pu-238 could be produced for one-half to one-third the present cost.

In order to more fully realize the potential cost benefits of curium heat sources, future RTG designs should permit operation and performance of acceptance tests in air to facilitate ground handling. Equally important, future RTG designs should involve a nonsealed converter concept to facilitate qualification testing with electric heaters and heat source insertion or removal. Also, emphasis should be given to reducing the thermoelectric converter costs, particularly in the case of curium-fueled RTGs in which the converter cost becomes comparable with the heat source cost.

One design concept[4] which fulfils the above requirements involves the use of utilized thermoelectric modules. This concept

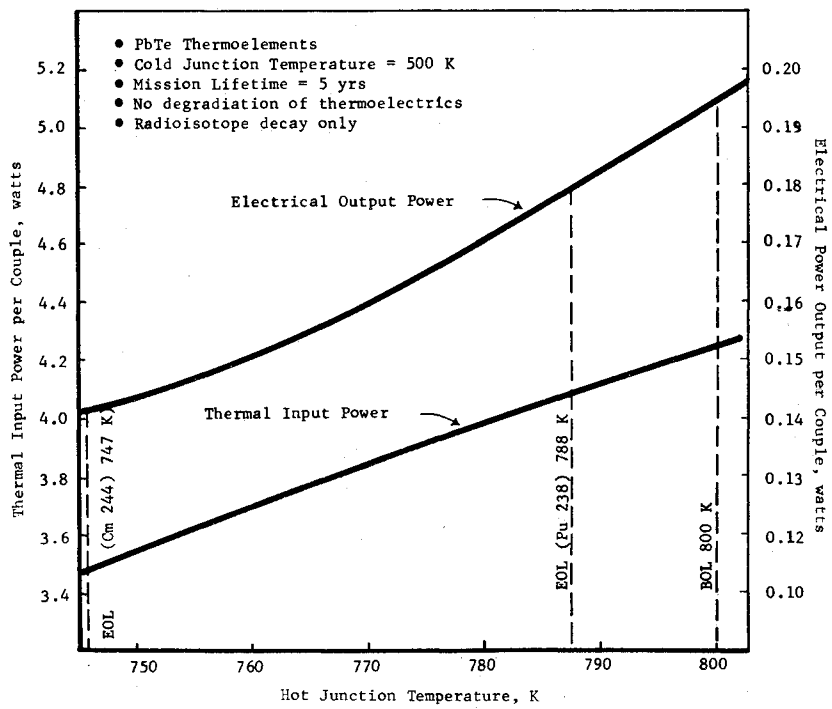

Fig. 2 Comparison of the effect of radioisotope decay on hot-junction temperature and electrical output power.

‡ BOL refers to "beginning of life" of RTG mission and EOL refers to "end of life" of RTG mission.

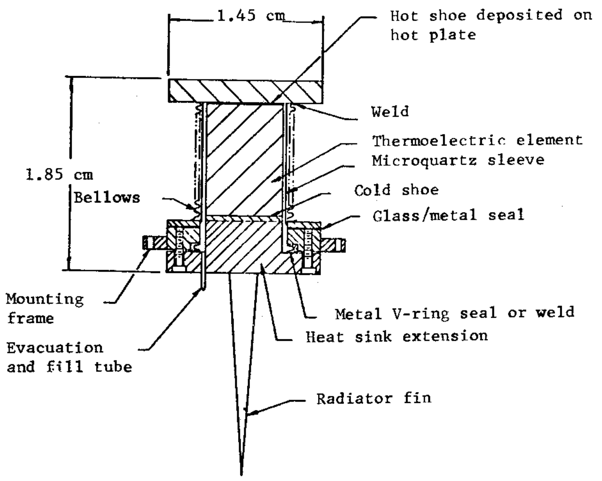

Fig. 3 Unitized bellows thermoelectric module concept involving single stage thermoelements.

is discussed below together with an enumeration of its principal advantages and limitations.

Unitized Thermoelectric Module Concept—An Approach to Cost-Effective RTG Design

The approach taken in the development of radioisotope thermoelectric generators (RTG) during the past decade has been principally one of designing a specific (or unique) generator system for each mission application. Consider, for example, the diversity of generator designs as exemplified by the Transit,[5] SNAP 27,[6] SNAP 19,[6] and New Moons[7] RTG systems. Attendant with these diverse generator designs are a host of problems which are intrinsically peculiar to each new design and must, therefore, be overcome before the generator is "qualified" for use.

Typical "unique-design" related problems are as follows.

1) Interrelated heat-source generator safety studies and survival qualification testing.

2) Extensive subassembly and generator thermopile "life testing" to substantiate long-term power performance where the semiconductor material is subjected to generator environmental (e.g., selection, treatment, and effect of the interstitial thermal insulation) and design (e.g., pressure loaded vs bonded junctions) effects.

3) Design and development of specialized cold-junction hardware for spring-loaded or bonded thermoelectric elements, and further, making the design compatible with generator assembly procedures.

4) Specialized generator sealing techniques to isolate the semiconductor from potential sublimation conditions or other environmental degradation mechanisms, e.g., oxidation.

All of the foregoing development problems have one common characteristic in that they dilute the effort that needs to be applied to identifying the most stable operating conditions for a given thermoelectric materials system. Also, they add substantially to the cost of developing, qualifying, and manufacturing the resulting thermoelectric generators.

An analogous situation can be noted in the electronics field, viz, the standardization of packaging for electronic tubes, resistors, transistors, diodes, etc. The cost and reliability advantages of this standardization of certain basic components are obvious.

The extent to which thermoelectric generator design and fabrication can be standardized is inherently limited by comparison with the electronics field described in the foregoing. However, with some standardization, it seems feasible that substantial savings in development costs, as well as improved performance stability and reproductibility, can be realized. The concept described in the following illustrates one approach that offers the standardization desired while being sufficiently flexible to accommodate a wide range of thermoelectric materials and operating temperatures and offers the nonsealed RTG configuration needed for the effective utilization of Cm-244 heat sources.

Description of the Module Concept

The concept referred to as the unitized bellows thermoelectric generator (module) concept involves the enclosure of individual thermoelectric elements (*n* or *p* leg) in a bellows assembly as shown in Fig. 3. This basic building block is a self-costained, hermetically sealed, spring-loaded enclosure. The thermoelectric element is exposed to a minimum of active surfaces, such as thermal insulation, and can be backfilled with any compatible gas at "over pressures" of up to 150 psi.

The advantages of operating thermoelectric elements at an overpressure of an inert gas have already been demonstrated by research conducted at Sandia Labs.[8] Specifically, it has been shown that the rate of evaporative erosion of thermoelectric materials is approximately inversely proportional to the inert gas pressure. For example, by increasing the internal pressure of the thermoelectric element environment from 15 to 60 psia, the evaporation rate would decrease by 75%. Present generator designs limit the internal pressure to usually 30 psia or less. However, as mentioned in the foregoing, the miniature bellows, which encapsulate the thermoelectric elements, can readily withstand internal pressures of up to 150 psia while maintaining the desired amount of spring loading pressure.

An additional advantage of the hermetically sealed bellows module concept is that of minimizing the sources of gaseous contamination, viz, oxygen-contaminated thermal insulation materials. For example, an independent study has been performed by the author[9] which has revealed that the preferential Te sublimation rate in *p*-type PbTe thermoelectric materials is as much as several orders of magnitude higher in an oxygen-containing inert atmosphere than in a pure inert or reducing atmosphere. This preferential sublimation of Te from the *p*-type PbTe has been found to be the principal contribution to degradation during thermoelectric life tests. Specifically, the operation of PbTe thermoelectric couples at a hot-junction temperature of 750 K in a reducing atmosphere permitted stable operation ($<10\%$ degradation in output power) for periods in excess of 18,000 hr, a two- to three-fold improvement over conventional RTG systems. According to the author's hypothesized degradation model, the hermetically sealed module concept will afford a comparable level of performance stability.

The availability of materials suitable for use in fabricating the bellows was one of the most critical factors in demonstrating the feasibility of this enclosure concept. Studies performed under NASA Contract NAS3-9421[10] have indicated that Inconel 718 shows adequately low relaxation and good performance in vacuum at temperatures of 1000 F for periods exceeding 2000 hr. Hence, the key component in this concept, viz, the bellows, might be fabricated using Inconel 718. The increased heat-path length afforded by the bellows convolutions, together with the low thermal conductivity of Inconel 718 (0.20 w/cm C at 500°C), results in acceptably low bypass heat losses ($\sim$10–15%). Although this level of additional heat loss may seem undesirable, there are several considerations which tend to offset this disadvantage. These are as follows.

1) The bellows may permit the thermoelectric material to be operated at a hot-junction temperature substantially higher (hence, higher energy conversion efficiency) than attainable otherwise. For example, consider the Transit RTG concept, which, because of its designed operation in vacuum, is limited to hot-junction temperatures of <400°C.

2) In certain applications, the generator may now be able to utilize vacuum foil "super" insulations in the space between the bellows encapsulated thermoelectric elements in place of higher thermal conductivity (and often containment-ridden) fibrous thermal insulations.

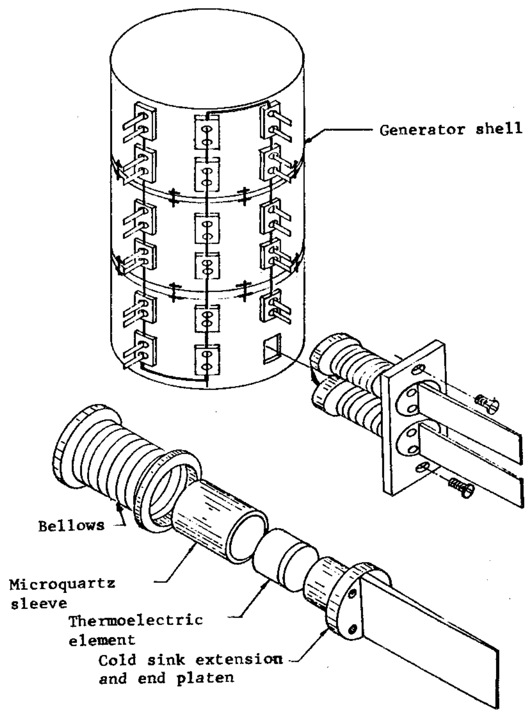

Fig. 4 Thermoelectric generator concept employing unitized "bellows" thermoelectric modules.

3) The inherently high thermal conductance of this heat-sink design (no sliding contact as required for conventional spring-loaded generators) allows the thermoelectric elements to operate typically 10–25°C lower in cold-junction temperature than in conventional spring-loaded generators, and hence affording higher energy conversion efficiency.

4) The cost benefits afforded by a nonsealed converter and the case of repair and replacement of faulty couples may well offset the costs associated with the additional fuel inventory required as a result of the increased bypass heat losses.

Over-all Unitized-Bellows Generator Design Concept

A conceptual drawing of an over-all generator concept is shown in Fig. 4 and illustrates the flexibility of this generator design concept. The arrangement is similar to the SNAP-10 experimental generator. The principal differences between this RTG design concept and the SNAP-10 experimental generator[11] are that this bellows concept utilizes: a) the spring force of the bellows to hold the thermoelectric elements in compression rather than using conventional springs, b) the direct contact of the thermoelectric elements with the heat sink, and c) the hermetic sealing of each thermoelectric element within the bellows enclosure. The basic building block in this generator design is then the thermoelectric couple which is composed of two bellows-encapsulated thermoelectric elements (*n*- and *p*-type). These basic building blocks are then attached to an appropriate generator cold frame (whose configuration can be tailored to a specific application) to form an intermediate building block of, e.g., 5–10 w or more. These intermediate assemblies may then be assembled into final generator configuration having the desired electrical output power.

One additional feature of this design is that each thermoelectric building block couple can be "pretested" and qualified prior to installation into the intermediate or final generator casing. Even after couple installation has been completed, if one or more couples malfunction (as determined by, e.g., in situ external resistance measurement on individual couples), they can be readily replaced without even the need for cooldown of the complete generator. The major feature, however, is that the thermoelectric elements will be developed, qualified and ultimately operated under *unchanging conditions*, viz, in the bellows container.

Another important advantage, particularly from the standpoint of the flexibility of this design, is the ability to use this basic bellows module/generator concept for a wide variety of thermoelectric materials, e.g., PbTe, TAGS alloy, GeTe-PbTe, etc. In fact, the same generator hardware (except for heat-source thermal inventory) could be used for a variety of thermoelectric materials. Thus, as new thermoelectric materials are developed, totally new generator designs will not be necessary.

Also, this bellows-encapsulated RTG concept permits the heat source (or electrical heater) to be inserted or removed in air without damage to the hermetically-sealed thermoelectrics. This non-sealed RTG concept also facilitates removal of the heat source (particularly, Cm-244) for repair of any couple failures.

A detailed weight breakdown for the bellows RTG concept is shown in Table 2. The weight summary presented in Table 2 indicates that the unitized bellows RTG concept is comparable (with the exception of the MWH RTG) to present RTG designs in terms of specific power [w(e)/kg]. In addition, it should be noted that this comparison is based on operation of the thermoelectric materials at a hot-junction temperature well within the state of the art, viz, 800 K. Another feature of this concept is that it provides the potential for significant improvements in the stability of the thermoelectric materials encapsulated due to the minimization of gaseous contamination of thermoelements by the thermal insulation and the ability to provide significantly higher inert gas overpressures than heretofore possible in over-all generator containers. In contrast, the MHW concept is based on a hot-junction temperature well above the present state-of-the-art for flight-tested RTGs, e.g., the Nimbus (SNAP 19) and Apollo (SNAP 27) missions.

Recent Experimental Developments

The "bellows-encapsulated" thermoelectric module concept has been under development at Battelle's Columbus Labs since late 1970. This work was being conducted under the sponsorship of NASA-Goddard (Contract NAS5-11394) and was aimed at evaluating the energy conversion efficiency and output stability of SiGe-PbTe segmented couples in selected environmental conditions, viz, the bellows thermoelectric module.

One bellows encapsulated couple with SiGe-PbTe segmented elements was fabricated (see Figs. 5 and 6) and operated at cold- and hot-junction temperatures of 450 and 1175 K, respectively. Although the hermetically sealing capability of this concept was demonstrated, the life testing of the couple was limited by inadequacies in the design of the hot-shoe/SiGe junctions. The details of this experimental work are discussed in the literature.[12]

Conclusions

The preliminary findings of this study indicate that the effective utilization of curium-fueled RTGs and the realization of its cost benefits depends on such factors as the manner in which the

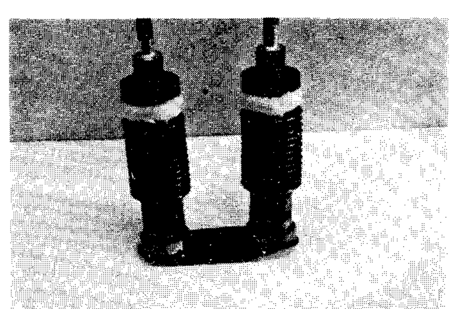

Fig. 5 Bellows-encapsulated SiGe-PbTe segmented elements following evacuation, backfill with argon, and closure.

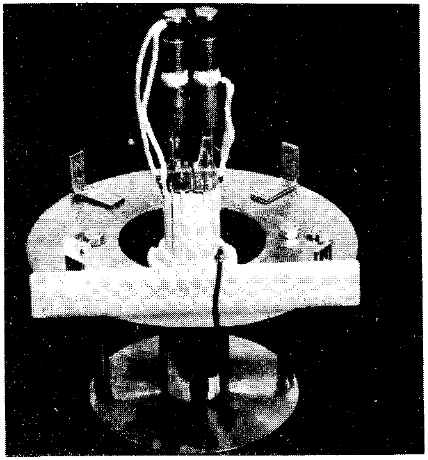

Fig. 6 Life-test and efficiency-measurement apparatus with SiGe-PbTe segmented elements attached to heat-flux transducer/heat-sink assembly.

RTG is deployed, the mission lifetime, and the design of thermoelectric/electrode junctions. The biological shielding requirements associated with the use of Cm-244 greatly complicate ground handling and suggest the need for unsealed converter designs capable of being fueled and tested in air. The proposed hermetically sealed, bellows-encapsulated module concept appears to be one feasible solution to this problem. In addition, this concept minimizes the problem of RTG repair in the event of couple failure, eliminates contamination of the thermoelements by the atmosphere or gases evolved from the thermal insulation, and reduces the rates of evaporative erosion. Furthermore, the unitized module concept offers potentially lower converter costs which accrue from the standardized approach to module design and ease of repair as well as the ability to conduct tests and fuel the generator in air. It is noteworthy that the technical and economic benefits of this RTG concept apply to both the plutonium and curium radioisotope heat sources.

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