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Thermal Insulation Design of Portable Radioisotope Electrical Generators

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Abstract

Radioisotope generators can provide power for several decades without the need of any further energy input, such as solar or chemical energy. A portable radioisotope generator can foresee many applications in future military and civilian uses that require minimum access and maintenance, such as to power sensors in a polar region, on a floating buoy, or undersea. In this work, we report the design, simulation, and measurement results of the thermal insulation of a miniaturized radioisotope system. We tested a prototype powered by an electrical heater with the same size as a plutonium fuel pellet. We tested the material compatibilities and showed the designs suitable for generators using thermoelectric and thermophotovoltaic converters respectively. In addition, we proposed a new insulation that uses a layered dielectric's omnidirectional reflectivity as a futuristic insulation mechanism to shield radiation heat for micro to meso-scale thermal systems.

Introduction and previous works

Radioisotope generators were invented in the 1950s, and were extensively used as power sources for extrasolar spacecraft, including the famous Voyagers, Cassini-Huygens, and New Horizons. Due to radioisotopes' extremely high specific energies, they can extend the battery lifetimes to several decades without the need to recharge. The most commonly used radioisotopes include ²³⁸Pu, ²⁴¹Am, and ⁹⁰Sr. The large decay heat from these isotopes are converted to electrical power through either thermoelectric materials and/or thermophotovoltaic cells [1]. Stirling engines and alkali-metal-convertors were also explored in previous prototypes, but suffered from reliability problems. Scaling down a generator to the portable size is an important development trend for the next generation power sources. Those mini batteries can potentially be used on nanosatellites and micro-rovers for space exploration, on sensors in inaccessible regions, and even wearable for soldiers and explorers in desolate places. Similar to the General Purpose Heat Source (GPHS) used in large-scale generators, most of the portable batteries use the light weight radioisotope heating unit (LWRHU) with 1.1 W thermal power or the Angle radioisotope heating unit developed in Russia with roughly 10 W heat output.

A radioisotope generator is a high temperature system with the heat source operating between 800°C – 1200°C. A portable generator often operates at slightly lower temperatures between 500°C – 800°C because of a size limitation. The effective design of the thermal insulation is one of the most important parts for an efficient system. For a high temperature system operating in high vacuum, radiation is the dominant mode of thermal leakage. The most widely used radiative barriers include the multi-layer insulation (MLI) as in space used Radioisotope Thermoelectric Generator (RTG) [2] and microporous insulation. A portable generator has the additional properties of a large surface-to-volume ratio and an irregular geometry, making the manufacture of insulation more challenging. Moreover, advanced generators using thermophotovoltaic converters often incorporate spectral control to improve efficiency, so that more in-band emissivity can be converted by the TPV cell while the photons in the far infrared are either suppressed or reflected. The micro-structured selective emitters and filters used in spectral control and the low bandgap III-V cells are very sensitive to chemical attacks [3]. Material outgassing in high temperature can easily degrade the micro-structured surface and result in a decrease in performance with time.

The typical device efficiencies can reach 10% for thermoelectric materials, and up to 20% for thermophotovoltaic cells. The prototype systems demonstrated so far have the overall conversion efficiency

below 1% due to low thermal efficiencies. The miniaturized radioisotope prototypes using thermoelectric material Bi_2Te_3 demonstrated an efficiency of 0.3% and 0.015% [4, 5]. The radioisotope thermophotovoltaic systems operated at higher temperatures and demonstrated an efficiency of 1% and 0.4% in two prototypes [6, 7].

Experiment and results

This work experimented with an electrical heater designed in the same shape as a plutonium fuel pellet measuring a size of 29.72 mm in diameter and 29.97 mm in height. The heater was housed inside an Inconel case with a hollow tube connected on the back side to a stainless steel support plate. The whole structure was fixed onto a ConFlat (CF) flange inside a high vacuum system. Three thermocouples probed the temperature of the heater surface, the stainless steel back plate, and the inner side of the flange surface. The heater temperature was swept from 200°C – 1000°C, while the power inputs were recorded and compared with the COMSOL Finite Element Analysis simulation. The setup is shown in Figure 1.

Fig. 1. Configuration of the thermal test apparatus. The electrical heater was housed inside an Inconel case to mimic the plutonium radioisotope fuel pellet. The structure was supported by a stainless steel back plate fixed onto a ConFlat vacuum flange. A gap existed between the heater and the vacuum flange.

Three different types of insulations were experimented for optimal performance and material compatibility, including the MLI made of copper foils separated by zirconia powder housed inside a micro-porous insulation material (Gemcolite), the MLI housed inside a copper case, and structure of MLI separated and supported by stainless steel meshes as shown in Figure 2. The first design showed the best thermal performance, followed by the MLI housed inside a polished copper case. The MLI separated by stainless steel mesh showed the worst thermal performance because the stainless mesh is too thermally conductive, and results in significant thermal leakage between adjacent MLI layers.

Fig. 2. The different insulation designs for the heat source and their measured and simulated performances. The solid lines represent the COMSOL simulation, while the dots refer to measurement points. The effective thermal conductivity was extracted from the measured data.

We surveyed literature for the best MLI material choice [8]. The copper used in our experiment is effective, but is best used below 800°C. Exceeding that temperature, the metal can still function, but starts to show signs of degradation during post heating inspection. The most widely used metal foil is the molybdenum foil. It is cost-effective and provides adequate shielding for the whole temperature range. The material is a little brittle, but is strong enough for most solid-state generators. Pure gold and tungsten foils have better reflectivity, but are too expensive for most applications. Gold plating is widely used for MLI in spacecraft, where the source temperature does not exceed 300°C. Due to diffusion, the plating gradually loses colour and high reflective properties as the temperature increases. The material to separate adjacent MLI layers ideally has zero thermal conductivity, such as vacuum gaps. For practical applications, a material with a very low thermal conductivity is chosen, such as zirconia, silica, or thoria. Silica is sometimes woven into a fabric, called Astroquartz cloth as used in some space RTGs.

Table 1. Foils and separators used in an MLI	
<i>Foil</i>	<i>Application Notes</i>
Copper	Can be used < 800°C
Molybdenum	Most widely used, cost-effective, but brittle
Gold	High cost and crinkles too much
Niobium	Incompatible with zirconia
Tungsten	High cost, forming carbide
Titanium	Highly reactive in high temperature
<i>Separator</i>	<i>Application Notes</i>
Zirconia	Widely used
Silica	Can be woven into cloth (as in RTG)
Ytterbia	Stable, but cause sticky between foils
Thoria	Stable, but slightly radioactive

In the next step, we examined the material compatibility of the insulation material with different thermal-to-electrical converters. The insulations made by the MLI separated by zirconia powder and stainless steel had very little outgassing. The chamber reached ultra-high vacuum at 10^{-7} Torr ultimately limited by the flange. The micro-porous insulation showed significant amount of outgassing due to binders used to glue the material together. The water was driven off across the whole temperature range, including adsorbed water (lost at 0 ~ 200°C), binder (200 ~ 500°C), and chemically combined water (>600°C). A residual gas analysis (RGA) was used to analyse the outgassing from a material bulk as shown in Figure 3.

Fig. 3. The residual gas analysis for micro-porous insulation material and the resulting oxidation of the heater. The outgassing is mostly water, leaving two big spikes of oxygen and hydrogen.

After firing, the microporous insulation became powder like and lost strength. As a result, the microporous insulation is more suitable to be used in a gaseous environment rather than vacuum, such as in inert gas or even in atmosphere if no other material degradation is a concern.

In the next step, we move toward a new kind of thermal insulation that used the omni-reflectivity of a one-dimensional dielectric stack as a radiative barrier [9]. Different from a metal insulator, a dielectric insulator has extremely low loss, and can potentially function as a shield with better performance. Winn et al. demonstrated that a one-dimensional dielectric stack is sufficient for the existence of an omni-directional reflection gap and predicted that the dielectric stack can be used as a radiative barrier. For a meso to micro scale power system, an insulation made of alternating layers of dielectrics can be made by micro-fabrication. Figure 4 shows the band structure of alternating layers made of SiO_2 and Si, leaving the shaded orange region within the light cone as a complete bandgap that no propagating modes of an electromagnetic wave exist. For a periodic quarter wave stack with a unit length of $1\text{ }\mu\text{m}$, the bandgap corresponds to a wavelength range of $3.16\text{ }\mu\text{m} - 4.17\text{ }\mu\text{m}$, falling in the infrared region. If the desired spectrum needs to be shifted toward lower wavelength, the period of the stack needs to be shortened, and vice versa. Potentially, this stack of material can be used to build a housing around the heat source, leaving cut-outs for the energy conversion elements such as the TPV cell or the thermocouples.

Fig. 4. The feasibility of constructing an omni-reflective mirror for the shielding of a heat source. The shaded orange region presents a complete bandgap that no electromagnetic waves within that frequency range can pass through.

Summary

A portable radioisotope generator converts thermal energy into electricity using thermoelectric materials or thermophotovoltaic cells, and needs adequate insulation design to drive the power toward the energy conversion elements, rather than lost as waste heat. From the experiments in this work, we concluded that a system operating in a gaseous environment and is insensitive to oxidation attack can choose the microporous insulation housing an MLI inside. Such systems include thermoelectric generators using SiGe thermocouples or thermophotovoltaic systems using a blackbody emitter. For a system using PbTe and Bi_2Te_3 with a layer of sublimation suppression coating can potentially use such insulation design as well. However, the ability of the coating to sustain oxygen attack needs further testing. On the other hand, a thermophotovoltaic system incorporating spectral control is most suitable to choose a pure MLI as the insulation to avoid contamination. An omni-reflective dielectric mirror can potentially be used as an insulation barrier for portable high temperature systems. Further modeling and tests are necessary to verify the feasibility of such a design experimentally.

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