

PRELIMINARY DEVELOPMENT OF A MILLIWATT GENERATOR FOR SPACE

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Abstract

This paper presents the results of a Phase I STTR program to develop a small thermoelectric generator for use in space. The generator is designed to use the existing 1 watt radioisotope heater unit (RHU) which is currently used to keep instruments warm in space. The design and manufacture of the monolithic thermal conversion unit (TCU) is discussed as is a conceptual design of a generator which uses both the RHU and the small TCU to produce 40 mW of power at 5 volts D.C.

Background

In August of 1996, Hi-Z Technology, Inc. (Hi-Z) won a National Aeronautics and Space Administration (NASA) Phase I STTR contract (NAS396050) to investigate the construction of a thermoelectric generator that would use the existing 1 watt radioisotope heater unit (RHU) designed by Los Alamos⁽¹⁾ as the heat source. An important part of Phase I was concerned with the design and construction of a prototype thermal conversion unit (TCU) that would be used in the generator. The TCU had to be small in size yet contain several hundred thermoelectric elements to produce the desired 5 volt output.

The first year of development of the 40 mW thermoelectric generator is now funded by the U.S. Department of Energy. This will be followed by a second two year phase in which a number of generators will be built and put on life test to qualify them for space flight in the 2002 to 2003 period.

There are a number of potential uses for a small thermoelectric generator. NASA recently changed its technical direction to incorporate the use of a large number of unmanned, small, low-cost probes to investigate space. These probes will be used to form networks of mini-meteorological stations on Mars or other planets to investigate local weather and geologic conditions. Such networks will require small decentralized power supplies that can provide power for several years. It is also possible that such small power supplies can be used either to power small surface rovers similar to Sojourner on extended missions or they could also be used for burst mode data transmission in using the Powerstick approach suggested⁽²⁾ by the Jet Propulsion Laboratory (JPL).

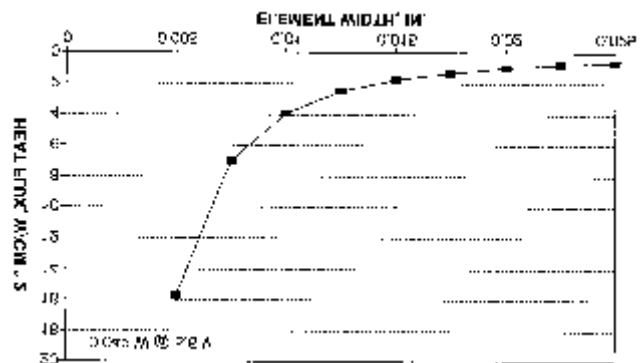
Small, low-powered, high-voltage thermoelectric modules were built for the MB-M75 generators in the late 1970s and early 1980s by the principals of Hi-Z while they were at General Atomic. These generators produced 125 mW at beginning of life when used with a sealed 4.5 W heat source. This technology was transferred to Hi-Z when the company was formed in 1988. However, the tooling to produce both the modules and the generators no longer exist.

One objective of the generator design is to limit the RHU temperature to below 275°C. This limit was set for two reasons. First, to minimize diffusion of He gas, which is a by-product of plutonium decay, from the RHU capsule. The second reason is to limit the maximum temperature that the RHU can attain during reentry into the atmosphere.

Thermoelectric Module

This low RHU design temperature goal restricts the thermoelectric material selection to bismuth-telluride alloys because these alloys currently provide the most efficient materials available in the temperature range. One of the necessary requirements for fabricating small, low-powered, high-voltage modules from bismuth-telluride is that one must use a fine grained material because of the small physical dimensions of the elements. This means that Bridgeman cast materials, which are typically used for many applications, cannot be used because typically the flaw size within the cast material can be about 1 mm while the cross-section dimension contemplated for the 40 mW module is 0.38 mm. We therefore selected the hot pressed bismuth-telluride as the reference material because it has both the physical and thermoelectric properties required to meet the design requirements.

The TCU was conceived as a monolithic structure of 324 elements bonded together in a square array. This construction

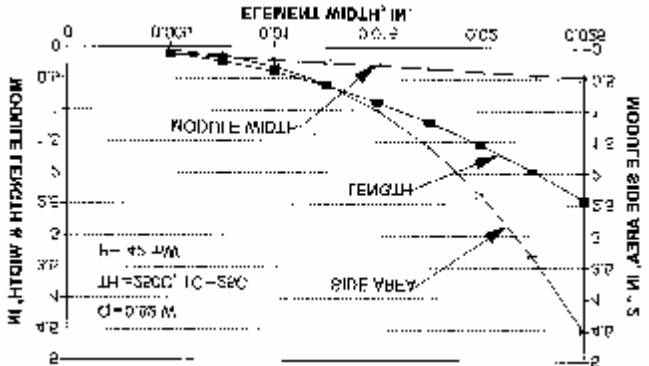


is one that can withstand the high shock and vibration loads associated with a space launch. Similar systems⁽³⁾ have been successfully shock tested hot at up to 80 g's with a pulse width at half the pulse height of 15 ms on all axis as well as being subjected to ± 3 g vibration from 8 to 200 Hz on all axis.

Figure 1: Module Length, Width and VRS Element Width

The graph of Figure 1 presents the calculation module length, width, and side (peripheral) area as a function of the module element width, assuming a square element. One can see how both the module length and side area start increasing

rapidly for element widths over 0.015 inches. The side area is of importance because it is directly related to the heat loss function of element width. One can see in this graph that the heat flux, and hence the temperature drop, across the various interfaces, increases quite rapidly at element sizes less than 0.015 inches. It is

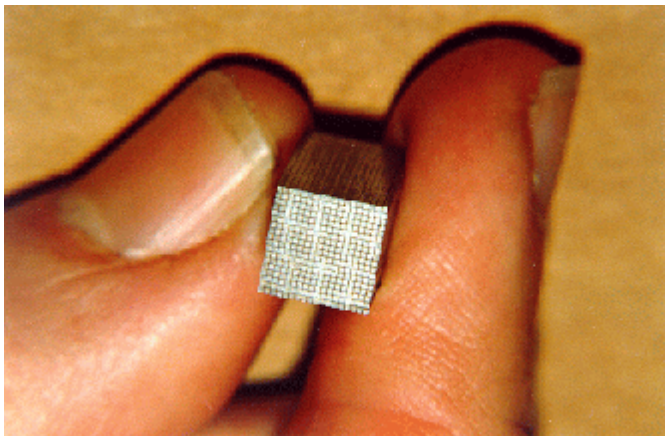


important to keep the various temperature drops low to keep the temperature of the RHU low and minimize heat loss.

Figure 2: Module Heat Flux - VRS Element Width

As a result, an element size of 0.015 inches was selected as the reference size for the 40 mW TCU. This results in a length of 0.9 inches and module dimensions of 0.291 inches by 0.291 inches by 0.9 inches long.

Preliminary tooling was designed and built to manufacture the module. The elements within the TCU must be aligned very accurately to allow the electric contacts which connect the individual elements within the module to be applied



using a photomask and vacuum sputtering. A picture of the resulting bonded element matrix is shown in Figure 3.

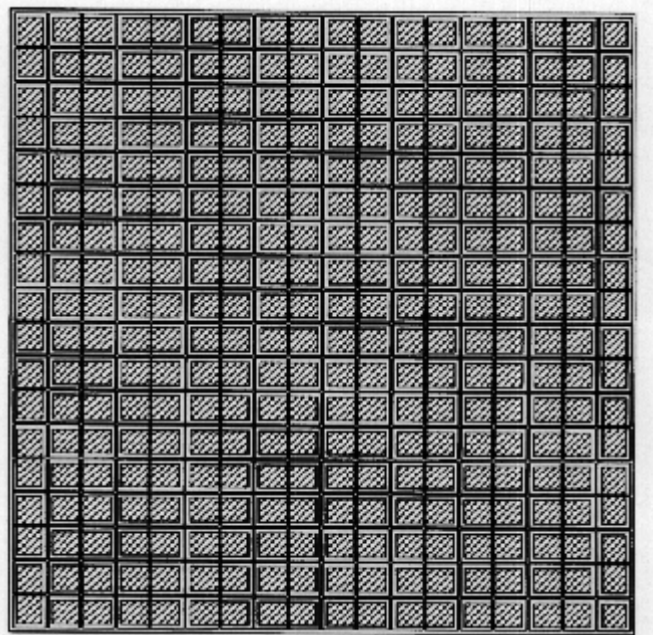
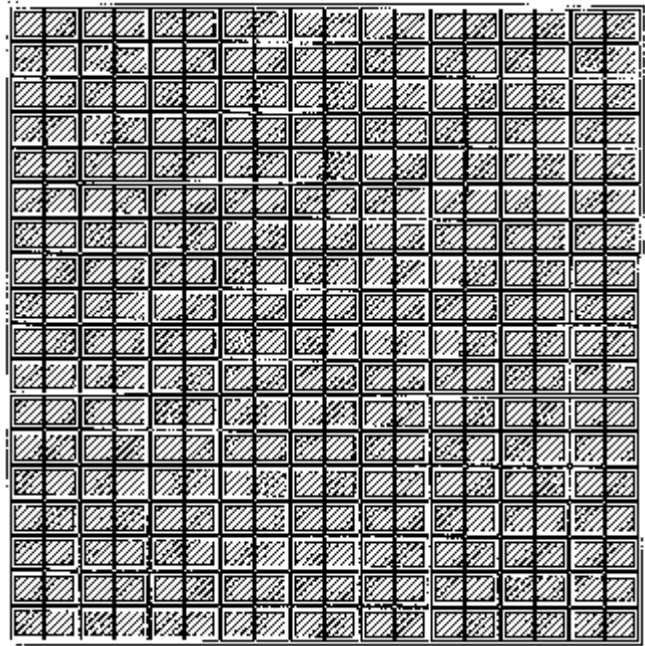
Figure 3: Trial TCU Module for Powerstick - 18 x 18 Matrix of 0.015 Inch Square Elements

Cold Side
Hot Side

The pattern for the electric contacts, for both the hot and cold sides, are shown in Figure 4. The contacts on the hot side are all applied in the same direction, while the majority of the

from the module.

Figure 2 presents the heat flux to the module also as a contacts on the cold side are placed in the same direction as those on the hot side, but displaced by one element to provide a series electric connection. The contacts at the end of the rows of elements are placed at 90° to join elements in adjacent rows. The contacts where connection is made to the external

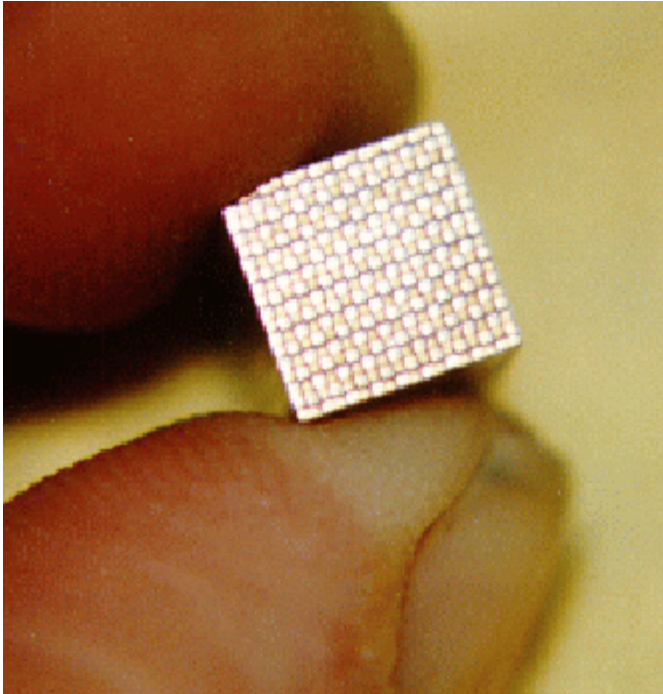


circuit are the two small squares in the corners. A photomask of the contacts is made and placed on the end of the module. A layer of contact material about 0.0005 inches thick was then sputtered through the mask to form the contacts.

The electric contacts have been placed on several prototype TCUs. Figure 5 is a picture of the contacts on the cold side of

Figure 4: Module Contact Pattern

the TCU. Metal was also sputtered on the side of the two corner connection element so that the wires to the external circuit can



be soldered to the side of the module rather than the end since
Figure 5: Cold Side of 40 mW TCU with Gold Contacts

that would interfere with cold side heat transfer. Three TCU modules were prepared and contacts were applied.

The method of manufacture used for the 40 mW TCU is similar to that used for the 75 mW generator module. The manufacturing methods have been updated to include the improvements in materials and technology which have occurred since the 1980s. As a result of these improvements allowed us to make the TCU in one operation, whereas the module of the 75 mW generator had to be made in four separate subsections which were subsequently bonded together to form the finished module. The new approach provides better overall alignment and allows us to bond the module as a single unit.

The electric contacts of the 75 mW generator were each spot-welded by hand, using a parallel-gap welder. This was a very tedious and expensive process requiring a high degree of operator skill. A change has been made from welding contacts to using a photomask and sputtering the contacts which is a much more controlled process and should be less expensive.

The tooling used to fabricate the prototype module is now being redesigned and upgraded. The new tooling will improve our ability to maintain the element alignment accuracy required during manufacture of the module.

Radioisotope Thermoelectric Generator Design

The design of the generator is based on the use of the 1 watt RHU heat source (*op sit*) and the 40 mW TCU discussed in the

previous section. The RHU is a right cylinder, 26 mm in diameter and 32 mm long, with a weight of 40 grams. The weight of the TCU module is 7 grams.

A conceptual drawing of the generator is shown in Figure 6. The RHU is contained in a polished aluminum capsule holder

with an internal Belleville spring stack allows differential thermal expansion between the RHU and the capsule holder and

Figure 6: 40 mW Generator Concept

holds the bottom of the RHU against the bottom of the capsule holder with a pressure of 200 lb/in². This pressure minimizes the temperature drop between the RHU and the capsule holder and insures that the RHU will not move within the capsule holder as a result of shock and vibration. The capsule holder is pressed against the end of the TCU, also with a pressure of 200 psi. This pressure is developed by tension in the four titanium tie wires which are connected between the titanium tie wire restraining ring and the base extension. The tie wire retaining ring is positioned on four lugs machined inside of the capsule holder. Tension in the tie wires is produced by four sets of Belleville springs located between the nuts on the end of the tie wires and the underside of the base extension. A thermally conductive electric insulator is placed between the capsule holder and the hot side of the TCU to prevent electric shorts.

The base end of the TCU is bonded to the base using a thermally conductive epoxy and Kapton. This Kapton is also used to electrically isolate the base from the TCU.

The thermal insulation system selected consists of multiple foils of aluminized Kapton. These foils, which are about 0.002 inches thick, are separated by ceramic paper. The volume remaining within the containment shell will either be evacuated or will be backfilled with Xenon gas through the pinch-off tube at the end of the containment shell. The inner surface of the containment shell will be gold-plated to increase its spectral reflectance.

The choice of vacuum or Xenon gas backfill for the containment will be made when more information is available on the off-gassing characteristics of the RHU. The RHU is a vented capsule so that some of the helium which is produced by radioactive decay of the ²³⁸Pu could escape the capsule. A pressure of 1 Atm of Xenon gas in the containment shell would minimize the diffusion of helium from the capsule. It has been reported⁽⁴⁾ that because of the relatively low temperature in the plutonium-dioxide fuel, it is expected that none of the inert decay gases will not be released. We do not have any actual RHU helium release data at the present time and will confirm this information during the program.

Xenon over-pressure will also suppress vaporization of the bismuth-telluride, compared to a vacuum environment, but this is an over-kill. Vaporization is not a problem because the partial pressure of Te over bismuth-telluride is less than 10^{-9} Atm at 250°C and the vaporization rate in the generator should be even lower because the TCU is very highly baffled which should have the effect of decreasing the vapor release. Based on previous data the generator should perform satisfactorily in vacuum at a T_H of 250°C.

To provide a point of reference one can compare the thermal systems of the 75 mW generator (MBM - 75B) and the 40 mW discussed here. Both generators employ similar construction techniques and thermoelectric materials. The measured power output of the 75 mW generator at beginning-of-life (BOL) was 120 mW, using a 4.5 Watt heat source. The pressure shell diameter was 1.8 inches and the insulation package consisted of xenon gas back-fill and two aluminized Kapton radiation foils

to suppress convection. In the 75 mW generator, 53% of the energy from the heat source passed through the TCU module and about 5% of that energy was directly converted to electricity. The remaining 47% of the heat source energy was lost through the insulation system or by other parasitic means

The heat flow through the TCU module in the 40 mW generator will be increased from the 53% for the 75 mW to 82% and the insulation and parasitic losses decreased from 47% to 18%. We believe this reduction in heat loss can be achieved because of both the increased size of the generator pressure shell for the 40 mW from 1.8 inches to 2.5 inches, which decreases to conductive loss, and the increase in the number of radiation foils from 2 to 20. This should reduce the radiation component by about 80%.

A paper⁽⁵⁾ by Schock and Or suggest that the RHU may overheat during re-entry because its temperature is 150° to 200°C higher at the start of re-entry, in the RTG case, than when it is being used as an instrument heater. Schock was concerned with the platinum-carbon eutectic that forms at about 1700°C. We believe that reaction between platinum and carbon can be blocked for the short (1 minute) transient period that the temperature is exceeded by placing a thin coating or foil such as iridium or tungsten at the platinum carbon interface. Also, in the generator's configuration, the RHU is held in an aluminum capsule holder and during re-entry, the capsule holder will melt at 660°C. This phase change absorbs

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3. J.C. Bass, *et al*, "Shock and Vibration Test Program for the MB-M75 (A) Radioisotope Thermoelectric Generator", Proceedings of the 14th IECEC, Boston, 1979
4. A.B. Chemielewski and R. Ewell, "The Power Stick" AIAA-94-3816-CD, 1994
5. Schock, A., Or, C.T., "Parametric Design Study of 'PowerStick' and Its Derivatives", American Institute of Physics, 461-478, 1995

energy and, therefore, will tend to slow the capsule temperature rise so it may attain a lower temperature than previously predicted. The degree to which the temperature is limited by the phase change will depend on both the details of the capsule and generator designs and the selection of materials used in the generator.

Results

The manufacturing process for a 40 milliWatt TCU module has been successfully developed that is an 18 x 18 array of thermoelectric elements (a total of 324 elements). The largest single array previously developed for small elements was an 8 x 8 array of 64 elements.

The calculations for the size of the TCU are based on the use of Hi-Z's hot-pressed bismuth-telluride alloy. This is the same material used in our commercially available HZ-14 and HZ-20 thermoelectric power modules. The hot junction temperature was selected to be 250°C and the cold junction temperature 25°C which are consistent with the operation of the TCU on a normal space mission. These temperatures are consistent with the 75 mW generator design.

A conceptual design of the 40 mW generator has been developed. This design incorporates much of the experience gained in the design and manufacture of the MB-M75 generators.

Current Program

Hi-Z was recently awarded the first phase of a three year Department of Energy-sponsored program to continue the development of the 40 mW generator. This phase will focus on fabricating a number of TCUs and putting them on long term test. In addition, the design analysis of the generator will be completed.

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References

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