Milliwatt Modules and Generators: Design, Fabrication, and Life Testing

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Abstract

Milliwatt modules for space applications are being fabricated and life tested for long life NASA applications that use Pu 238 as the heat source. Module testing using series circuit and redundant circuitry is in progress while generator testing using vacuum baked out multifoil insulation is just being initiated. Also, a milliwatt generator design, using multilayer quantum well materials, that offer a large gain in efficiency, will be presented.

Background

The design of the milliwatt generator began with a Phase I STTR program awarded by National Aeronautic and Space Administration (NASA) in 1996(1). The purpose of this program was to determine if a milliwatt radioisotope thermoelectric generator (RTG) could be built using the 1 W light weight radioisotope heater unit(2) (LWRHU) developed by the Department of Energy's Los Alamos Laboratory. The LWRHU, or RHU as it has become known, was designed to maintain the temperature of various instrument packages, at reasonable levels, in the frigid temperatures encountered during space exploration.

The actual size of the plutonium fuel capsule used in the RHU is rather small; however, it is surrounded by a rather large graphite heat shield to allow intact reentry from space. The size of the RHU has a significant affect on heat lost by the generator and therefore the overall generator size.

One basic problem in the design of a low power thermoelectric module operating over a reasonably high differential temperature is that the individual legs used must have a high length to area ratio. This problem was overcome by developing a monolithic module in which the long thin legs required were all bonded into a single solid unit. The single series circuit module consisted of an 18 x 18 array of N and P type bismuth telluride elements which were 0.038 cm x 0.038 cm in cross section and 2.286 cm long. They were made from high-density vacuum hot pressed bismuth telluride alloy material. The results of the preliminary design study are given in Reference 3.

The follow-on design of the generator continued under Department of Energy (DOE) contract starting in 1997. The initial generator design is similar to the design shown in Figure 1. The only major difference is that the four tie wires which hold the RHU containing fuel capsule against the thermoelectric module were straight instead of canted as shown in the milliwatt radioisotope power supply (MRPS) shown in Figure 1.

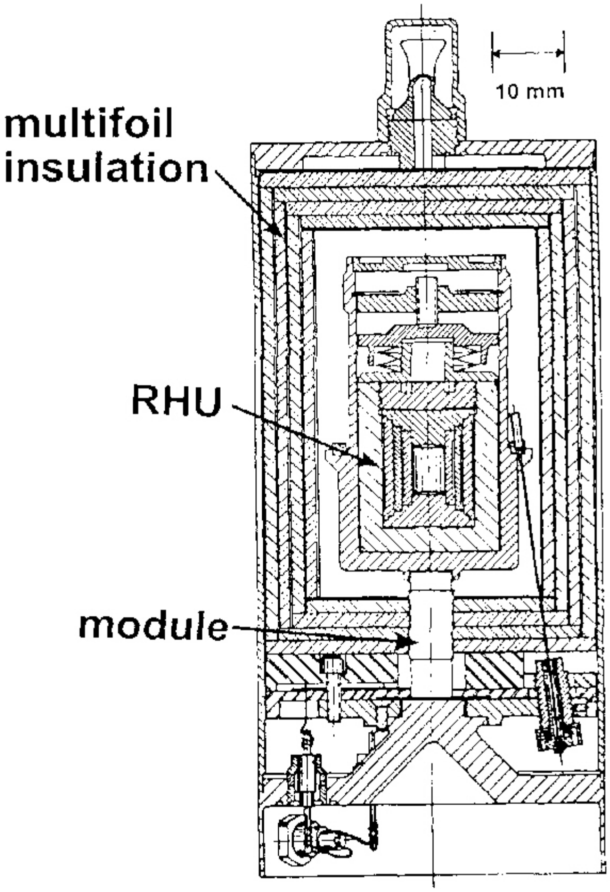

Figure 1. Layout of Flight System

There were no specific requirements for shock testing in the original DOE program plan for the 40 mW RTG. Later NASA/ARC became interested in the design as a potential power supply for their proposed PASCAL(4) mission to land a number of weather stations on Mars. As a result, the critical components of the original 40 mW design were shock tested at NASA/ARC. An initial mechanical analysis predicted that the generator should fail at about 80 Gs in a 45° side impact. However, drop tests conducted at NASA/ARC resulted in module failure of between 710 and 1025 G's at a 1 ms pulse. NASA was looking at shocks as high as 3,000 Gs. This requirement was what led to the canted tie wire design shown in Figure 1, to increased the G capability of the generator.

NASA recently took over the contract from DOE. The first part of the program will be to extend the module test program.

Hi-G Generator

With NASA considering the possibility of landing impacts involving multiple high G shocks, using their “beach ball” landing system, it was necessary to totally re-evaluate the basic generator design.

Another factor in this re-evaluation was DOEs desire to drop the vacuum insulated design and change to a design that incorporates a filler gas such as Xenon. The use of Xenon gas instead of a vacuum results in increased thermal conduction losses, which in turn, requires the use of two 1 W RHU fuel capsules to provide the 40 mW output desired. The higher shock loads on the tie wire, caused by the increased mass, results in higher stresses being imposed on the thermoelectric module if the original design were maintained.

Six different generator designs were evaluated. A schematic of the design selected is shown in Figure 2. The salient feature of this design is that the thermoelectric module is closely coupled with the fuel capsule holder. Heat from the cold side of the module is conducted to the base through flexible leads so that the fuel capsule and module move together in a shock situation. Four tie wires connect the fuel capsule to the tube frame and ultimately to the generator base.

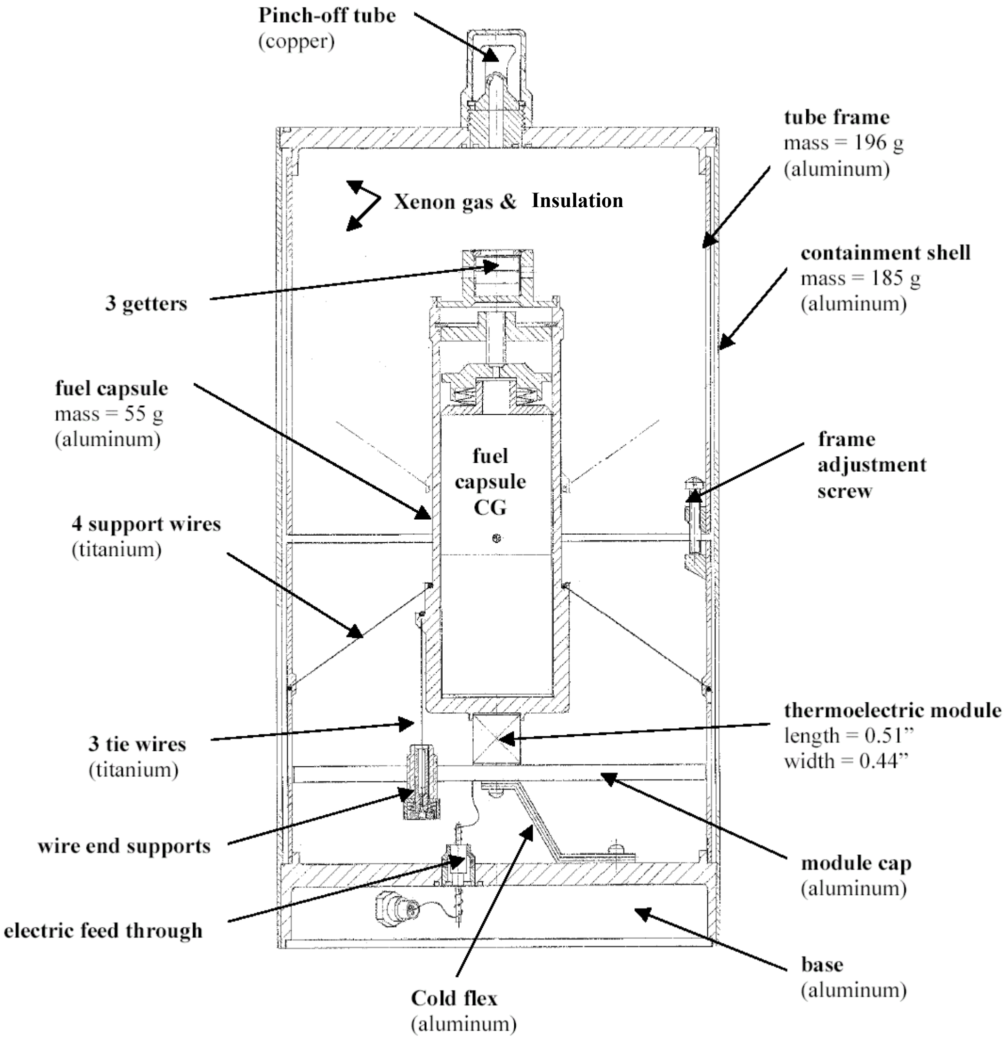

Figure 2. High G-Load, Gas-Backfilled MRPS.

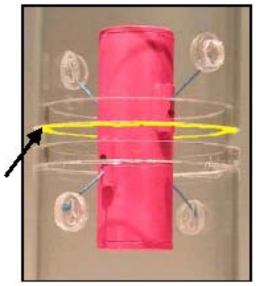
Yellow ellipse represents electron-beam weld

Figure 3. Model of Hi-G MRPS

A picture of a model used to verify the assembly features of the high G generator configuration is shown in Figure 3. The required tension in the tie wires is obtained by separating the upper and lower parts of the tube frame.

It should be noted that the Xenon gas insulated, two RHU generator is significantly larger and heavier than the original vacuum insulated system. This increase in generator size is due both to the conduction through the Xenon gas and to the increased fuel capsule surface area required in the two RHU design. Hi-Z currently plans to test a fully outgasssed vacuum insulated generator to prove the actual performance degradation that can be expected from such a system to possibly provide grounds for reconsideration of the vacuum insulated system.

Module Testing

A number of the 40 mW type modules have been fabricated in both single circuit and redundant circuit configurations. The element size in the single circuit configuration shown in Figure 4 is 0.038 cm by 0.038 cm by 2.286 cm long and in the redundant circuit configuration shown in Figure 5, it is 0.0254 cm by 0.0254 cm by 2.286 cm long. Both modules use essentially the same basic assembly procedures.

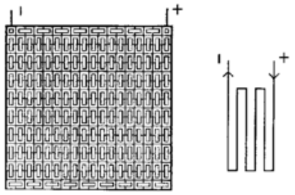

Figure 4. Single Circuit 40 Watt Module

One of the single circuit modules was provided to the Jet Propulsion Laboratory (JPL) for independent evaluation. Several more were put on test at Hi-Z.

The modules put on test at Hi-Z were accelerated tests at temperatures higher than the design operating temperature. This was done to help determine the modes of degradation that could occur more rapidly. Tests were conducted in both vacuum and argon cover gas test stations at a module hot side temperatures of 265C.

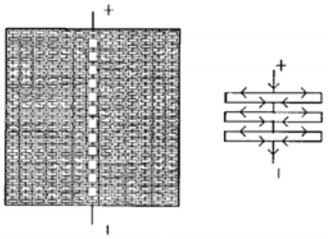

Figure 5. Redundant Circuit 40 mW Module Design

One of the possible means of degradation we were looking for was vaporization of the bismuth telluride at the hot junction and subsequent re-condensation at colder locations. To demonstrate this, the electric insulation material used on the sides of the modules was left off.

Figure 6 shows the normalized power (dark points) output for module 136-22 tested at $T_H = 261C$ with argon cover gas.

One will note the typical increase in power that is seen at the start of the test which is called “seating in”. This is followed by a steady degradation in power output. After 17,000 hours the module was cooled down and the station opened. The sides of the module were cleaned with a Q-Tip and the station was re-evacuated and brought back to its normal operating temperature.

One will notice the jump in power at the resumption of the test. The power output returned very nearly to starting levels followed by continuation of the degradation.

We believe that this type of degradation can be eliminated by coating the outside of the module with an insulator, such as Kapton or ZrO_2, that can be applied by sputtering or other techniques.

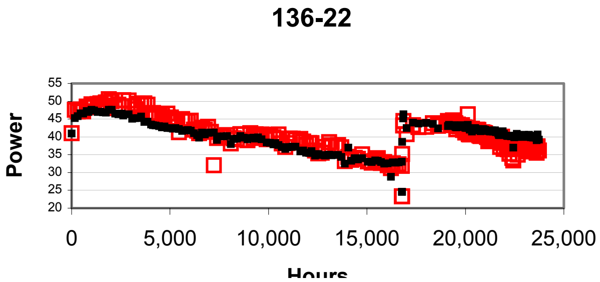

Figure 6. Power vs. Hours

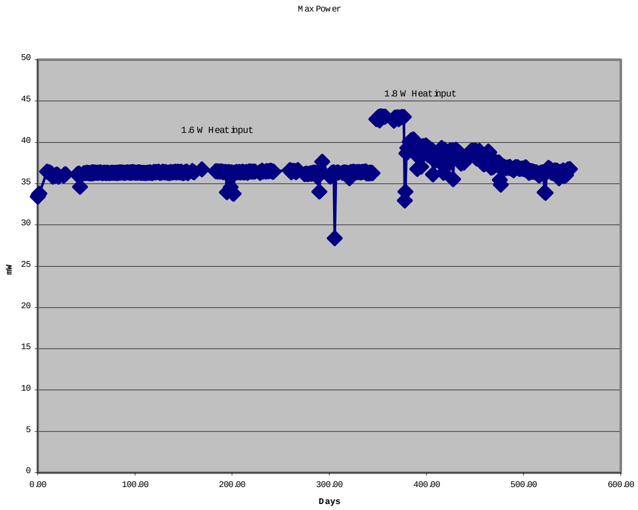

Figure 7. Module Life Test at JPL. Power ~ 36 mW

Other potential modes of module degradation include the diffusion of gold from the electric contacts down the thermal gradient. This has been observed in other modules. However, it is not known if this has a detrimental affect on module performance.

Another mechanism may be possible “cross talk” between the N and P elements which may result from element material vaporization. These mechanisms will be investigated in detail as the program continues and the degradation mode are eliminated or modified.

As shown in Figure 7, the 40 mW module was life tested at out to 350 days at JPL by Dr. Jeff Snyder. It remained constant in power output at ~36 mW, and operated at a T_H of

190 – 216C. At 370 days, the power input was increased from 1.5 to 1.8 Wt increasing the module power to 43 mW. After about two weeks, the module degraded and then leveled off. Periodic problems with the vacuum system were also encountered possibly oxidizing the module. It is unknown at this time if the poor vacuum environment contributed to the module's degradation.

Quantum Well Design

Hi-Z has reported (5) on its development of quantum well thermoelectric films. These materials are made up of alternating layers of materials with different electronic band gaps. Each of these layers is deposited to a thickness of about 100 Angstrom thick. The multiple layers are built up to a total thickness of about 11 μm. These films have been deposited by several methods including MBE and sputtering. The quantum well films made at Hi-Z are usually made by sputtering on to a substrate such as silicon.

Experiments with a couple of N type Si/SiGe and P type B_4C/B_9C on a silicon substrate shown in Figure 8 resulted in a conversion efficiency of over 14% at a temperature difference of 200°C.

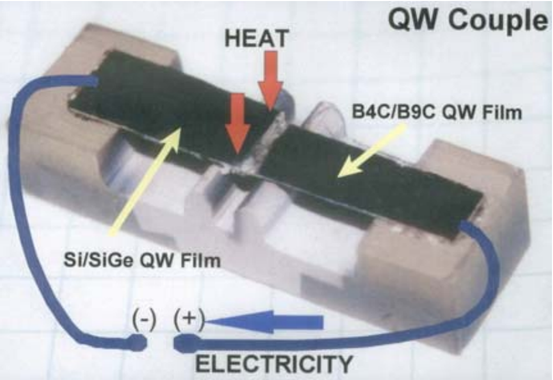

Figure 8. Quantum Well Test Couple

We were interested in both the potential performance of the 40 mW generator if the bismuth-telluride bulk material thermopile is replaced with quantum well films and also how such a change could be implemented.

Dr. Ghamaty's test couple produced 0.952 mW with an input power to the electric heater of 6.657 mW, or a gross conversion efficiency of 14.3%. In his paper, Dr. Ghamaty explained some of the problems associated with producing devices on a Si substrate, *i.e.,* the substrate can result in significant thermal bypass losses. However, if we just accept the couple test results as they are and assume that it can be reconfigured into a useable multicouple configuration, then the output of the milliwatt RTG would increase from 40 mW(e) to 114 mW(e).

If the couples are deposited on a doped SiGe substrate instead of pure Si, then one obtains a different result. The much lower thermal conductivity of SiGe substrate reduces the thermal bypass considerably. Calculations have been made using the measured thermoelectric properties of B_4C/B_9C and Si/SiGe quantum well films and the published thermal conductivity of N and P type bulk Si/SiGe. The films were assumed to be 11μm thick and the substrate 5 μm thick, as in the test couple. In this case the substrates used were doped N and P SiGe for the appropriate N and P quantum well film deposition.

For a T_H of 220°C, a T_C of 20°C and a thermal input of 0.8 W, the output was calculated to be 130 mW. The module required 18 couples to produce 5.64 Volts at a load matching factor of 2.24.

One will note the high load matching factor. In most bulk thermoelectric systems, there is not much difference in power between the load matching factor at peak power and that at maximum efficiency. However, with quantum well thermoelectric materials with a very high figure of merit (Z), there is a significant difference.

The resulting module would be constructed as a solid matrix module similar to the 40 mW module fabrication presented by Elsner *et al*(6). The major difference is that the plates from which the module is made are not cut from a solid block of thermoelectric material, they are built up by bonding layers of quantum well film and substrate together to form plates 0.221 cm thick. N and P plates made in this fashion would be used to make the first stack in a single circuit module.

There are 18 couples in the single circuit module arranged in a 6 x 6 array. The dimensions of the finished module would be about 1.344 cm on a side by 2.286 cm long. This compares with the 40 mW module that is 0.742 cm on a side by 2.286 cm long.

The dimensions of the quantum well module for the milliwatt generator have not been optimized. We believe that an optimized module would be somewhat smaller than the one presented here. Also, the estimated 130 mW output is felt to be conservative because the actual thermal conductivity of the quantum well films should be significantly lower than that of bulk material.

The implementation of quantum well materials leads to the possibility that one can design an RTG with a gas filled insulation system that can produce 40 mW in a single RHU design. The 40 mW quantum well module only requires 0.25 W input rather than the 0.8 W used in the current module. This would allow at least 0.75 watts available for thermal loss through the insulation system.

Conclusions

Work continues to improve the design of the 40 mW RTG. Long term module testing has revealed potential methods of module degradation from which corrective action can be taken.

A concept for a generator capable of high G landings. This generator will use a gas back filled insulation system and requires two of these RHU capsules.

Quantum well thermoelectrics hold promise for higher module performance which may permit a return to a single RHU design, even with a gas back filled insulation system.

Acknowledgements

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