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Fabrication and Testing of Thermoelectric Modules and Milliwatt Power Supplies

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Abstract. This paper reports the recent progress at Hi-Z technology, Inc., following from earlier work in development of milliwatt radioisotope power supplies for space applications. Several generator units have been built and tested. From the results of these tests, from ongoing design and analysis and from continued communication with DOE and with potential users of these generators at NASA, there have been suggested revisions and improvements. In this paper we discuss the most recent testing of power conversion modules and of units representing a Flight System MRPS design, and we describe two improved generator designs and their features.

INTRODUCTION

Hi-Z Technology, Inc. (Hi-Z) is continuing with a program for the U S Department of Energy (DOE) to develop a milliwatt radioisotope power supply (MRPS) that uses the thermal power of 1 W from the Light Weight Radioisotope Heater Unit (RHU) (Tate, 1992), which is already developed and has been deployed by the National Aeronautics and Space Administration (NASA). The nominal output of this generator is 40 mW at a matched load voltage of 6.5 volts. Several papers (Bass & Elsner, 1998; Allen *et al.*, 2000; Allen & Murbach, 2001; Hiller *et al.*; 2002 and Bass *et al.*, 2002) have been presented previously regarding the development of this MRPS, and the focus of the development is a Flight System MRPS that is illustrated in Figure 1.

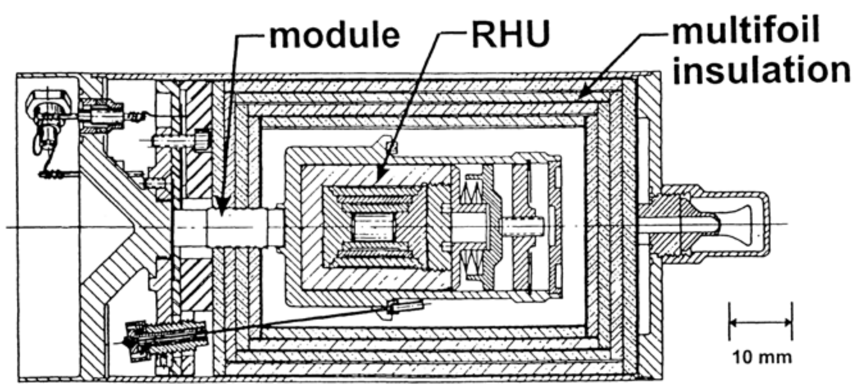


FIGURE 1. Layout of Flight System MRPS.

Several units of this generator design have been built and tested. From the results of these tests, from ongoing design and analysis and from continued communication with DOE and with potential users of these generators at NASA, there have been suggested revisions and improvements. In this paper we discuss the most recent testing of power conversion modules and of units representing the Flight System MRPS design, and we describe two improved generator designs and their features.

MODULE TESTING

Figure 2 shows the basic thermoelectric conversion module used in the generator designs in this paper. Shown is an array of 18 x 18 elements each 0.38 mm (0.015 inch) square and 22.9 mm (0.90 inch) long. The module dimension is 7.4 x 7.4 mm (0.29 x 0.29 inches). Figure 1 shows the relative size of one of the modules. The legs alternate P- and N-type $(Bi, Sb)_2 (Se, Te)_3$ oriented semiconductor material. Separating legs is 25 Fm (0.001 inch) Kapton® insulation. Fabrication details were published previously (Allen *et al.*, 2000).

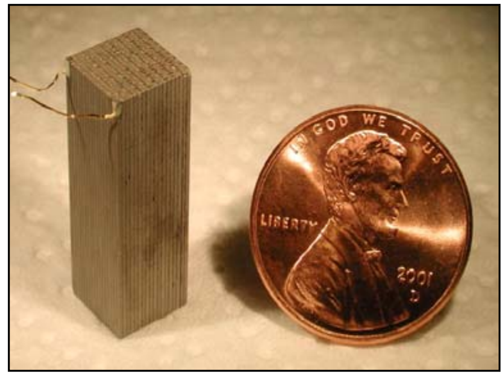


FIGURE 2. 40 Milliwatt Module with 324 Series-Connected Legs.

Hi-Z has a production facility for manufacture of this class of "Milliwatt Modules". Over a half dozen modules have been on test at Hi-Z over the past five years, with up to five on test at one time in a specialized module test station. In general, testing is done at reference design temperature conditions of hot side temperature, T_H, at 250°C and cold side temperature at ambient ($T_C \approx 30$°C). One application of the MRPS might be on Mars (Allen & Murbach, 2001). In that case the calculated average T_H is approximately 225°C while the T_C would be - 2 ± 28°C.

As of this writing four of these modules have been on test for over 10,000 hours and two of these for over 20,000 hours. One has been on test for over 25,000 hours. Accelerated testing of these modules at T_H = 250 to 260°C has been stable with some decline in output, as was expected. The mechanisms of this gradual decline in output are not entirely understood, but this phenomenon has generally been attributed to gold diffusion down the thermal gradient and possibly vaporization. This has been documented in reports by others with similar modules in years past (Rosell *et al.*, 1976). Previously, fueled RTGs which operated near the design T_H = 220°C exhibited little or no degradation when operated for approximately ten years (Allen *et al.*, 2000). Efforts continue to characterize the performance over time and to build a predictive model of the phenomenon.

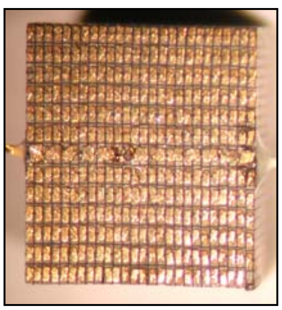


FIGURE 3. Cold Side of the Parallel Circuit Module, Consisting of 676 Elements 0.27 mm (0.010 inch). Square. Module Dimensions: 7.4 x 7.4 x 23 mm (0.29 x 0.29 x 0.9 inches).

One module was run at 300°C hot side temperature for accelerated testing. That module is undergoing post-operational examination.

The most recent module put on test is of a more ambitious design than the earlier ones. It has an array of 26 x 26 elements each 0.27 mm (0.010 inch) square. The thermoelectric couples are connected in two parallel circuits with periodic cross-connections. This module design offers improved reliability because of the redundant circuits, and it was described in more detail two years ago (Bass *et al.*, 2002). This module had accumulated more than 3500 hours as of 01 October 2003, and performance of has been stable.

FLIGHT SYSTEM MRPS DESIGN

The Flight System MRPS, shown in Figure 1, is designed around the RHU, which is used on U.S. spacecraft for localized heating of components. The RHU was designed and developed almost twenty years ago. It consists of a pellet of $^{238}PuO_2$ 6.3 mm (0.25 inch) in diameter and 9.4 mm (0.37 inch) long clad in 1mm (0.039 inch) thick Pt-30%Rh nested in a three layer pyrolitic graphite insulating assembly enclosed in a carbon-carbon composite aeroshell for accidental re-entry. Overall the RHU is 26 mm (1.02 inches) in diameter and 32 mm (1.26 inches) long, and its mass is 40 g. The multifoil insulation, indicated in Figure 1, consists of a radial cylindrical wrap and axial layers of alternating aluminized Kapton® and Cryotherm® micro-fiberglass paper in vacuum. The generator is 130 mm is 63.5 mm (2.5 inches) in diameter and 130 mm (6.0 inches) long, and its mass is 315 g in total.

No specific mission for the generator has been identified. However, among potential applications this design is being considered for the power supply of a proposed NASA mission called PASCAL, which would be a network of Mars science stations for long-term surface weather monitoring (Allen & Murbach, 2001).

Generator Thermal Insulation Performance

Two units of the generator with an electric heater simulating the RHU have been built and tested in excess of 2000 hours each. The principal objective of the testing of the complete generators was to prove and characterize the vacuum multifoil insulation. These tests were not conducted with a sealed generator having static vacuum, but rather the unit was connected to an active vacuum pump. In the first test pressure in the generator was maintained at 0.25 to 0.40 N/m^2 (2 to 3 mtorr). Insulation thermal conductivity and value predicted agreed within 3 or 4% with the best vacuum in the generator.

The second unit of the two was intended to be a full-up MRPS with the RHU, but circumstances prevented the execution of this plan. This electrically heated MRPS was used for several purposes, however, as follows:

- Performance with generator cold side held at varying temperatures, including very low temperatures that would be experienced on the Mars surface.
- Effect of variation in vacuum, variable gas backfill and additional internal structure.
- Long-term module performance trend in reference configuration and environment.

Generator Mechanical Shock

Critical components of the generator have been subject to mechanical shock test to validate the capability of surviving a Mars surface landing. Initially the PASCAL lander design was one in which the probe landed on a crushable nose, and as such mechanical loads along the main cylindrical axis of the generator were the greatest.

One element of the generator design is a trade-off between the thermal design for minimum bypass heat from the 1 watt RHU source around the thermoelectric module and mechanical design from the standpoint of surviving the landing impact. Focus of this process was optimizing material and thickness of the capsule tie-down wires. Ti-6V-4Al alloy wire of 0.64 mm (0.025 inch) diameter was determined by analysis and test to have the lowest ratio of thermal conductance to breaking strength.

Module and generator testing was done at the Engineering Test Lab at NASA Ames Research Center (NASA/ARC) on hydraulic tensile and compression test machines and a calibrated drop table. Generator tests were at temperature with electric heater and with instrumentation. The weakest part of the generator is the module, since the strength of the thermoelectric material is less than the other materials of the generator. The module could withstand 2338 Gs along the generator axis, and the unit survived 710 Gs in shock testing at 45° but failed at 1060 Gs, in both cases for 5 ms pulse width decelerations on a drop table.

The PASCAL mission design underwent a change as it evolved, and the shock load criterion was revised to 500 Gs in all axes, in order to withstand a balloon-type cushioned landing with several bounces. For these new conditions the Flight System MRPS was redesigned, and this is discussed below.

Station Electronics

Based on conservative estimates of the required power utilization and intended duty cycles of the PASCAL surface station, a software model and then an electronics breadboard were developed. One of the actively pumped generators was tested together with this breadboard at NASA/ARC. The breadboard includes the ultracapacitors and switches and emulation of the sensors and the subsystems for data storage, communications and control.

Outgassing Issue

Since the generator depends on the performance of multifoil insulation, the issue arises of how to attain a sufficient vacuum and how to assure it for the anticipated 20-year lifetime of an application such as PASCAL. Tests were done at Hi-Z and at Oak Ridge National Laboratory to characterize the outgassing of the components of the generator. These tests consisted of gravimetric and residual gas analysis testing of individual material samples and also instrumented valve closure and pressure rise tests (Hiller *et al.*, 2002). As an alternative to the vacuum insulation, a design with xenon gas backfill has been prepared, and this is discussed below.

FIGURE 4. Finished Unit Ready for Instrumentation and Testing

Long Term Test Unit

A third generator for long term testing with a closed vacuum has been assembled and will be put on test in the near future. Unlike the previous full generator units, this has been built in an inert gas-filled glove box with all of the components having been outgassed prior to assembly. This is also an electrically heated test unit, and the internal volume will be monitored with a vacuum gauge and a residual gas analyzer (RGA). The test will begin with active pumping while the internal components outgas, and then it will be sealed for life testing. The generator is shown in Figure 4 welded closed with ultra-high vacuum fittings on each end – on the bottom for instrumentation and on the top for the pump-out with copper pinch-off tube visible.

IMPROVED MRPS DESIGNS

From the results of tests, from ongoing design and analysis and from continued communication with DOE and with potential users of these generators at NASA, there have been suggested revisions and improvements. Two such designs are discussed.

High G-Load, Gas-Backfilled MRPS Design

A design has been adopted based on use of two RHUs as the heat source. Two are necessary to overcome the increased thermal loss directly from the RHU due to the greater thermal conductance of the thicker mechanical supports and the due to the gas backfill.

A four-wire support scheme is proposed, as shown schematically in Figure 5. In this arrangement 4 wires passing through the center of mass is calculated to be the strongest structure (omni directional) per unit of heat loss for a given G-Load

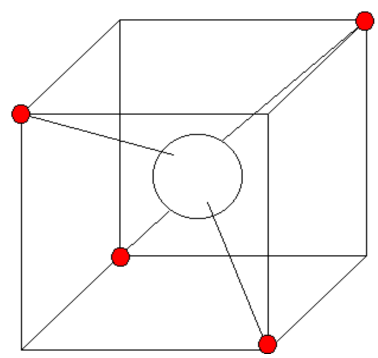


FIGURE 5. Schematic of RHU Support

Five principal features differentiate this design from the design previously developed to utilize vacuum multi-foil insulation. These are as follows:

Gas Fill: The MRPS will be filled with xenon gas to obviate the outgasssing problem. Xenon is the appropriate inert gas to use because it has the lowest thermal conductivity.

Wires Replace Module as Fuel Capsule Support: The fuel capsule is supported by wires rather than the module. The module is the weakest component of the generator so by not using it as a fuel capsule support the allowable G-load is dramatically increased.

Optimized Configuration of Support Wires: The number of the wires supporting the fuel capsule and the wire cross sectional area are minimized so that heat loss from the fuel capsule is minimized. This was achieved by passing the wires' line of force through the fuel capsule's center of gravity and angling the wires such that the maximum angle between the nearest neighboring wire is 109°.

Thermal Radiation Redesign: The aluminized Kapton® and Cryotherm® micro-fiberglass paper can be replaced by metal foil thermal radiation barriers. With xenon the number of barriers to be effective is considerably fewer than in the vacuum insulated design.

Maximization of Generator Output Power: The product of generator module heat and module efficiency has been maximized using pure and manipulated experimental data from the Flight System electrically heated MRPS test units.

Shown in Figure 6 is a sketch to scale with dimensions. Overall the unit will be approximately 100 mm (4 inches) in diameter and 200 mm (8 inches) long. Features of the generator are identified. The mass estimate is 760 g (1.7 lbs.).

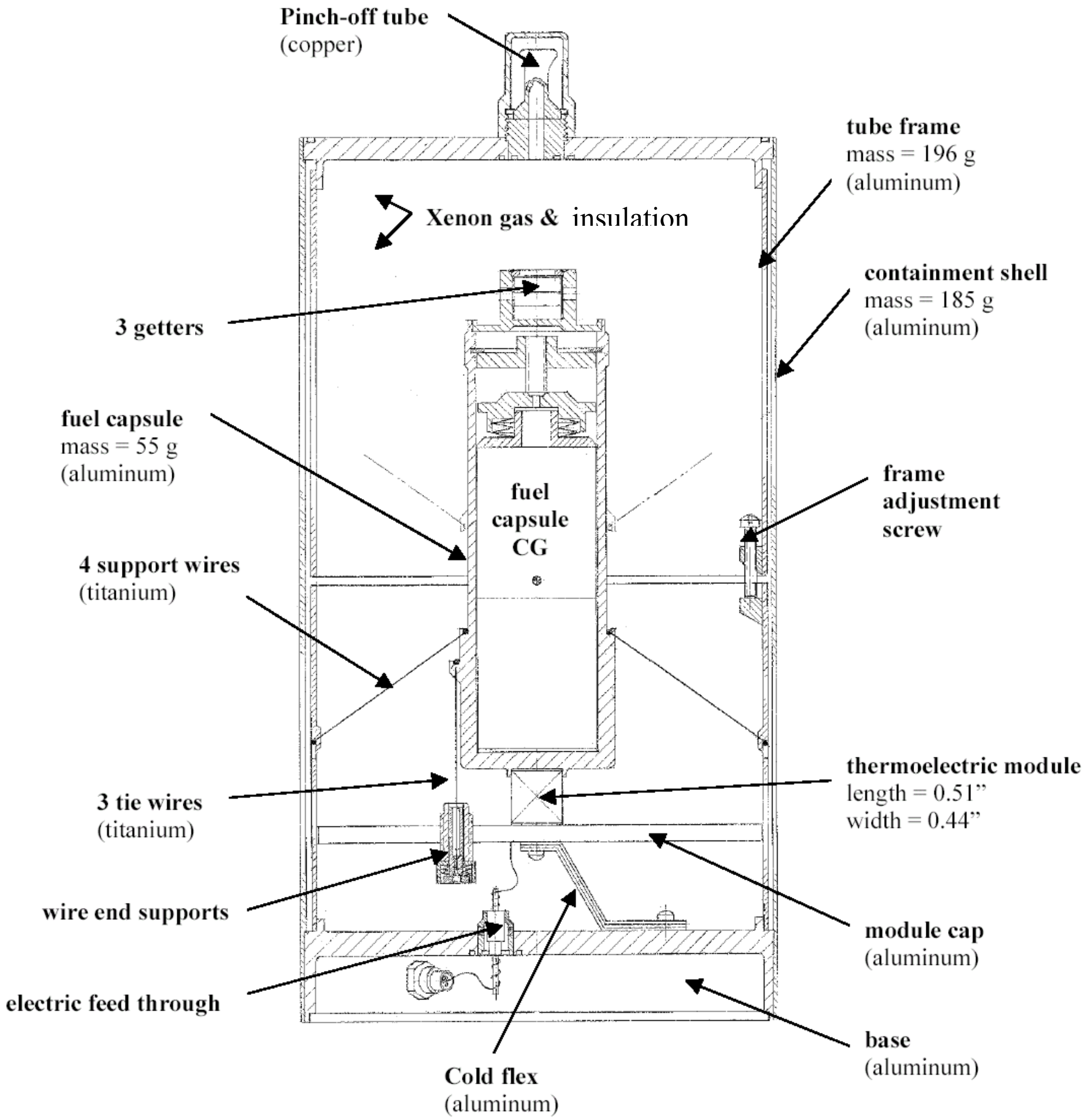


FIGURE 6. High G-Load, Gas-Backfilled MRPS.

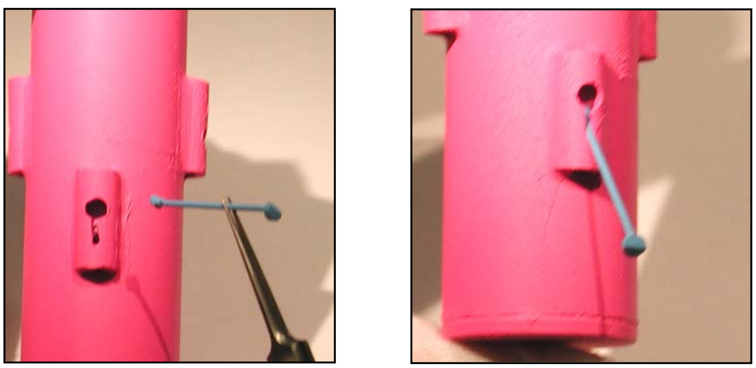
The expected output power of the generator is 33 mW. The outside diameter of the generator 100mm (4 inches). If it is reduced to 90mm (3.5 inches), the output power is 27 mW. There is a factor of safety of 3 on G-load. This was based on a factor of 2 for the worst-case translation of static load to dynamic load and then 50% margin.

A module for the generator was sized. This calculation is based on the optimized temperatures on the hot and cold side of the module of $T_H = 115°C$, $T_C = 25°C$. Of the 2 W from the RHUs, the heat to the module is calculated to be 1.2 watts. Table 1 gives the major parameters of the design.

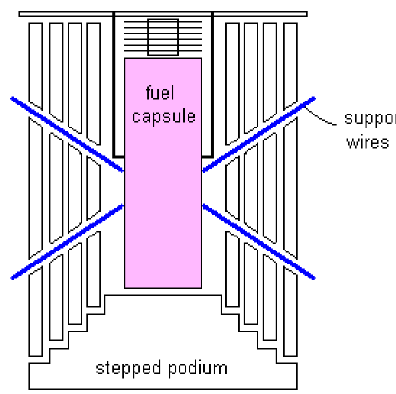
TABLE 1. Parameters of High G-Load, Gas-Backfilled MRPS.

Parameter	**Value**
element cross section	250 µm x 250 µm (0.010 x 0.010 inch)
module length	13 mm (0.51 inch)
matched load voltage	6 V
number of couples/circuit	400
total number of elements	1600
element array	40 x 40
power output	34 mW
heat flux	1.16 W/cm^2
conversion efficiency	2.8 %
module side dimension	11 mm (0.44 inch)

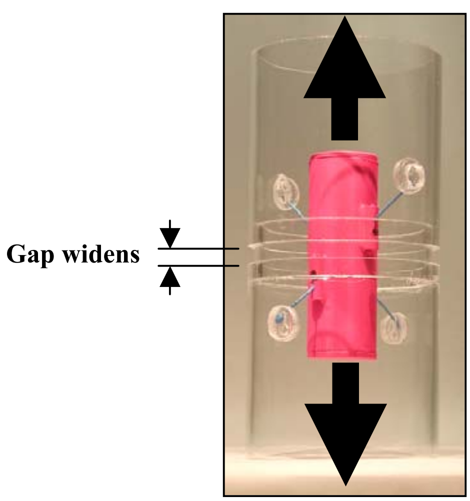
Design of the wire tensioning have been engineered. Figure 7 illustrates the sequence of assembly the application of tension in the wires with the frame adjustment screws.



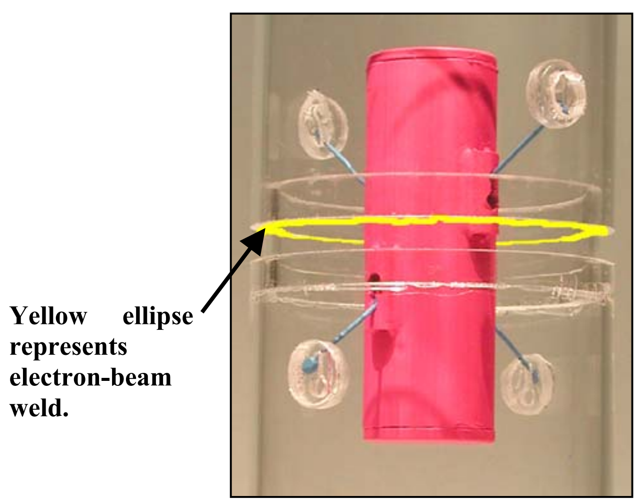
(a) and (b) Insert Support Wires.



(c) Add insulation.



(d) Use Frame Adjustment Screws for Tensioning.

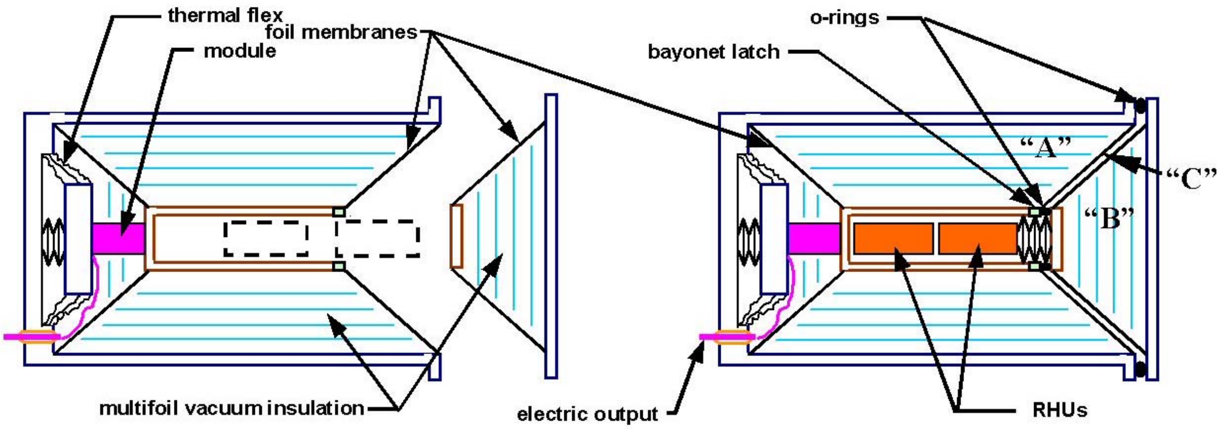


(e) Weld to Secure Frame.

FIGURE 7. Assembly Steps for Wire Tensioning of High G-Load, Gas-Backfilled MRPS.

Alternative Vacuum Insulated MRPS Design

In Figure 8 is a sketch of a design in which there are two RHUs in a housing that is supported by two 45° cones of thin titanium alloy foil. The foil membranes replace wires used for support in the Flight System MRPS and the High G-Load, Gas-Backfilled MRPS. An estimate is that a foil thickness of between 25 to 50 µm (1 to 2 mils) will support a mechanical load of 1350 Gs, which is about 2300 N (527 lbs.). Cavities "A" and "B" in the figure are two separate vacuum chambers containing multi-layer insulation (MLI), like the Flight System MRPS. The cavity for the two RHUs can be accessed by separating the two parts of the MRPS. Space "C", which communicates with the RHU capsule, does not have to be evacuated, but it is sealed with an o-ring at the outside diameter. If a method can be found of making these foils and the connections at either end vacuum leak tight, this configuration solves two significant potential problems in the utilization of the MRPS.



(a) As Fabricated and Outgassed

(b) As Finally Assembled with RHUs

FIGURE 8. Alternative Vacuum Insulated MRPS.

The flight article can be tested with an electric heater in place of the RHUs, and in such a test all features of the generator can be validated. The key feature of the design is that the RHUs can be put in at the very last minute before launching. This feature was considered to address the logistic problem of limited authorized worksites and tight security that would be required once the RHUs would be installed.

Another benefit of this design is apparent. In the Flight System MRPS the final outgassing is done after the RHU is sealed in. Therefore the design temperature difference is imposed on the thermoelectric module thereafter, and the outgassing temperature is set by a limit on the maximum thermoelectric module temper-ature. The proposed unit without the RHUs can be brought to higher temperature for final outgassing and sealing because the RHUs are absent at that step. Figure 9 shows a further advantage in an application like PASCAL. Here the entire science station is built and tested with all final vacuum chambers sealed prior to introduction of the RHUs.

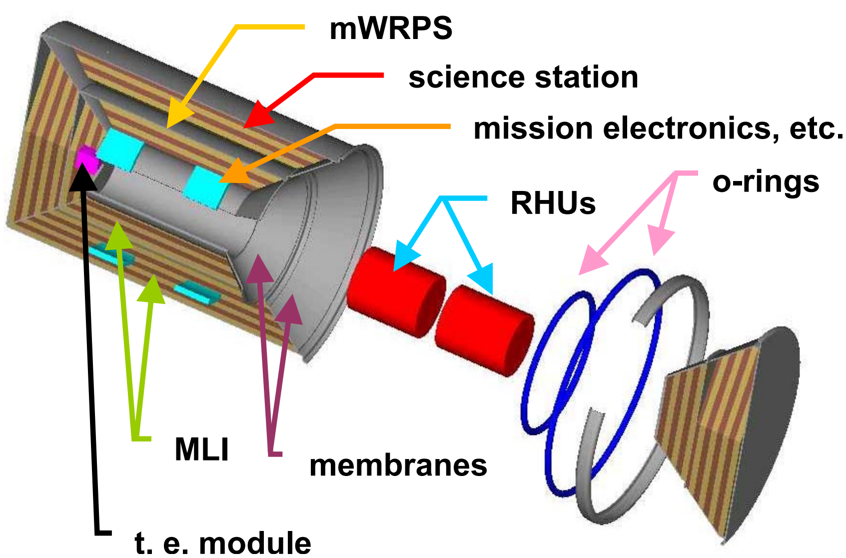


FIGURE 9. Science Station with Alternative Vacuum Insulated MRPS.

CONCLUSIONS

The technology has been demonstrated for "Milliwatt Module" fabrication, and significant strides have been made towards module lifetime proof testing. The initial insulation has worked well in testing when the vacuum was adequate, and testing will begin soon on a closed vacuum life test generator. An alternative to the Flight System MRPS is the High-G Load design, which addresses the outgassing and omni directional shock issues. Integration with a representative mission electrical system was successful. A second alternative design of the MRPS considers the problem of special handling requirements on the RHU.

ACKNOWLEDGMENT

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