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Corresponding Author: Dr. Mitsuru Kambe, Ph.D

Corresponding Author's Institution: CRIEPI

First Author: Mitsuru Kambe

Order of Authors: Mitsuru Kambe; Mitsuru Kambe, Ph.D; Takahiro Jinushi

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Mitsuru KAMBE

I have revised my manuscript according to your comments. Thank you.

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Mitsuru KAMBE
Central Research Institute of Electric Power Industry (CRIEPI)
11-1, Iwado Kita 2-chome, Komae-shi, Tokyo 201-8511, Japan
E-mail: kambe@criepi.denken.or.jp

Takahiro JINUSHI and Zenzo ISHIJIMA
Hitachi Powdered Metals Co., Ltd (HPM).
2-1, 5 chome, Minoridai, Matsudo-shi, Chiba, 270-2295, Japan
E-mail: z-ishiji@hitachi-pm.co.jp

Abstract

An encapsulated thermoelectric (TE) module consists of a vacuum tight stainless steel container of 55×50×11 mm in which a SiGe or BiTe TE module is encapsulated. This situation enables maximum performance and durability because 1) the thermal expansion mismatch between the hot and cold sides of the container can be accommodated by a sliding sheet in the container, 2) the TE module inside is always kept in a vacuum environment, therefore no oxidation can occur, and 3) the difference in pressure between the inside and out sides of the container reduces thermal contact resistance inside the container. A compliant pad is made of porous material in which braze filler material is infiltrated, If heated over the melting temperature of the braze filler, the thermal gap conductance at the interface would be enhanced due to strong affinity of the braze filler with an adjacent member. Sliding of this interface is possible so long as the braze filler is liquid. This design strategy provides a high flux, direct conduction path to the heat source and heat sink, and enables 1.7 times greater temperature gradient on the TE module itself as that of conventional one; therefore it can demonstrate 3 times greater power.

1. Introduction

In the development of thermoelectric (TE) systems, not only the semiconductor material, but also the TE module and heat exchanger system play important roles to achieve higher system conversion efficiency and long life durability.

Conventional multicouple TE module is usually sandwiched between electrically insulating base plates to protect sensitive semiconductor elements. At operating temperatures, however, the dome shaped deformation of the TE module due to differential thermal expansion between the hot and cold base plates would result in severe thermal stress in the TE module. Another design available is a skeleton module which has an electrically insulating base plate on one side while the other side of the module is open. If the base plate is attached to the colder side, it is easier to relief the thermal stress in the module. However, this module is very fragile. Therefore most of the modules of standard products on sale have two base plates. To relief thermal stress in the module completely and to achieve long life durability, the authors developed **encapsulated TE modules** in which a **both-sides-skeleton module** is encapsulated. Structure and performance of the encapsulated modules are presented in this paper.

In most of the TE systems for terrestrial applications, TE modules were placed between the hot duct (heat source) and cold duct (heat sink) with a pressure load. This is called as "**conduction coupling**". This configuration encounters two contradictory issues. 1) At operating temperatures, the differential thermal expansion between the hot and cold ducts must be accommodated without inducing large stress in the TE module. In view of this, a moderate pressure load is preferred. 2) On the other hand, the thermal contact resistance at the TE module/duct interface should be minimized, or poor electrical output is available. Increasing the pressure load would reduce the thermal resistance; however, it would damage fragile TE modules. Under these circumstances, the authors proposed **bond-free compliant pads**[1)] to accommodate greater thermal expansion mismatch and severe thermal transient. Structure, properties and performance of the bond-free compliant pad are also discussed in this paper.

2. Encapsulated Thermoelectric Modules

2.1 Encapsulated Thermoelectric Module for Space and High Temperature Applications

The encapsulated TE module (**Fig.1**) consists of a vacuum tight stainless steel container of 55×50×11 mm in which a SiGe TE module is encapsulated. In the container, mica sheets for electrical insulation and carbon sheets to accommodate differential thermal expansion are also inserted on both sides of the module. Because this module has no electrically insulating base plate, thermal stress relief in the module is perfectly achieved. However, a both-sides-skeleton module is very fragile, considerable attention should be paid to handle such modules during assembling and encapsulation. Therefore systematic handling procedure as well as holders at module brazing, assembling and welding steps is developed. Once encapsulated, the container inside is a vacuum because electron beam welding of the container is done in the vacuum chamber. Accordingly the module is stably held inside the container due to differential pressure of 1 bar (0.1 MPa) exerted on the top container of 0.1 mm thick. This pressing force has another important role to reduce thermal contact resistance between each member in the container.

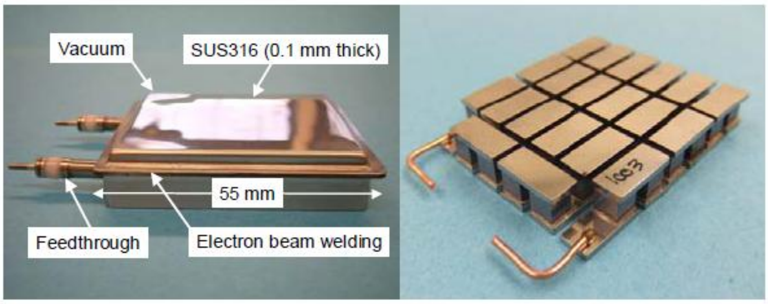

Fig. 1 Encapsulated TE module (left) in which SiGe module (right) is encased

Another advantage of encapsulation is that the module itself is always kept in a vacuum even though the container is placed in hot air or corrosive atmosphere which is foreseen for TE modules applied to make use of industrial waste heat and automobile exhaust gas. Hence it ensures long life durability of the TE semiconductor which is very sensitive to humidity, oxidation and corrosion. Our encapsulated SiGe module features higher operating temperature; up to 650 ºC for both hot and cold sides. Module performance is shown in **Fig.2**. Durability of 1400 heat cycles at 550°C is proven on the SiGe module.

In addition an encapsulated BiTe module is also available. The BiTe module adopted here is "one-side-skeleton module" because thermal expansion mismatch is not so greater than that of SiGe module. The operating temperature of BiTe module covers 180ºC to

–190°C for both hot and cold sides[2)].

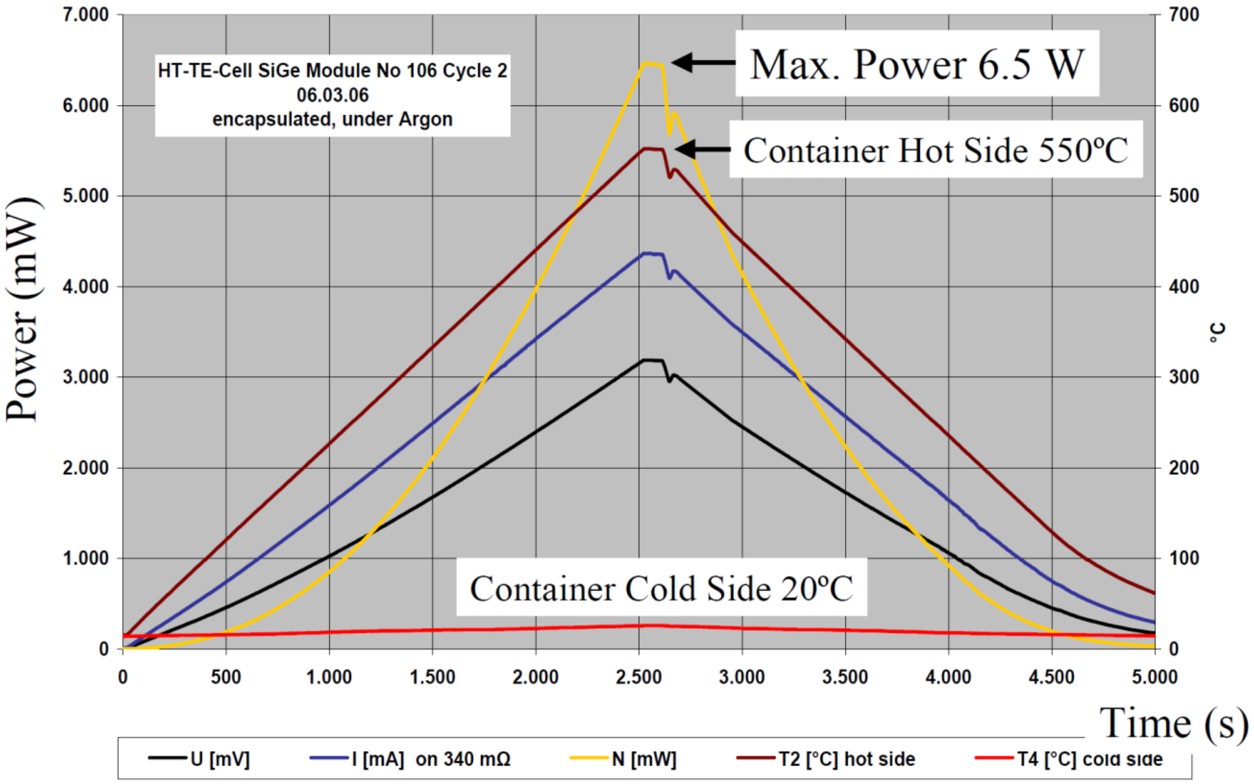

Fig. 2 Encapsulated SiGe module performance

2.2 Encapsulated Thermoelectric Module with Integrated Cooling Panel

This module is provided with an integrated cooling panel in which cooling water could pass through. In case the module hot side is heated by radiating heat source (**radiation coupling**) or convection of hot gas or fluid (**convection coupling**), no pressing force on the module is necessary. Therefore it features minimum contact resistance to the cooling duct without pressing force, maximum TE power, and minimum installation cost.

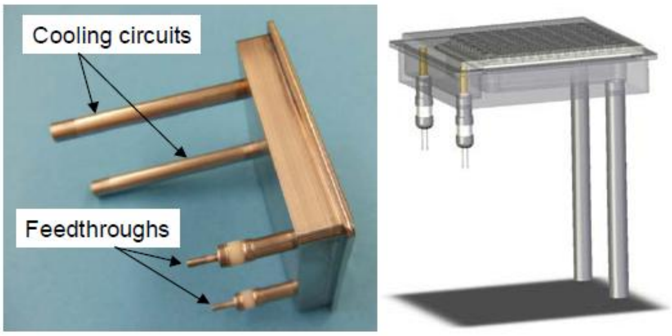

Fig. 3 Encapsulated TE module with integrated cooling panel

3. Compliant Pads

Greater the capacity of the TE energy conversion system, larger the heating and cooling ducts between that TE modules are clamped. In addition the operating temperature of the TE power conversion systems for space applications is generally higher than those for terrestrial systems. A bond-free compliant pad **(BFCP)** [1, 3)] should be used to accommodate such severe thermal expansion mismatch parallel to the duct surface (**Fig. 4**). BFCP is made of porous material in which braze filler material is infiltrated. If heated over the melting temperature of the braze filler, thermal gap conductance of the interface would be enhanced due to strong affinity of the braze filler with adjacent member. Sliding of this interface is possible so long as the braze filler is liquid. The advantage of this concept is that the braze filler comes out of the pores continuously to compensate loss of braze filler mainly due to vaporization. The thermal gap conductance would be kept as much as initially obtained. Therefore the long life durability could be assured. The following BFCPs are manufactured and tested so far.

- Bismuth (melting temperature 271°C) infiltrated in oriented carbon fibers (**Bi/C**) (**Fig. 5**).
- CB2 braze filler (trade name of Goodfellow GmbH, 96Ag-4Ti, melting temperature 970°C) infiltrated in oriented carbon fibers for space systems (**CB2/C**) [3].
- Bismuth infiltrated in porous copper (**Bi/Cu**).
- Salt ($NaNO_3/KNO_3$, melting temperature 213°C) infiltrated in porous copper (**Salt/Cu**).

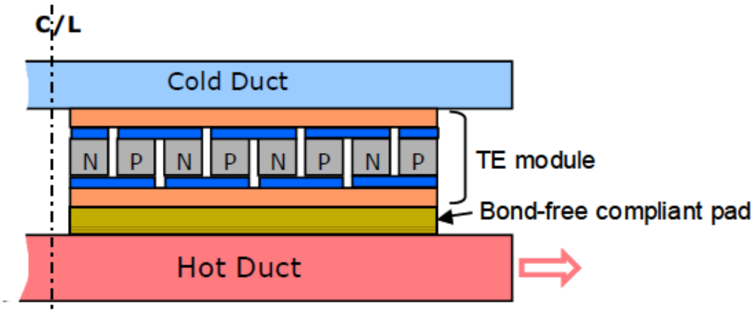

Fig. 4 Bond-free compliant pad concept

As shown in **Fig. 5**, bismuth is infiltrated by squeeze casting process into 80% density oriented carbon fiber. Performance of the **Bi/C** bond-free compliant pad is demonstrated in **Fig. 6**. Due to superior thermal conductivity of carbon fiber in the longitudinal direction, thermal conductivity of the pad in the direction normal to the contacting surface is also excellent. The effective thermal resistance of the pad (i.e. thermal contact resistance of both contacting surfaces of the pad as well as thermal resistance of a 10 mm thick pad) suddenly decreases by one order of magnitude if heated over melting temperature of bismuth (271°C).

Conduction coupling TE system with BFCP provides a high flux, direct conduction path to heat source and heat sink, and enables 1.7 times greater temperature gradient on the TE module itself as that of conventional one; therefore it can provide 3 times greater power[1].

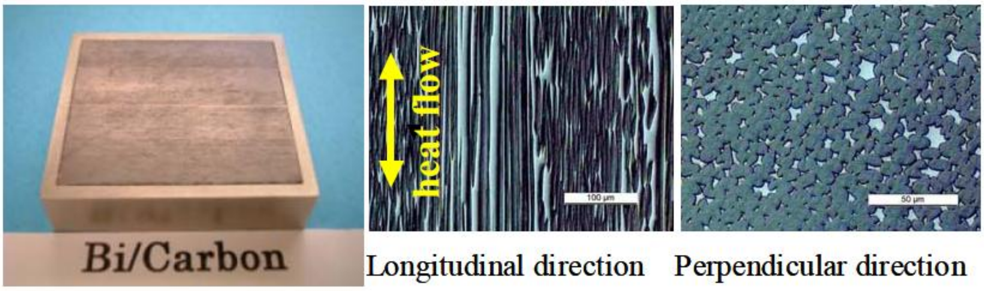

Fig. 5 Bismuth infiltrated carbon (**Bi/C**) bond-free compliant pad

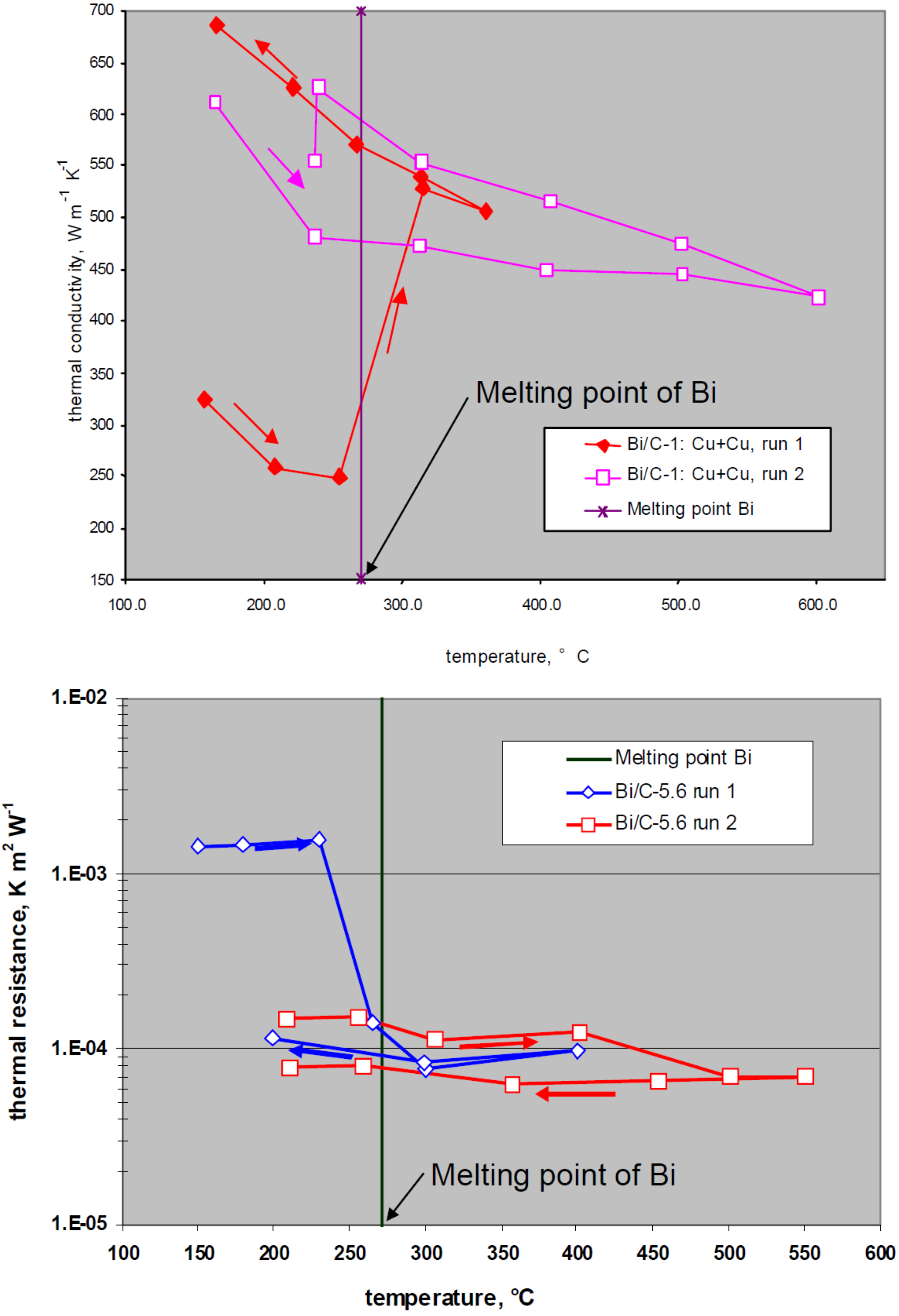

Fig. 6 Thermal conductivity (top) and effective thermal resistance (bottom) of the **Bi/C** BFCP

4. Conclusion

The encapsulated TE modules and bond-free compliant pads could enhance TE system power and long life durability. Bond-free compliant pad could achieve thermal gap conductance one order of magnitude greater than that of mechanical contact.

5. References

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