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THERMAL CONTACT CONDUCTANCE OF RADIATION-AGED THERMAL INTERFACE MATERIALS FOR SPACE APPLICATIONS

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ABSTRACT

Thermal interface materials (TIMs) serve a critical role in thermal management by enhancing heat transfer across contact interfaces. Specifically, they are most commonly used in electronics to enhance the flow of heat from source to sink by decreasing the overall thermal resistance of the system. In space, these materials are exposed to high doses of Gamma radiation due to the lack of an atmosphere to serve as an absorbing medium. With typical design lifetimes of 5 to 10 years, total radiation exposure can be significant and can adversely affect the thermal contact resistance (TCR) of the TIM. In this manuscript, we report the effect of radiation-aging on the TCC of several commercially available electrically insulating, thermally conductive interface materials that are commonly used in satellite systems. Although radiation dose levels can vary significantly during the course of a space mission, a dosing of 10 Mrad per year for TIMs is a reasonable estimate. The TIMs were aged in a Gamma cell at a rate of 250 rad/s to total doses of 50 and 100 Mrad to simulate mission lengths of 5 and 10 years, respectively. The TCR of each radiation-aged sample, as well as un-aged samples, were measured under vacuum (less than 3 x 10^{-4} Pa). Radiation-aging of the TIMs led to a significant increase in the TCR of the tested samples. For example, the pressure-dependent TCR was shown to increase 20-150% for Cho-Therm 1671 and 50-250% for ThermaCool R10404 samples subjected to 50 Mrad of gamma-ray irradiation. These results show that radiation-aging of TIMs cannot be ignored in the design and simulation of space systems.

NOMENCLATURE

A	Apparent area of contact
a, b	Constants
P	Pressure
Q	Heat rate
R	Thermal contact resistance
ΔT	Temperature drop

Subscripts

1, 2	Heat flow meter number
b	Bulk
c	Contact interface

INTRODUCTION

Heat transfer across the interface of contacting materials is of fundamental importance in the design and simulation of thermal systems. Due to the microscopic roughness found on all manufactured materials, heat is restricted to flow through a small number of contact spots formed between two mating surfaces, which give rise to a thermal contact resistance R given by

$$R = \frac{A\Delta T}{Q} \quad (1)$$

where Q is the heat rate, ΔT is the temperature drop across the interface, and A is the apparent area of contact. For typical surfaces the actual contact area (sum of the contact spot areas) is typically 2 to 6 orders of magnitude less than the apparent area of contact [1]. As a result, thermal contact resistance (TCR) can be quite large, often accounting for a significant fraction of the total thermal resistance of a system [2–4].

Thermal interface materials (TIMs) are interstitial materials that are inserted at contact interfaces as a means of reducing TCR by improving the contact between the two materials. By providing additional low resistance pathways for heat flux, TIMs are capable of significantly enhancing heat transfer across the interface [5,6]. The majority of current research is focused on decreasing contact resistance using TIMs consisting of metallic foils [4], conductive polymers [7], and nanomaterials such as carbon nanotubes [8,9] and graphene [10]. This work is predominately driven by the consumer electronics industry and focuses on measurements conducted under atmospheric and vacuum conditions. However, significant cooling issues exist for military and space applications, which not only require high-reliability cooling solutions, but also excellent vibrational damping and electrical isolation characteristics, for extended periods of time (up to 10 years or more) in severe environments [11].

Milanez and Matelli [12] studied a bimetallic thermal switch designed for space applications. Their theoretical predictions differed from experimental measurements; these inaccuracies were attributed to inaccurate prediction of the TCR at the metallic interfaces. Marchetti *et al.* [13] measured the contact resistance between metals (aluminum, copper and stainless steel) and composite materials (glass fiber printed circuit board and carbon fiber laminate) commonly used in space applications. Pressure dependent TCR measurements were obtained for 8 different material combinations, however, only bare interfaces were considered in this study. Peterson and Fletcher [4] investigated metallic foils for use as TIMs in space station cold plates. Gandhi and Pathak [14] measured the TCR of graphitic sheets for use as TIMs for cooling of satellite electronics. Although these works present advancement of knowledge related to thermal management in space systems, they neglect the effects of the harsh environment presented in space.

In space, systems are subjected to a wide array of radiation sources including gamma, UV, X-ray, and charged particles—all of which have the potential to drastically affect material properties [15,16] and structure [17]. The effects of radiation on electronic components has been studied extensively and is described in the review by Hughes and Benedetto [18], however, its effects on the solutions used to help cool these components has been neglected in the literature. Here, we report the effects of gamma irradiation on the TCR of two commonly used interface materials in satellite systems (Cho-Therm 1671 and ThermaCool R10404) under vacuum conditions for interfacial pressures from 70 to 2300 psi. These two TIMs were chosen because they provide the vibrational damping and electrical isolation characteristics required of many space applications while exhibiting moderate thermal conductivity.

Table 1: Manufacturer specified physical properties of the TIMs.

Property	**Cho-Therm**	**ThermaCool**
Color	White	Light green
Thickness (mm)	0.4	3.2
Thermal conductivity (W/mK)	2.6	0.36-0.86*
Thermal resistance (mm^2K/W)	150	3400-8600*
Hardness (Shore 'A')	90	13
Density (kg/m^3)	1550	1105

* Highly sensitive to compression of the TIM

EXPERIMENTAL DETAILS

Materials

Two TIMs were investigated in this study: 1) Cho-Therm 1671 and 2) ThermaCool R10404, which will be referred to as Cho-Therm and ThermaCool, respectively. Cho-Therm is a silicone elastomer filled with boron nitride particles and reinforced with a fiberglass cloth. ThermaCool is a closed cell silicone sponge rubber. Both TIMs are thermally conducting, electrically insulating materials that are commonly used to electrically isolate satellite electronics from the heat sink while also enhancing cooling. The manufacturer specified physical properties of each material are summarized in Table 1.

Figure 1: Photograph of test samples in the Gamma cell.

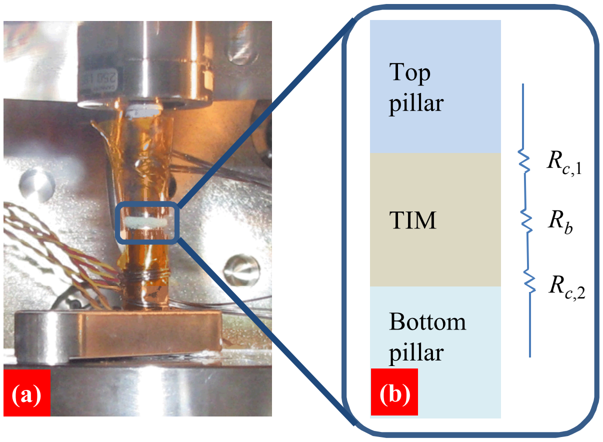

Figure 2: (a) Photograph of the measurement system. (b) Thermal circuit equivalent when a TIM is inserted between the two heat flow meters.

Experimental System

Thermal measurements were conducted using a one-dimensional steady-state conduction technique based upon ASTM standard D470-06 [19]. The system, shown in Figure 2(a) consists of two metallic pillars that serve as heat flow meters. Each is 2.5 cm in length and 0.8 cm in diameter instrumented with 6 thermocouples each and placed between a hot plate and cold plate. Two different sets of heat flow meters are used during testing. Aluminum and titanium were chosen due to their common use in space applications. The TIM is placed at the interface of the two heat flow meters and the interfacial pressure is adjusted by changing the applied load from two mechanical translators. Although pressures of 200-300 psi are typical of most design specifications, the TIMs were tested over a larger range to enable data to be readily available in the event of an out-of-spec interface and allow for future designs where pressures are outside of this range. The system is housed in a vacuum chamber to eliminate the effects of convection and gas conduction. As shown in Figure 2(b), when a TIM is inserted at the contact interface, the overall thermal resistance is a sum of three resistances in series: 1) the contact resistance between the top metal pillar and the TIM ($R_{c,1}$), 2) the bulk thermal resistance of the TIM (R_b) and 3) the contact resistance between the bottom pillar and the TIM ($R_{c,2}$).

Radiation-Aging

End of mission dose levels can vary greatly, usually between 100 Mrad and 1 Grad to the external components of the satellite [20]. Since gamma-rays are of high energy, allowing them to pass through materials with little attenuation in intensity, similar doses are expected at the interior components of the satellite. Accelerated gamma radiation dosing of the TIM samples was conducted in a Gamma cell (shown in Figure 1) at a rate of 250 rad/s. Total doses of 50 Mrad and 100 Mrad were delivered to the test samples to simulate 5 and 10 year lifetimes, respectively, for a dose rate of 10 Mrad/yr [20]. For the irradiation process, it is assumed that any gamma induced changes in the material properties will depend on the total dose, but are independent of dose rate [17]. Although the TIM samples were radiation-aged, the metal heat flow meters were left un-aged. This combination was selected such that any change in measured TCR could be directly attributed to changes the TIM.

RESULTS

Cho-Therm and ThermaCool samples were tested between aluminum and titanium heat flow meters. The measured contact resistance had a sample-to-sample coefficient of variation less

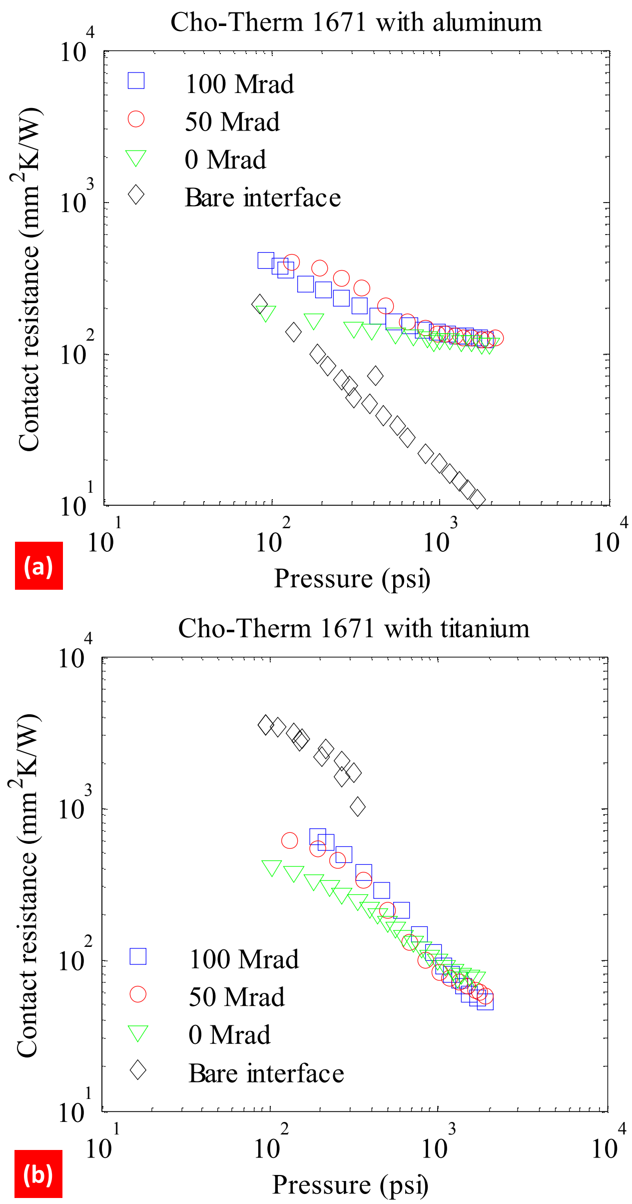

Figure 3: The effect of gamma irradiation on the thermal resistance of the Cho-Therm 1671 TIM between (a) aluminum and (b) titanium.

Table 2: Fitting parameters and applicable pressure range for TIM and bare interface contact resistance values.

TIM	Dose (Mrad)	Aluminum			Titanium		
		a	*b*	*P* (psi)	*a*	*b*	*P* (psi)
Bare interface	0	2.11E+04	-1.02	80-2130	2.12E+05	-0.86	90-510
Cho-Therm	0	3.65E+02	-0.16	90-1960	1.52E+04	-0.72	100-1660
	50	4.08E+03	-0.48	130-2140	9.25E+04	-0.99	130-1940
	100	2.26E+03	-0.40	90-1850	3.61E+05	-1.18	190-1910
ThermaCool	0	9.84E+03	-0.35	70-2140	4.31E+03	-0.36	70-1940
	50	7.23E+03	0.00	70-170	2.65E+03	0.00	70-170
		1.11E+05	-0.61	170-2320	3.36E+04	-0.57	170-1730
	100	8.23E+03	0.00	100-170	3.02E+03	0.00	70-170
		1.78E+05	-0.65	100-1710	4.37E+04	-0.58	70-1600

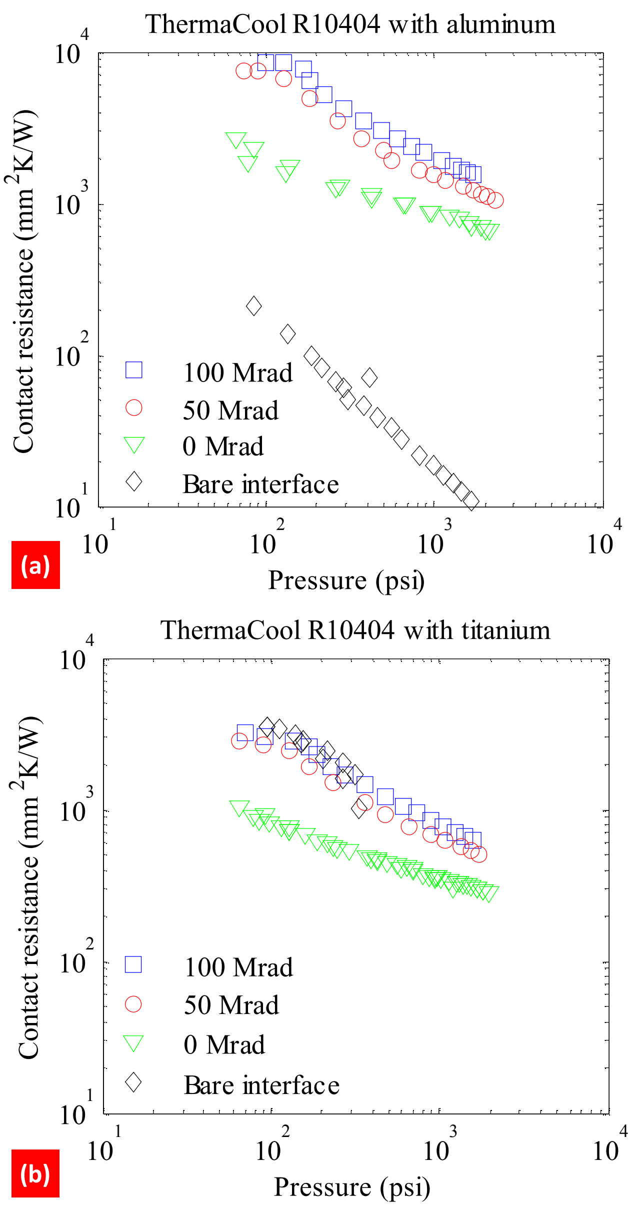

Figure 4: The effect of gamma irradiation on the thermal resistance of the ThermaCool R10404 TIM between (a) aluminum and (b) titanium.

than 0.07 over the entire pressure range tested. The mean pressure dependent TCR of the samples is shown in Figures 3 and 4 for Cho-Therm and ThermaCool TIMS, respectively. It can be seen that the slope of the curves is much less when a TIM is used in comparison to a bare interface. As a result, thermal resistance will change less when the materials are subjected to heating and cooling (thermal expansion/ contraction) or vibrational events when a TIM is used at the interface. It can be seen that when these interface materials are inserted at the aluminum interfaces the contact resistance increases. This is due to the fact that these bare interfaces exhibit low TCR. The TIMs have a much lower thermal conductivity and therefore a larger bulk resistance, and thus the added thickness at the interface decreases thermal conduction. The opposite trend is observed when the TIMs are inserted at titanium interface. Here, the initial TCR is high and the greater contact area created by the TIMs gives rise to small values of $R_{c,1}$ and $R_{c,2}$ which more than offset the bulk resistance added by the TIM. Thus the overall resistance of the interface is reduced. The pressure dependent contact resistance, R, can be fit to the equation [21]:

$$R = aP^b \qquad (2)$$

where P is the interfacial contact pressure (in psi) and a and b are constants. The fit values of a and b for every material combination tested is summarized in Table 2. It should be noted that these values fall within the manufacturer specified values listed in Table 1.

Radiation-aging causes a significant increase in the contact resistance of the Cho-Therm samples as shown in Figure 3. Here a 20-120% increase in TCR is observed over the vast majority of the tested pressure range. There is very little change, however, in the contact resistance between the 50 Mrad and 100 Mrad samples, where less than a 20% difference is observed between the TCR of the two radiation doses. Similar trends are shown for the ThermaCool samples in Figure 4. Here, three important trends are observed. First, there is a 50-250% increase in the contact resistance from the 0 Mrad to the 50 Mrad samples. Second, there is a discernible increase (20-40% over the pressure range investigated) in the contact resistance

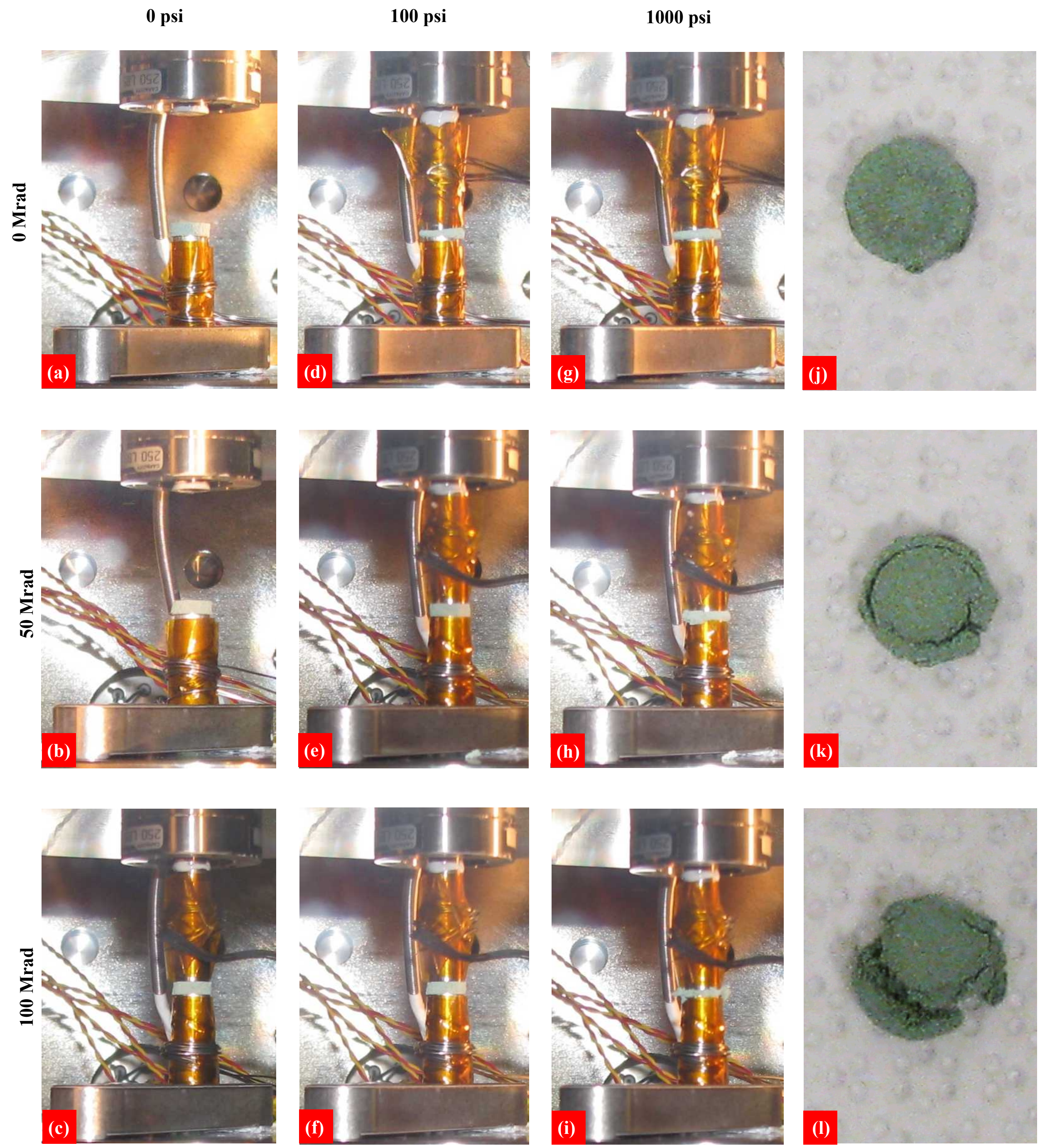

Figure 5: Photographs of ThermaCool R10404 during testing under loads of (a-c) 0 psi, (d-f) 100 psi and (g-i) 1000 psi, for samples dosed with 0 Mrad, 50 Mrad, and 100 Mrad, respectively. After testing photographs of the ThermaCool R10404 TIM dosed with (j) 0 Mrad, (k) 50 Mrad and (l) 100 Mrad.

between the 50 Mrad and 100 Mrad samples. Third, at interfacial pressures below 170 psi, the TCR of the radiation-aged samples is essentially pressure independent, which can be explained by examining the compression of the radiation-aged TIM.

Figures 5 (a)-(i) show the compression of the ThermaCool samples for interface pressures of 0, 100 and 1000 psi. The 0 Mrad sample was sponge-like and deformed easily under any applied load. When the samples were radiation-aged, the ThermaCool samples became harder and more brittle, as expected for polymer materials [16,17], resulting in little deformation of the interface material at pressures below 170 psi. At these lower pressures, the majority of the overall interface resistance is due to the bulk resistance of the TIM. Due to the lack of compressibility of the ThermaCool R10404 below 170 psi, there is little change in its thickness, and correspondingly, little change in the TCR. Above 170 psi, the samples begin to compress similar to the 0 Mrad case. However, due to the increased brittleness of the material, cracks formed and propagated throughout the TIM, which is easily observed in the post-test samples shown in Figures 5 (j)-(l). After testing, the 0 Mrad sample returned to its original shape. On the other hand, noticeable cracks developed in the 50 Mrad sample and the 100 Mrad sample fractured into several pieces. These results show that radiation-aging of ThermaCool could lead to potential contamination issues if the TIM fractures during a space mission, creating particles that could adversely affect the electronic systems they are designed to help cool [14]. Two separate sets values are given in Table 2 for the radiation-aged ThermaCool R10404 samples: a constant value for pressures below 170 psi and a fit to Equation (2) for pressures above 170 psi.

CONCLUSION

Thermal contact resistance was measured for two different electrically-isolating, thermally conductive TIMs commonly used in satellites and other space systems. When subjected to typical end of mission gamma radiation doses, the thermal resistance of the interface materials is shown to increase. For the Cho-Therm samples there was a large increase in contact resistance for the un-aged and radiation-aged samples, however, little difference was observed between the 50 Mrad and 100 Mrad dosed samples. Similarly, a large increase in contact resistance was observed for the un-aged and radiation-aged ThermaCool samples. A smaller increase was measured between the 50 Mrad and 100 Mrad dosed samples. The results show that the effectiveness of the TIMs decreases from the beginning of a mission to the end of a mission, which could lead to increased device temperatures and eventual device failure. Furthermore, radiation-aging increases the brittleness of the interface materials, and could cause cracking or flaking of the TIM, which can cause contamination to the system.

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