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THERMAL RESISTANCE IN SATELLITE BOLTED JOINTS

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ABSTRACT

Thermal Contact Resistance (TCR) of satellite bolted joints impedes the heat flow from satellite components to its radiator(s), and therefore, has to be considered in the design of thermal control system of satellites. This paper reviews some of the studies performed on the thermal contact resistance of bolted joints of various configurations, applicable to space applications. Models for single-bolt joints, and experimental studies on multi-bolt joints are reviewed, and some guidelines are given for prediction of the TCR in common satellite bolted joints. In addition, a configuration has been proposed for measurement of thermal conductance of bolted assemblies under vacuum conditions.

Keywords: Thermal contact resistance, Bolted joint, Thermal interface material.

1. INTRODUCTION

In a satellite, heat exchange from and to various components is usually through radiation and conduction. The heat produced in the electronic components is guided through thermal paths to the satellite radiator(s), where it is finally radiated to the space. The thermal resistance in the satellite bolted and riveted joints, termed as Thermal Contact Resistance (TCR), impedes the heat conduction between the electronic components and the satellite structure. Therefore, satellite thermal system designers must consider the TCR in their design. Thermal contact resistance is defined as:

$$R_j = \Delta T / Q \quad (1)$$

where R_j is the thermal resistance of the joint, ΔT is the temperature difference between the two sides of the joint (Fig. 1), and Q is the heat flux perpendicular to the joint surface. Similarly, thermal contact conductance is defined as:

$$h_j = Q / (A_a \Delta T) \quad (2)$$

where A_a is the apparent contact area of the joint.

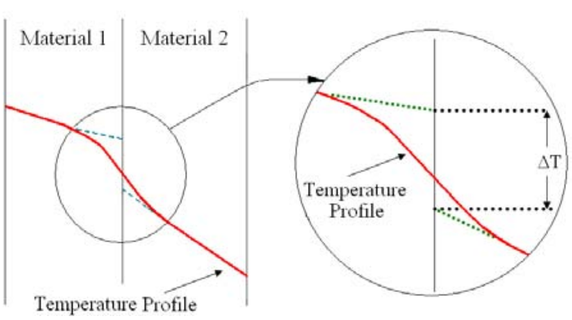

Fig 1: Temperature distribution around a joint

Thermal contact resistance is a very complex issue, and many geometrical, mechanical and physical parameters such as geometry of the contact surfaces, contact pressure, type of the thermal interface material (vacuum, air, grease, foil, etc), thermal conductivity of the contacting bodies, micro-hardness of the surfaces, Young's moduli of the two bodies, and the joint mean temperature, play a role in it [1]. In case all these factors are known in a given joint, reliable models are available for prediction of thermal contact resistance. Otherwise, the most reliable method is to conduct experiments.

One of the effective methods for reducing thermal contact resistance is to use interface materials, capable of filling the micro-gaps between the contacting surfaces. The thermal interface materials most commonly used in space applications generally fall into two categories: polymeric gaskets, and room-temperature-vulcanizing (RTV) materials. For selection of the best type of interface material for a specific application, factors such as contamination, outgassing under vacuum conditions, creep and deformation under load, chemical and structural changes with time, and electric breakdown voltage must be considered.

Satellite parts are mainly joined together by bolts. Therefore, study of thermal contact resistance in bolted joints has been a subject of interest for satellite thermal engineers. The main problem with bolted joints is that due to non-uniform stress distribution, the contacting bodies deform and the regions away from the bolts separate a little. Although extremely small, this separation greatly affects the thermal flow pattern between the surfaces, and heat is transferred mostly through the regions under or near the bolts. By increasing the contact area and decreasing the thickness of the contact plates, this problem is intensified and more bolts are needed to maintain proper thermal conductance between the two parts. In this case, use of proper thermal interface materials should also be seriously considered.

In the last four decades, a lot of theoretical and experimental research work has been done on the thermal contact resistance of bolted joints [1-11]. This paper reviews some of the studies performed on the thermal contact resistance of bolted joints of various configurations, applicable to space applications. Models for single-bolt joints, and experimental studies on multi-bolt joints are reviewed, and some guidelines are proposed for prediction of TCR in common satellite bolted joints.

2. SINGLE-BOLT JOINTS

Several models have been proposed by researchers for prediction of thermal resistance in single-bolt joints. Mantelli and Yovanovich [2,3] have developed a model which can be used for satellite bolted joints [4]. In this model (Fig. 2), a single-bolt joint with two circular plates of the same thickness and radius, and a number of washers between the plates, is considered.

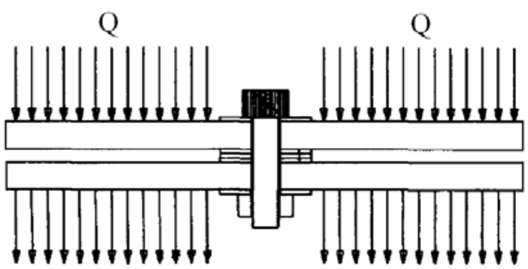

Fig 2: The Single-bolt joint model of Mantelli and Yovanovich [2]

In this model, a is the bolt radius, b is the outer radius of the washers, and c is the radius of the plates. For the range $b/c<0.3$, the model predicts the total thermal resistance of the joint (contraction/expansion resistance in the plates plus the contact resistance) as [3]:

$$R = \frac{1}{k_p t_p \pi}\left[\ln(c/b) - 0.75 - \Phi\right] + n\frac{t_w}{k_w \pi (b^2 - a^2)} + (n-1)\frac{(\sigma/m)_w}{1.25 k_w \pi (b^2 - a^2)(P/H_w)^{0.95}} \quad (3)$$

where Φ is a factor whose value in most practical applications is 0.1 [2]. Also, H_w is the microhardness of washer surfaces, P is the compressive pressure on the washers, σ is the roughness of washer surfaces, m is the mean slope of the micro-asperities of washer surfaces, and k_p, k_w, t_p, and t_w are thermal conductivity of plates, thermal conductivity of washers, thickness of each plate, and thickness of each washer, respectively.

Eq. 3 is applicable to cases with at least one washer between the plates ($n \geq 1$). For the case of contact without any washer in between, Eq. 3 reduces to [2]:

$$R = \frac{1}{k_p t_p \pi}\left[\ln(c/b) - 0.75 - \Phi\right] \quad (4)$$

Mantelli and Yovanovich [3] performed a sensitivity analysis to identify the important parameters influencing the total thermal resistance of single-bolt joints. Their analysis shows that:

- The share of thermal radiation is negligible, and heat transfer occurs mainly through thermal conduction.
- For $a/b>0.8$, the total thermal resistance is very sensitive to the changes in the parameter a/b.
- For $c/b>10$, the total thermal resistance is not much sensitive to the changes in the parameter c/b.
- Thickness of washers and plates are very important, and must be measured precisely.
- The number of washers (n) is an important parameter.
- The total thermal resistance of the joint is very sensitive to the changes in the thermal conductivities of the plates and washers. Therefore, thermal conductivities must be measured precisely.

3. MULTI-BOLT JOINTS

Due to the complexity of the issue, very little analytical work has been done, and most of the research studies have been conducted experimentally. These experimental works (e.g. [5-11]) are the basis for prediction of thermal resistance in multi-bolt joints.

In the experimental work of Bevans et al. [5], three different configurations of bolted plates of mean thickness 2.4 mm were studied (Fig. 3). In this study, measurements were done on both, bare joints and joints filled with RTV-11 silicon compound as the interface filler material. Based on this study, a design chart has been proposed [12], which can be used for perimeter-bolt-pattern configurations with plate thicknesses close to 2.4 mm. Figure 4 shows the thermal conductance diagram for a multi-bolt joint with perimeter bolt pattern, based on studies of Bevans et al. [5] on configurations of Fig. 3.

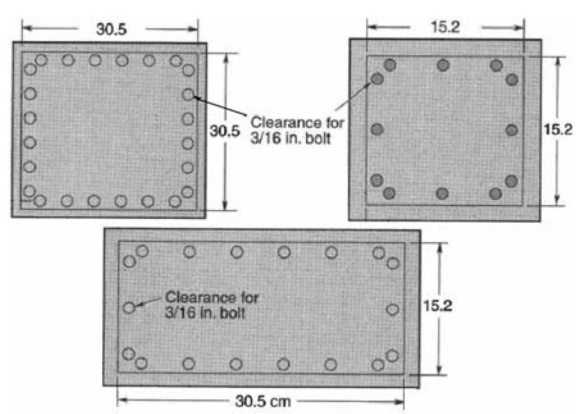

Fig 3: Configurations studied by Bevans et al. [5,12]

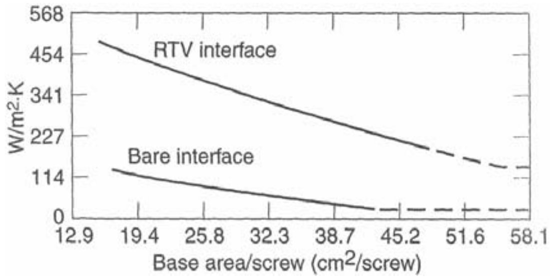

Fig 4: Thermal conductance of a multi-bolt joint with perimeter bolt pattern [5,12]

Another experimental study was done by Welch and Ruttner [6] on two 279 *152 mm^2 Al6063-T6 plates of 7.9 mm thickness, joined by 16 stainless steel bolts in a perimeter pattern. To evaluate the thermal performance of the interface material Calgraph (from PolyCarbon, Inc.), the experiments were done with bare joint, and were repeated in presence of a 0.2mm layer of Calgraph. Tests were done in a vacuum chamber. As shown in Figures 5 and 6, nine thermocouples were placed on each plate. A patch heater was placed on the top plate, and a cold plate was placed under the bottom plate to absorb the heat. An MLI blanket was used to minimize heat loss. The bolts were first torqued to 1.13 N.m, and then to 2.26 N.m.

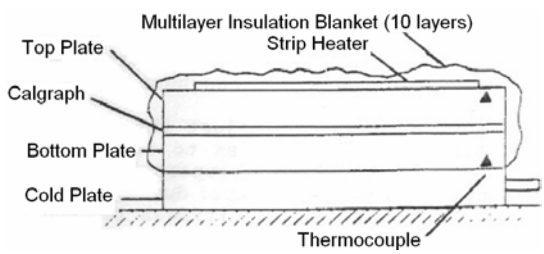

Fig 5: Experimental configuration of Welch and Rutter's study [6]

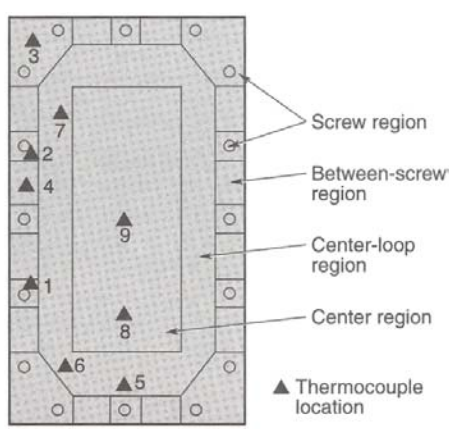

Fig 6: Configuration studied by Welch and Ruttner [6,12]

Thermocouple data were used to run a thermal network model, and to find the thermal conductance through four different parts of the plates, as shown in Fig. 6. The results showed that heat was mostly transferred through the regions under and near the bolts (Table 1), and the regions away from the bolts were almost thermally separated from the corresponding regions on the other plate. An estimation of the overall conductance was also given (Table 2). The data of Tables 1 and 2 can be used to estimate thermal conductance of aluminum plates of about 7.5 mean thicknesses, bolted in a peripheral pattern. Table 1 shows that Calgraph improved heat transfer in the screw region by about 3 times, but did not cause significant improvement in the center region. Table 2 shows that use of Calgraph improved the overall heat transfer through the joint by about 1.5 to 1.9 times.

Table 1: Thermal conductance values (W/m^2K) in the four regions of Fig. 6 configuration [6,12]

	Bare		**Calgraph**	
	-34 °C	71 °C	-34 °C	71 °C
Screw region	1420	2560	3980	7960
Between screws	850	850	1420	1135
Center loop	570	570	1135	1135
Center region	0.6	5.7	2.8	34

Table 2: Overall thermal conductivity of the configurations studied by Welch and Ruttner [6,12]

Torque (N.m)	**Temperature** (°C)	**Thermal Conductivity** ($W/m^2.K$)	
		Bare	Calgraph
1.13	-34	284	511
1.13	71	369	705
2.26	-34	330	506
2.26	71	398	705

Another experimental work on multi-bolt joints was done by Scialdone et al. [8]. In this work, the effectiveness of two thermal interface materials, Cho-Therm 1671 and RTV CV-2946, was tested. Two configurations were studied, one with two aluminum plates (Fig. 7), and the other with a copper plate and an aluminum plate (Fig. 8).

Scialdone et al. [8] measured thermal resistance for several bolt torques, under air and vacuum conditions. Figures 9 through 12 show the results of these measurements.

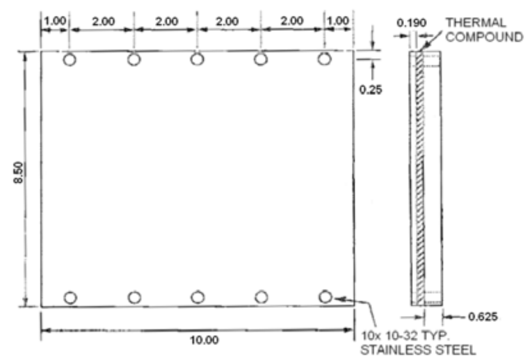

Fig 7: The first configuration studied by Scialdone et al. [8] (dimensions are in inches)

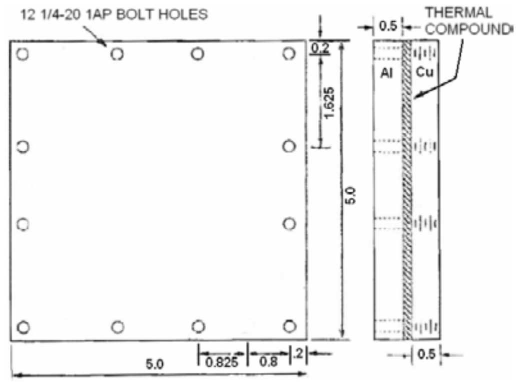

Fig 8: The second configuration studied by Scialdone et al. [8] (dimensions are in inches)

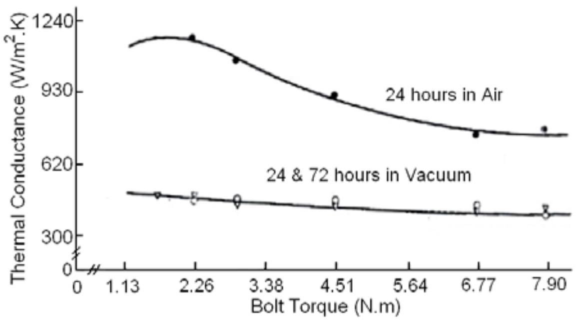

Fig 9: Thermal conductance for configuration of Fig. 7, with Cho-Therm 1671 gasket between the plates [8]

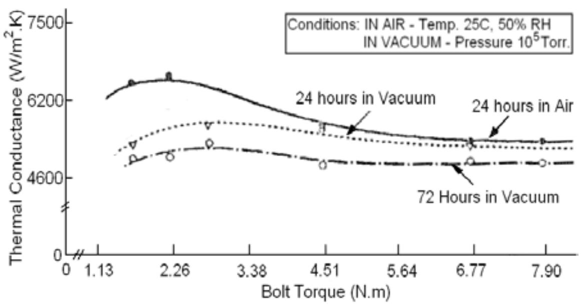

Fig 10: Thermal conductance for configuration of Fig. 8, with Cho-Therm 1671 gasket between the plates[8]

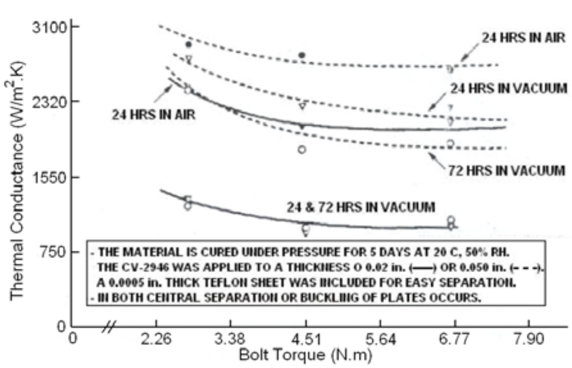

Fig 11: Thermal conductance for configuration of Fig. 7, with RTV Silicon CV-2946 between the plates [8]

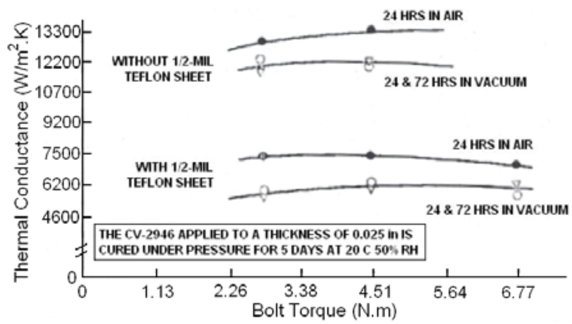

Fig 12: Thermal conductance for configuration of Fig. 8, with RTV Silicon CV-2946 between the plates [8]

Although very few experimental studies have been conducted to date, rough estimation of thermal conductance of a given multi-bolt joint is possible. For this purpose, the experiment sufficiently resembling the given conditions should be selected. In this regard, the most important factor seems to be the plate thickness, as clearly suggested by the results of the above-mentioned studies. Bolt pattern is another important issue. For perimeter bolt patterns, the mentioned studies can be consulted, but for non-perimeter bolt patterns, other studies must be considered (e.g. [12]). Plate area, plate material, number of bolts, and bolt tightening torque are other factors that influence the overall thermal conductance.

Thermal interface materials are usually used in satellite bolted joints. The effectiveness of these materials depends on the material type, and geometrical and mechanical properties of the joints. But as a rule of thumb, we can consider 1.5 times improvement in large and thin plates, and 3 to 5 times improvement in small and stiff ones. RTV silicon compounds and solid polymeric compounds more or less have the same effectiveness, but RTV compounds generally have better performance in large and thin plates. Due to ease of use and contamination concerns, polymeric gaskets are preferred to RTV compounds where there is small difference in their improvement factors.

4. EXPERIMENTAL MEASUREMENT

Estimation of thermal conductance of multi-bolted joints is influenced by many parameters, making its estimation a complex issue and associated with relatively large degree of uncertainty. Therefore, for applications requiring precision, the only reliable method is to conduct experimental measurements.

There are no standard methods available for such measurements, and one should consult the previous studies (e.g. [5-11]). To give an example, we have proposed a measurement configuration, shown in Fig. 13 in an exploded view.

In this configuration, the bolted assembly (5) is placed between two copper plates (3,7), which are meant to accommodate bolt heads and nuts. Thermal gaskets (4,6) are placed between the bolted assembly and the copper plates, to minimize thermal resistance. A patch heater (8)

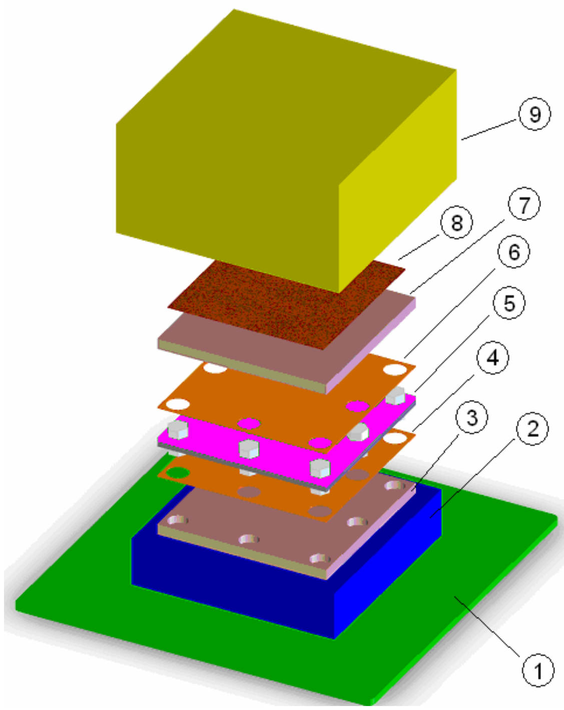

Fig 13: The proposed configuration for measurement of thermal conductance of bolted assemblies

is placed on the upper copper plate, which ensures its uniform heating. The whole assembly is placed on a cooling box (2), containing a cooling coil, circulating cold ethylene glycol for absorbing the heat from the assembly. Several thermocouples are placed on the bolted assembly to measure temperatures at different points. This is necessary because in spite of uniform heating of the assembly, the temperature distribution is non-uniform, which is due to difference in the thermal contact resistance at various points in the contact surface. In order to minimize the heat exchange between the test assembly and the surroundings, a radiation shield (9) is used to cover the whole assembly. The test assembly is installed on a test bed (1), and a bell jar surrounds it to facilitate conducting the tests in a vacuum environment. The necessary vacuum (of the order of 10^{-5} torr) is provided by a set of diffusion and mechanical rotary vacuum pumps (not shown in the figure).

5. CONCLUSION

The available literature on the studies performed on the thermal contact resistance of bolted joints of various configurations, for use in space applications, has been reviewed. A model for single-bolt joints and some experimental studies on multi-bolt joints have been reviewed, and some guidelines have been given for prediction of the TCR in common satellite bolted joints. In addition, a configuration has been proposed for measurement of the thermal conductance of bolted assemblies under vacuum conditions. It is hoped the present work would serve as a ready-to-use reference for thermal engineers, working on the design of satellite thermal control systems.

6. REFERENCES

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7. NOMENCLATURE

Symbol	Meaning	Unit
a	bolt radius	(m)
A_a	Apparent contact area	(m^2)
b	Outer radius of washer	(m)
c	Plate radius	(m)
h	Thermal contact conductance	($W/m^2.K$)
H	Microhardness	(Pa)
k	Thermal conductance	(W/m.K)
m	Mean surface asperity slope	---
P	Contact pressure	(Pa)
Q	Heat flux	(W)
R	Thermal contact resistance	(K/W)
T	Temperature	(K)
t	Thickness	(m)
σ	RMS surface roughness	(m)

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