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# EMPIRICAL EVALUATION OF THERMAL CONTACT RESISTANCE OF BOLTED JOINT CONFIGURATIONS FITTED WITH VARIOUS INTERFACE MATERIALS UNDER VACUUM CONDITIONS

**E. Moeini**

AutSat Project, Amirkabir University of Technology, Tehran, Iran**,** emoeini@aut.ac.ir

A. G. Esfahani*, V. Sedghi*, S. M. Karimian*

**Abstract**: This paper presents the results of the experiments conducted with two different test setups, representing the orthodox configurations of bolted joints and structural geometries in wide usage for space applications, to evaluate the thermal contact resistance across abovementioned joints when fitted with various polymeric gaskets and RTV silicone compounds and subjected to heat flux in vacuum conditions. The test subjects include a special bolt and washer configuration frequently employed in spacecraft designs and not studied comprehensively hitherto, in the form of two Al-6065 and Al-7071 specimen bolted together with interface materials between the two aluminum sheets and flat and spring washers inserted between the bolt heads and the upper plate and nuts and the bottom plate. The mentioned assembly is sandwiched between a copper and an aluminum slab, on the top of which the heater is installed. The whole configuration is covered with a MLI blanket and is attached to the base plate of a thermally conditioned vacuum chamber. The second test subject represents a more complex geometry comprising a hollow aluminum box with a hatch connected to the top of the box, and another aluminum plate to which the bottom of the box is jointed. The lower aluminum plate is in turn connected to an aluminum slab and thermal filler materials are inserted between the interface of the aluminum plate and the slab. An electrical heater is mounted on the top of the box and again, the whole setup is installed in the vacuum chamber. The effects of filler parameters like thickness on thermal contact resistance are studied and the results are discussed. These series of tests are designed to facilitate selection of the best performing-value for money- thermal fillers in these specific configurations for thermal control engineers in practical cases.

## I. INTRODUCTION

With the advent of integrated circuits nearly four decades ago, began a long development path resulting in many remarkable achievements, one of which is the considerable reduction of electronic components in size to a mere a hundredth of comparable counterparts in late 1970s. One of the byproducts of this development is a drastic increase in the heat flux to dissipate. Today, computer chips' heat fluxes are of the magnitude 100 W/cm$^2$ [1]. Due to the fact that spacecrafts make extensive use of the mentioned components for a variety of purposes, disposing the heat fluxes generated in electronic compartments, the magnitude of which might be in order of 1000 W for a single module, to maintain the equipment in an operational temperature range of -50ºC to +110ºC, turns into a major concern for designers [1,2]. Taking into account that in a spacecraft, only conduction and radiation heat transfer modes are observed, the majority of the heat produced in the electronic compartments is guided through thermal paths to the

* Aerospace Engineering Department, Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran
ataghasemi@aut.ac.ir

satellite radiators (e.g. base plates on which the electronic boxes are mounted) where it is finally radiated to the space[1,3,4], mainly because the amount of heat transferred via radiation is negligible [1,5,6] compared to the conduction mode in the previously mentioned common operating temperatures. As a result, of many perceivable solutions to the waste heat disposal, enhancing the heat conductance between the electronic modules and the satellite structure (i.e. heat sink or radiator) is considered canonical due to relative ease of its implication.

Knowing that satellite components are normally assembled by bolting constituents together and that these conjunctions represent the greatest impedance to heat conduction, it is inferred that no major improvement can be achieved but by reducing Thermal Contact Resistance (TCR) at bolted joints. Contact thermal resistance is a result of deviations, or imperfection, of machined surfaces from the desired geometry in the form of waviness and roughness which denote the scale of imperfections as being large or small, respectively. The consequence of these imperfections, as depicted in Fig.1, is that the two surfaces in contact in a joint actually touch each other in a few discrete points, thus limiting the paths through which heat flux can flow. This phenomenon in turn impedes heat flux and thus is responsible for TCR.

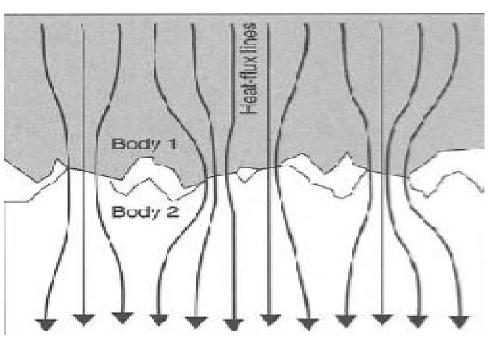


Fig. I: Heat flux flow in vacuum conditions through conduction mechanisms is only possible at the points where the two surfaces in a joint make contact [1]

The concentration of heat flux lines is manifested in the form of the temperature drop observed across contact surfaces in a joint which is demonstrated in Fig.2.

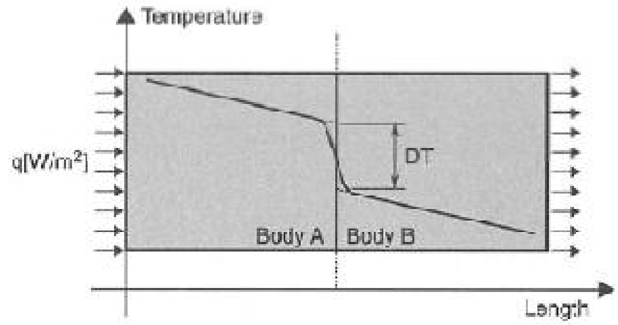


Fig. II: The temperature drop observed in a joint [1]

Thermal contact resistance is defined as follows

$$R_j=\Delta T / Q \quad [1]$$

where $R_j$ is the thermal resistance of the joint, $\Delta T$ is the temperature difference across the joint and $Q$ is the heat flux perpendicular to the joint. Also the reciprocal of thermal contact resistance, $h_jA$, is in wide usage in relevant literature where $A$ is the nominal contact area of the joint and $h_j$, contact conductance, is define as follows

$$h_j = Q / A\Delta T \quad [2]$$

It has to be reminded, however, that the complexities arising from a variety of factors turn the task of evaluating thermal contact resistance across bolted joints, which is the topic of interest, into a formidable undertaking. These include (but are not limited to): plate thickness, roughness of contacting plate and the washers, plate hole radius, washer radius, bolt hole spacing, mechanical properties of the plates/washers/bolts, micro hardness, Poisson's ratio, interfacial pressure, thermal conductivity of the plates and interstitial fluids (if any) and mechanical loading/bolt torque [7,8]. Of many parameters involved, a handful has been studied comprehensively and their general effects on thermal contact resistance are understood via experiment. These include number of bolts, torque applied to bolts, interfacial contact pressure [7] to name a few. Some other research efforts in this field have been targeted towards deriving closed form analytical relations for simple configurations [9,10]. Although valuable, the proposed analytical models have proven to be highly inaccurate when applied to configurations which deviate slightly from the ones that constitute the basis for derivation of these formulae [2] and given the variety of configurations employed in spacecraft, the only viable alternative seems to be the evaluation of thermal contact resistance in the target configuration via empirical methods.

Again, numerous experiments have been conducted to determine contact resistance especially in multi-bolt configurations that are encountered in electrical boxes containing electronic mission equipment in satellites and spacecraft [11,12]. In order to study heat transfer mechanisms in geometrical configurations that are as close to authentic cases as possible, several researchers have incorporated the effects of introducing thermal fillers in bolted joints and studied the mentioned layouts under vacuum conditions [4,12].

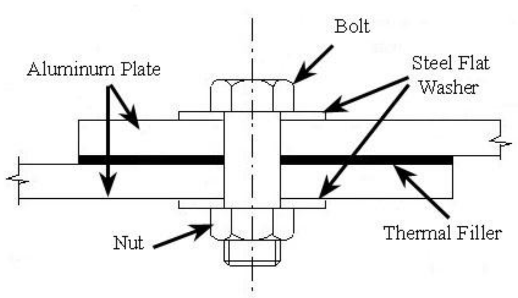


Fig. III: Schematic diagram of conventional configurations employed in satellite designs

The major drawback of the previous experiments is oversimplification of the tested model and as a result, the data obtained cannot be applied directly to a specific satellite design. The present paper is the result of an attempt to address this problem by testing geometries and materials earmarked for use onboard an operational satellite. Two series of experiments have been conducted to evaluate thermal contact resistance of complex multi-bolt configurations with thermal fillers. In order to determine which type of available thermal fillers would provide the best performance (defined according to the drawn specifications), various fillers are inserted in the joints studied and tests are repeated. The main emphasize is on simulating the conditions which will be encountered in low earth orbit by satellites, so the tests are conducted in vacuum conditions and vacuum chamber temperature and heat flux are adjusted accordingly. The details of test setups and experimental facilities are presented in the following sections.

## II. EXPERIMENTAL SETUP

The experiments have been conducted at thermal control lab of Amirkabir University of Technology research center and mainly by the help of the vacuum chamber, designed and built according to the specifications drawn up by the research center specialists. The mentioned vacuum chamber is capable of delivering temperatures from -80°C to +300°C. Other specifications can be found in Table.1.

| | |
|---|---|
| Inner dimensions | 75×75×65cm |
| Inner walls effective emissivity (black surfaces) | 0.9 |
| Inner walls effective emissivity (polished surfaces) | 0.1 |
| Vacuum pressure | $10^{-6}$ mbar |
| Depressurization time | 6 min |
| Max inner wall surface temp. gradient | 2°C/ $m^2$ |

Table. I: Vacuum chamber specifications

In this chamber, black painted walls encompass the test model from all sides and a polished surface in the form of base plate lies beneath the test model.

### II.I First Test Setup

The first test setup is designed to study the effects of using various thermal fillers between two large sheets of aluminum. The effect of increasing the number of bolts will also be studied here. Fig.5 displays the schematic of this test setup. As seen, two aluminum sheets of AL-6065 and AL-7071 (on top and on bottom, respectively) with the same dimensions of 200×300x3 $mm^3$ are jointed to each other with 4 (or 6) M4 standard stainless steel bolts. All bolts are fastened by a fixed torque of 10 N/m. Bolts are inserted from the top of plates and nuts are used in the bottom of plates to fasten the bolts. In each bolt, a steel plane washer and a steel spring washer are applied between bolt and the upper plate and between the nut and the lower plate, respectively. Obviously the selected filler will be installed between these two aluminum plates. As shown in Fig. 5, to have uniform temperature on two aluminum sheets, two slabs of copper and aluminum with dimensions of 200x300x20 mm$^3$ are used. Heat is generated by a plane electrical heater which is installed on the hot slab, and will be transferred out through the cold slab to the base plate of vacuum chamber. The heater is connected to a DC power source in order to have a controlled heat flow.

To ensure that the generated heat is transferred through the contact of two aluminum sheets in its entirety, Multi-Layer Insulation (MLI) blanket is used to cover up the test setup as shown in Fig.4.

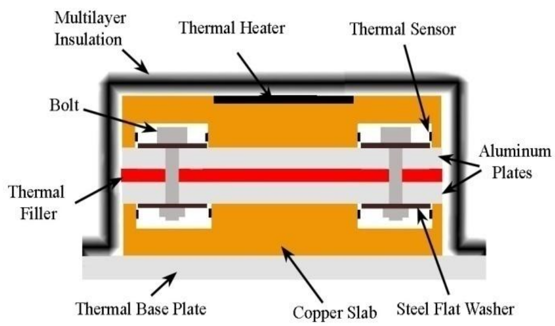


Fig. IV: Schematic depiction of first test setup

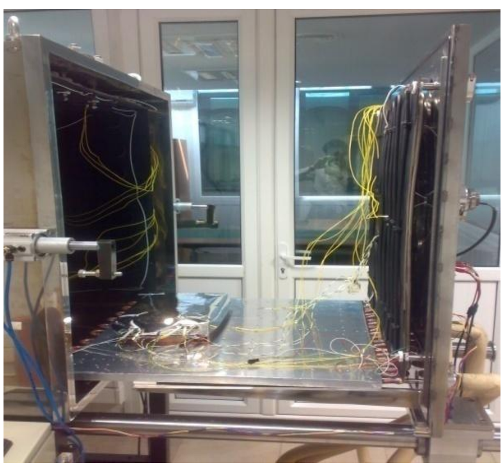

Fig. V: Installation of first test setup on vacuum chamber's thermal base plate

One wire DS18B20 thermal sensors are installed on both plates as depicted in Fig.6 .All sensors in this test setup are installed using heat conductive adhesives which are electrically non conductive.

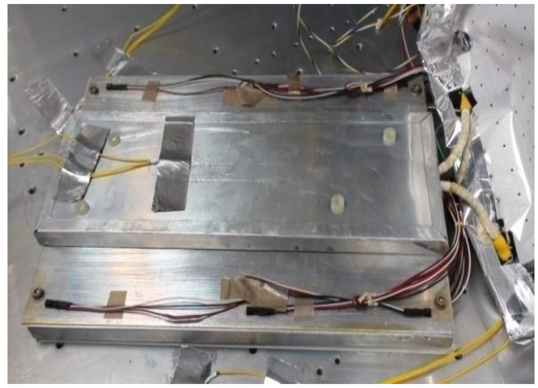

Fig. VI: Installation of thermal sensors on Aluminum plates

The bolt system studied as first test setup has found extensive use in satellite applications [ref]

## II.II Second Test Setup

The purpose of the second test setup is to study heat transfer via conduction mechanism between an aluminum box and a cold plate in the presence of various thermal fillers usually employed in satellite and electronic system applications. In this setup, as is shown in Fig.7, an aluminum box with dimensions of 100×120×50 mm$^3$ is jointed to an aluminum slab with dimensions of 200×300×20 mm$^3$ using 6 stainless steel M4 standard bolts. The box is empty and is made of aluminum sheet with a thickness of 2 mm for its case and hatch. The hatch is screwed to the case with four M4 standard bolts. All bolts are fastened by a fixed torque of 2.6 N/m. Plain washers are inserted between the bolts' heads and the box.

Thermal fillers will be placed between bottom face of the box and the upper face of aluminum slab. To generate heat, an electrical heater is attached to the upper face of aluminum box. The lower face of aluminum slab is placed over base plate of vacuum chamber. In this case the heat source is placed on the box hatch. To measure the temperature gradient accurately, three sensors are placed on the bottom face of the box in a diagonal fashion, as seen in Fig.8 and three sensors are attached to the aluminum slab. Sensors are attached to the surfaces by aluminum tapes. In this case, heat conductive grease is also applied between sensors and the surface to improve conductive heat transfer.

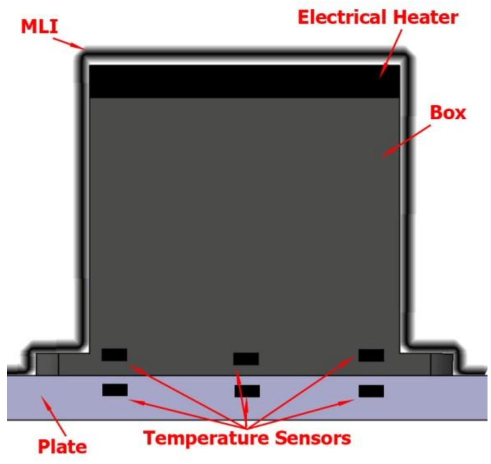


Fig. VII: Schematic of the second test setup

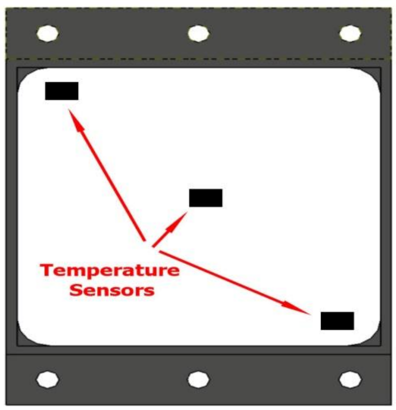


Fig. VIII: Temperature measuring sensors configuration

Figure.9 depicts how the thermal sensors are installed at the bottom of the box. It must be noted that all of the involved geometrical or heat transfer parameters are constant except the type of the thermal filler employed in each test run in order to study the effects of various fillers on thermal contact resistance at the specified bolted joint configurations. Results are obtained for different types of fillers including Chotherm 1671, T-Pli 220, and Sigraflex, and high vacuum grease. Specifications of these fillers are given in the Table 2.

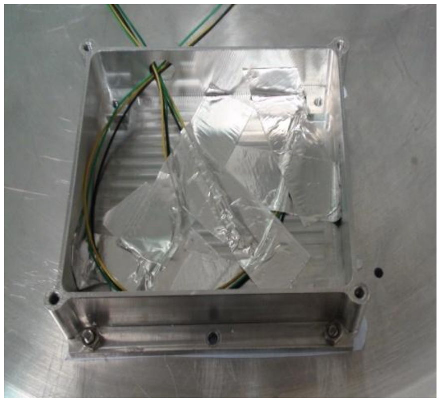

Fig. IX: Fixation of thermal sensors by means of Aluminum tapes at the bottom of the box

| Filler | Manufacturer | Thickness (mm) | Thermal conductivity (W/m.K) |
|---|---|---|---|
| Chotherm 1671 | Chomerics | 0.38<br>0.76 | 2.6 |
| T-pli 220 | Thermagon | 0.51 | 6 |
| Sigraflex | Sigraflex Universal | 0.53 | --- |
| Dow Corning High Vacuum grease | Dow Corning | --- | 0.54 |

Table. II: Specifications of tested thermal fillers

## III. Results and Discussion

All of the experiments are conducted with constant heat flow that is achieved when the system reaches steady state. Steady state condition is achieved if the time rate of temperature fluctuations is less than 1 °C/hour. In vacuum conditions (a pressure of approximately $10^{-5}$ mbar) heat is transferred only via radiation and conduction mechanisms. However as described earlier, radiation heat transfer is blocked employing a multilayer insulation blanket. Equation (1) is employed to calculate thermal contact resistance. It must be noted that $\Delta T$ is the temperature difference between two contact surfaces, i.e. AL6061 and AL7071 in the first test setup, and Aluminum box and the aluminum plate in second test setup. Q is the constant heat flow provided by DC powered planar electric heater. Test results of test setup 1 are shown in the tables 3 and 4for different fillers. In all cases, the test duration takes more than 7 hours to achieve steady state conditions. All temperature data was saved on computer every 5 minutes.

| Filler | $T_{cold}$ (K) | ΔT (K) | Q(Watt) | R(K/W) |
|---|---|---|---|---|
| Bare Joint (no filler) | -24 | 4.9 | 25 | 0.1914 |
| Chotherm 1671* | -24.3 | 12.7 | 40 | 0.3155 |
| T-Pli 220 | -24 | 8.9 | 40 | 0.2204 |

* 0.38 mm thickness

Table . III: Test results of test setup 1 employing 4 bolts

| Filler | $T_{cold}$(K) | ΔT(K) | Q(Watt) | R(K/W) |
|---|---|---|---|---|
| Bare Joint | 65 | 8.9 | 54 | 0.1655 |
| Chotherm 1671* 1 layer | 38 | 9.4 | 47 | 0.2007 |
| Chotherm 1671*2 layers | 40 | 8.8 | 51 | 0.1726 |
| T-Pli 220 | 46.5 | 2.7 | 47 | 0.0575 |

* 0.38 mm thickness

Table. IV: Test results of test setup 1 employing6 bolts

For the experiments conducted using test setup 2, Fig.6 shows details of the box and the slab, and the exact locations of bolts. Test results obtained from experiments on test setup 2 are shown in the Table.5 for different fillers.

| Filler | $T_{cold}$(K) | ΔT (K) | Q(Wat) | R(K/W) |
|---|---|---|---|---|
| Bare Joint (no filler) | -34.5 | 16.5 | 49.7 | 0.3319 |
| Chotherm 1671*1 layer | -34 | 14.5 | 49.7 | 0.2924 |
| Chotherm 1671*2 layers | -30 | 18.03 | 49.7 | 0.3628 |
| T-Pli 220 | -43 | 4.6 | 51.7 | 0.09165 |
| Sigraflex | -38.1 | 4.7 | 49.7 | 0.0949 |
| Dow Corning High Vacuum Grease | -31.5 | 6.6 | 49.7 | 0.1327 |

* 0.38 mm thickness

Table. V: Test results of test setup 2

The accuracy of the values calculated for resistance across the joints, presented in tables 3 through 5, is contingent upon accurate measurement of several parameters involved. Any errors introduced in this process will have implications affecting the calculation of thermal resistance. Errors that may exist in determination of thermal resistance can be calculated through equation (3) in which $E_R$ is the total error produced by error sources in the test [13].

$$E_R = \frac{\delta_R}{R} \times 100 \quad [3]$$

$\delta_R$ in equation (3) is calculated according to equation (4).

$$\delta_R = \left\{\left(\frac{1}{Q}\right)^2 \left(\delta_{T_H}\right)^2 + \left(-\frac{1}{Q}\right)^2 \left(\delta_{T_C}\right)^2 + \left(\frac{T_C - T_H}{Q^2}\right)^2 \left(\delta_Q\right)^2\right\}^{\frac{1}{2}} \quad [4]$$

Where $T_H$ and $T_C$ are the temperatures of hot and cold plates, respectively and $\delta_{TH}$ and $\delta_{TC}$ are the errors associated with the measurement of hot and cold plate temperatures. Likewise, $\delta_Q$ is the error in measurement of heat generated by the planar electric heater (Q). $\delta_Q$ may be calculated employing equation (5) as follows.

$$\delta_Q = \{(V)^2(\delta_I)^2 + (I)^2(\delta_V)^2\}^{\frac{1}{2}} \quad [5]$$

Where V and I are the measured electrical voltage and current going through the heater, respectively and $\delta_I$ and $\delta_V$ are the associated errors. According to equation (4), in order to minimize the error in calculation of thermal resistance, one must not only minimize the error in measurement of heat flux and temperature, but also increase the heat flux as much as possible. So, the main sources of uncertainty are identified as temperature measurement error and heat flux measurement error. The thermal sensors employed in these series of tests are DS18B20 one wire digital sensors. According to the specifications provided by the manufacturer, the error associated with the temperature measurement in the range of -10 to +80°C is 0.5°C and for the temperature range of -50 to +127°C is 1.0°C. Since these sensors are digital, other physical parameters or data acquisition procedures have no effect on the accuracy of measurements.

As mentioned, the other source of uncertainty in resistance calculations is heat flux measurement error. In order to calculate the heat generated by the planar heaters, the electrical voltage and current of heaters were measured with precision of less than 0.1 Volts for voltage and less than 0.01 A for electrical current. Due to the electric resistance associated with the wirings and connectors employed in the tests, their loss should be taken into account. Having determined the electrical resistances of the wirings and connectors, their heat loss can be calculated for each test. This heat loss, in turn, is subtracted from the generated heat of heaters calculated through the measurement of electrical voltage and current of heaters.

Due to the low emissivity factor associated with the MLI blanket used to cover up the test setups, the heat dissipated through the blanket is assumed to be negligible. Therefore, according to equation (4), the error associated with each of the tests carried out may be calculated as tabulated in table.6.

| Filler | Error $\delta_R$ (%) | | |
|---|---|---|---|
| | Setup-1(4 screw) | Setup-1(6 screw) | Setup-2 |
| Bare (no filler) | 7.396773 | 8.737524 | 4.657136 |
| Chotherm 1671* - 1 layer | 4.720595 | 7.2152 | 5.180481 |
| T-pli 220 | 6.558908 | 24.46486 | 15.43672 |
| Sigraflex | --- | --- | 14.90969 |
| Dow Corning Grease | --- | --- | 10.75022 |

* 0.38 mm thickness

Table. VI: Errors associated with the experiments carried out

Having studied the effects of errors of measurement on thermal resistance calculations, the following sections are dedicated to the analysis of effects of other crucial parameters such number of bolts in a joint, thermal filler material and its thickness on thermal resistance across a bolted joint. It is known that installing additional bolts not only increases the applied pressure but also enhances the real contact area between two surfaces, especially in large surfaces since an increase in real contact area would serve to facilitate heat flow through the joint and therefore, according to equation (1), a decrease in thermal resistance across the joint is expected. Results of the calculations of thermal resistance for the first test setup, where plates are joined by either 4 or 6 bolts, tabulated in tables 3 and 4 and confirm this fact. These results are demonstrated again in Fig.10.

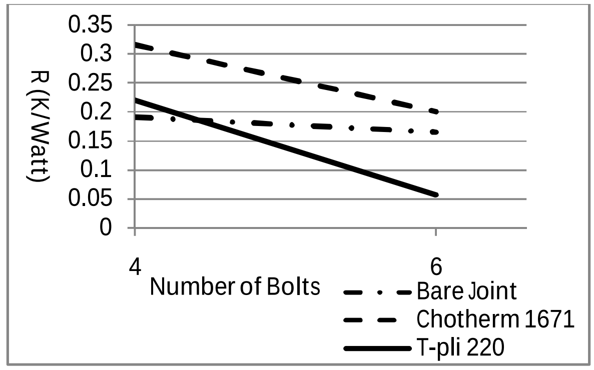


Fig. X: Thermal contact resistance across bolted joints for different number of bolts

Several noteworthy observations may be made in Fig.10. Comparing the rate of thermal resistance decrease in joint filled with thermal fillers with a bare joint, it is evident that the rate of contact resistance reduction is higher when Chotherm 1671 filler is used between the plates and even higher when T-Pli 220 filler is employed. This observation may be attributed to the fact that while an increase in the number of bolts will lead to an increase in macroscopic contact area, thermal fillers serve to fill the microscopic roughness of plates in contact and this would facilitate the flow of heat across the joint better than an increase in macroscopic contact area. These results demonstrate the superiority of T-Pli 220 filler in reducing thermal contact resistance when employed in the particular geometry studied in this paper. This fact is confirmed by the data of table.7 and reference [15 ref].

| Filler | Ratio of heat transfer to heat transfer in bare- joint contact | | |
|---|---|---|---|
| | Test Setup 1, 4 Bolts | Test Setup 1, 6 Bolts | Test Setup 2 |
| Bare Joint | 1 | 1 | 1 |
| Chotherm 1671* - 1 layer | 0.606656 | 0.824614 | 1.135089 |
| Chotherm 1671* - 2 layers | NA | 0.958864 | 0.914829 |
| T-Pli 220 | 0.868421 | 2.878261 | 3.621386 |
| Sigraflex | NA | NA | 3.497366 |
| Dow Corning High Vacuum Grease | NA | NA | 2.50113 |

* 0.38 mm thickness

Table. VII: Heat transfer enhancement due to various thermal fillers

By examining the data presented in table.7 it is evident that employing thermal fillers of any type in the first test setup with 4 bolts leads to a decrease in heat transfer across the joint compared the bare joint. This might be traced to the fact that 4 bolts do not exert enough pressure to keep the plates together and adding fillers only worsens the situation. But when 6 bolts are used to hold the plates with the same geometry together, employing the right thermal filler (T-Pli 220 in this particular case) would increase the heat transferred through the joint nearly threefold. It is also evident that addition of thermal fillers would lead to an increase in heat transfer across the joint in the second test setup, irrespective of the thermal filler material employed. Then again, T-Pli 220 displays the best performance when compared to other fillers.

Another important parameter regarding the performance of thermal fillers employed in joints is their thickness. Data of tables 4, 5 and 7 indicate that while increasing the thickness of Chotherm 1671 (widely used in spacecraft applications) in the first test setup enhances the heat transfer through the joint, doing the same in the second test setup leads to a decrease in heat transferred through the joints. These contradicting results may be interpreted by paying attention to the specific geometries studied in each case. In joints with relatively small contact areas the thick Chotherm 1671 cannot enhance contact area but due to its low thermal conductivity it will increase thermal resistance. Anyhow, thermal filler thickness is a crucial parameter which must be studied carefully in the design process especially in the cases where the contact area in a joint is relatively large.

## IV. Conclusion

The results of the experiments conducted in this study indicate the importance of employing thermal fillers at contact surfaces in joints in conjunction with an appropriate number of bolts. Thermal filler material are capable of improving heat transfer through bolted joints in vacuum conditions and will be more effective when the number of bolts used to hold the plates in a joint is increased. Selecting the proper thickness of thermal fillers is also of crucial importance as inappropriate selection of this parameter may lead to a decrease in heat flow through the joint. Finally, T-Pli 220 thermal filler demonstrated the best performance in both configurations studied in this paper. As the geometries tested represent the actual configurations employed widely in space applications, this result has important implications for thermal control engineers.

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