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# Thermal Interface Materials Selection and Application Guidelines: In Perspective of Xilinx Virtex-5QV Thermal Management

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NASA Electronic Parts and Packaging (NEPP) Program
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## 1.0 INTRODUCTION

Modern microdevices for space, such as Xilinx Virtex 4 and 5 (V4 and V5) field programmable gate arrays (FPGAs), can generate a large amount of heat. This large amount of heat is one of the reasons why class-Y type parts, such as V4 and V5, are non-hermetic; it is necessary to attach the heat spreader directly to the back of the flip chip die in V4 and V5 to dissipate the heat. The space vacuum environment presents a unique challenge in using such microdevices; unlike terrestrial applications, the heat can only be removed through conduction and radiation. An effective thermal conduction path has to be established from the top of the device to the chassis mounting structure of the spacecraft. Since class-Y type packages have the lowest thermal resistivity from the junction to the heat spreader, attaching a heat transfer device to the heat spreader of the package establishes the starting point for the most efficient heat conduction path. The heat transfer device can then be attached to a frame for the printed circuit board or directly to the chassis depending on the assembly design.

When the heat transfer device contacts the heat spreader, the surface roughness of the two reduces their actual contact area; this is the same for the interface between the silicon (Si) die and the heat spreader. As shown in Figure 1-1, the surfaces has microscopic peaks and valleys. Only the area actually in contact with each other will conduct effectively through conduction. The area not in contact is filled with air, or, in space, vacuum. The function of thermal interface materials (TIM) is to replace the air or the vacuum with a more effective heat conducting material.

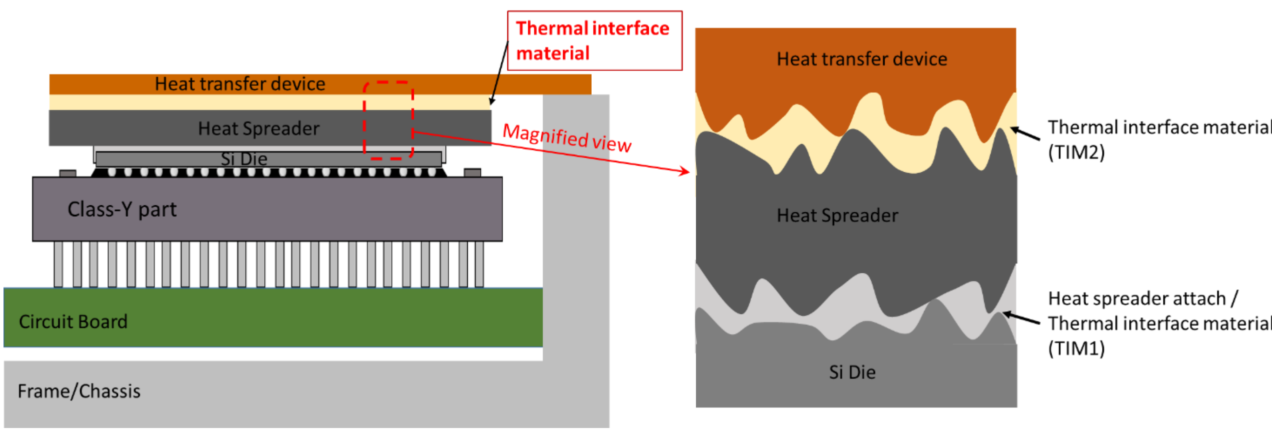



**Figure 1-1.** Schematic diagram of V5 assembly with a heat transfer device.

Figure 1-1 shows a schematic diagram of a situation where a heat transfer device is attached to the lid of a V5. There are two TIMs: the heat spreader attach material and the heat transfer device attach material. In commercial microelectronics packaging, the TIM to bond a Si die with the heat spreader is referred to as TIM1, and the TIM between the heat spreader and the heat transfer device is referred to as TIM2. The lid attach material, TIM1, is not within the scope of this task; the current task focuses primarily on TIM2, the TIM between the heat transfer device and the heat spreader. Henceforth, the term TIM will refer to the TIM2, the TIM between the heat transfer device and the heat spreader.

The current study focused on the properties and reliability of the TIM. TIMs have been widely used for commercial applications, particularly high thermal density commercial high power central processing units (CPUs) and graphics processing units (GPUs). This study leverages the existing knowledge on TIMs in the commercial sector. This study also leverages development tasks done for flight projects at Jet Propulsion Laboratory (JPL).

It must be noted that the thermal characteristics of the frame and chassis are also important, since the heat removed through the heat transfer device is ultimately transferred to the chassis mounting surface of the spacecraft. For example, if the heat removal device is attached between the device and the slice frame, the heat from the device needs to be conducted through the frame, the frame/chassis interface, chassis, and the chassis/mounting surface interface. In such a case, the combined thermal resistance from the frame to the chassis mounting surface also needs to be engineered to meet the thermal requirements.

## 1.1 Heat Transfer Device for High Power Devices in Space

In a space environment, the heat from a high power device is mainly dissipated by conduction. Class-Y parts are inherently designed to dissipate heat from the top side; for example, V5 has 33 times lower thermal resistance from the junction to heat spreader surface than to printed circuit board it is attached to [1]. Therefore, a thermal conduction path between the package lid and the frame or chassis has to be established with a heat transfer device, such as a heat strap or heat pipe, so that the heat can be transferred from the package lid to the chassis mounting structure.

A heat strap is typically a thin sheet metal, typically copper. Heat strap can be also made with a more thermally conductive material, such as Annealed Pyrolytic Graphite (APG). The heat strap does not conduct as much heat as a heat pipe, but it can be designed to have a small weight and be compliant so that its presence will have a minimum effect on the shock, vibration, and thermal cycling reliability of solder columns. As power dissipation of the device increases, the thickness and the width of heat strap need to be increased accordingly. The increased thickness and width can eliminate the advantages of the heat strap (compliance and low mass). In such a case, the rigidity and mass of the heat strap may have negative effects on the solder column reliability while having less heat transfer capability than a heat pipe. Depending on the parameters, such as the device power dissipation, the total thermal resistance from the frame/chassis to the chassis mounting structure, and the allowable flight temperature, it is often impossible to achieve the required junction temperature with a heat strap.

Heat pipes are metal tubes with wick structures inside. They are filled with a liquid that will evaporate at the evaporator region (the device side of the heat pipe where heat is transferred from) and condense at the condenser region (the cold side of the heat pipe where heat is transferred to). The vapor of the liquid is in a saturated state so that liquid vaporized at the evaporator region can easily condense at the condenser region. The hot side is cooled by the latent heat of evaporation of the liquid. The wick structure enables the condensed liquid to be wicked and returned to the evaporator side. Heat pipes with a properly configured wick structure can operate against gravity. The working temperature of a heat pipe is determined by the type of liquid used in the heat pipe. The liquid must be selected according to the working temperature range of the electronic assembly. Heat pipes offer effective thermal conductivities more than two orders of magnitude greater than bulk metals when they are within their working temperatures. The detailed qualification process for the heat pipe is not within the scope of the current study; tests such as burst pressure, cold start, heat transport, proof pressure, freeze/thaw, and stiffness need to be done to ensure the reliability and performance of the heat pipe. Since heat pipes have a certain stiffness, the rigidity of the heat pipe attached to the package can affect the stress level of the solder columns during shock, vibration, and thermal cycling.

Attaching a heat transfer device to a ceramic column grid array (CCGA) package can, potentially, affect the mechanical reliability of the solder columns, and often the reliability of an electronic assembly needs to be verified when a heat transfer device is used. There are also concerns that a rigid heat transfer device may create asymmetric loading and motion of the package during shock, vibration, and thermal cycling tests, negatively affecting the reliability of solder columns. The additional weight from the heat transfer device is known to affect the shock and vibration reliability of a CCGA package [2]. However, the negative effects of the heat transfer device can be mitigated by proper design practices; an initial finite element analysis (FEA) performed while developing an actual flight hardware at JPL showed that attaching a heat pipe on a V5 would increase the maximum load on the solder columns by 30% during random vibration. However, after the assembly design was improved to reduce the deflection of the board, the maximum load on the solder columns calculated by FEA was reduced by 80%.

## 1.2 Types of Thermal Interface Materials

One of the most commonly used materials as a TIM for commercial applications is thermal grease. Thermal grease, however, can outgas, cause contamination, and degrade. In addition, thermal grease cannot provide adhesion by itself, and mechanical clamping is required to attach the heat transfer devices. Therefore, thermal grease is not suitable for space applications.

Conformable TIMs, such as indium foils and thermal gap pads, are also frequently used for commercial applications. Conformable TIMs typically require pressure to fill the surface roughness during the application, and there are concerns that amount of pressure can be large enough to damage the solder columns or affect their long-term reliability. Unless the effect of the pressure is verified, conformable TIMs are not preferred for thermal managing of CCGA packages. TIMs need to have adhesive strength high enough to withstand shock and vibration. Many conformable TIMs do not have strong adhesion to surfaces and require a clamping mechanism, and there is currently no qualified method for flight to clamp a heat transfer device to a class-Y type part. Some commercially available thermal gap pads offer good conformability and certain level of adhesion. However, the current task did not find significant advantages of thermal gap pads over the conventional space grade thermally conductive adhesives to invest resources to qualify the material for space.

Phase change materials (PCMs) are drawing attention in the commercial sector since they can be easily applied, offer low thermal resistance, and do not degrade. PCMs change phase from solid to liquid at a low pressure and a temperature above a threshold temperature, wetting the interface and filling the surface roughness. However, PCMs also need mechanical clamping, and therefore are not suitable unless a clamping mechanism is qualified.

Thermally conductive adhesives are suitable for attaching heat transfer devices to class-Y parts since they do not require clamping mechanisms to hold the heat transfer device and the device together. Thermally conductive adhesives are typically silicone or epoxy based. The current task focused on silicone-based adhesives. The primary reason why silicones were chosen over epoxy was their reworkability. Spacecraft electronics may be subjected to design changes and rework. The heat transfer device, such as a heat pipe, may need to be removed if components located underneath the heat pipe need to be reworked. Due to the high cost of a V5, it would be preferable to preserve the V5 during any rework. In addition, removal and replace of large CCGA parts such as V5 is not preferred since many other parts on the board can be subjected to excessive amount of heat. Therefore, silicone is preferred over epoxy since a heat transfer device needs to be removed with a low amount of stress to avoid damaging the solder columns of the V5.

While clamping mechanisms are not available for attaching heat transfer devices to class-Y parts, heat removal devices can be attached to the frame or chassis with fasteners; therefore, the TIMs requiring clamping mechanisms can be used between a heat transfer device and the frame or chassis.

## 2.0 MATERIALS PROPERTIES AND ISSUES TO CONSIDER WHEN SELECTING A TIM

When selecting a TIM, the commonly available property of the material in the manufacturer's datasheet is the thermal conductivity. While the thermal conductivity is the measure of the material's inherent capability of transferring heat, it does not reflect the actual performance of the material in a real application. The total thermal impedance of a TIM more accurately reflects the performance of the TIM in actual application. The thermal impedance is a function of the TIM's bulk thermal conductivity, bond line thickness, and thermal contact resistances. In the configuration shown in Figure 2-1, the total thermal impedance of the TIM is given as [3],

$$R_{TIM} = BLT / k_{TIM} + R_{C1} + R_{C2}$$

where $R_{TIM}$ is the total thermal impedance of the TIM, BLT is the bond line thickness of TIM, $k_{TIM}$ is the thermal conductivity of the TIM, $R_{C1}$ is the thermal contact resistance between the heat spreader and the TIM, and $R_{C2}$ is the thermal contact resistance between the TIM and the heat transfer device. To achieve low thermal impedance, a TIM needs have high thermal conductivity, low bond line thickness, and low contact resistance. Although low thermal impedance is an important property for a TIM, the TIM also needs to have a good mechanical reliability. Often the thermal impedance of a TIM needs to be sacrificed to improve the mechanical reliability of the TIM by increasing the bond line thickness.

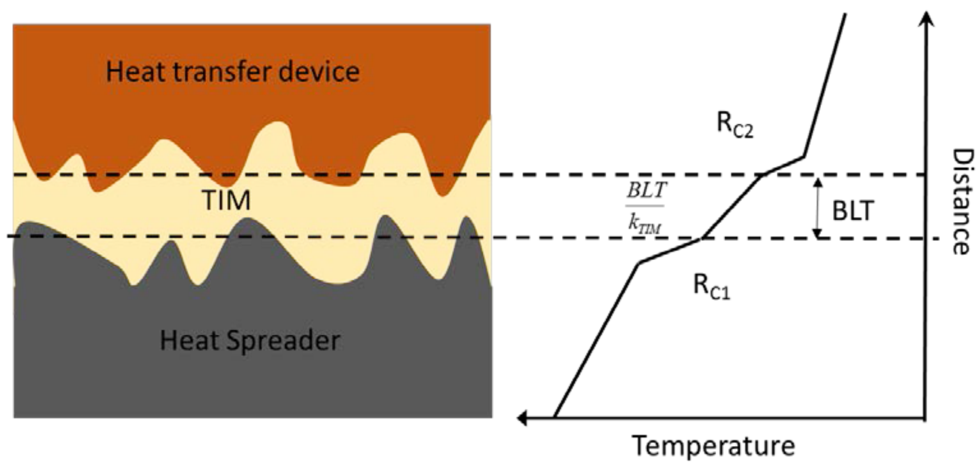



**Figure 2-1.** Schematic diagram illustrating factors influencing the total thermal impedance of a TIM.

### 2.1 Thermal Conductivity and Bond Line Thickness

Thermal conductivity of a material is generally available from the material's technical datasheet if the material is formulated and distributed as a TIM. However, the actual thermal conductivity may degrade when exposed to a harsh environment over a long period such that the mission condition must be taken into account when selecting a TIM.

A thin bond line thickness is necessary to achieve a low thermal impedance. For commercial applications, extremely low bond line thickness is often targeted. It is easier to achieve a low bond line thickness with TIMs with low viscosity. In addition, mechanical clamping is often utilized to provide pressure to achieve a thin bond line in commercial applications. For space applications, there is currently no qualified clamping mechanism for class-Y type devices. The TIM needs to bond the heat transfer device and the V5 with its own adhesive strength. Since the mechanical integrity of a TIM depends on its adhesion, both thermal and mechanical aspects need to be considered when determining the bond line thickness. Although having a thicker bond line increases the thermal impedance of a TIM, a thicker bond line can provide better strain relief when an external stress is applied to the heat transfer device during assembly or handling. Additionally, an increased bond line thickness can also enhance the thermal cycling reliability. The coefficient of thermal expansion (CTE) mismatch between the package heat spreader and the heat transfer device will create stress within the TIM, which can potentially cause delamination. Since the shear stress from the CTE mismatch decreases as the TIM thickness increases, increased TIM thickness can help prevent the delamination during thermal cycling.

The bond line thickness can be controlled by adding filler media, like glass beads, of a pre-determined size. However, an excessively high concentration of filler can lead to stack up of filler particles and result in increased or uneven bond line thickness. An excessively high filler concentration can also result in poor contact resistance or decreased adhesive strength, since the fillers can prevent the TIM from effectively penetrating the surface asperity of the package heat spreader and heat transfer device.

### 2.2 Thermal Contact Resistance

Low thermal contact resistance can be achieved when the TIM has good wetting with the surfaces of the heat spreader and the heat transfer device. Good wetting enables the TIM to penetrate surface asperities more effectively, especially if the TIM has a low viscosity. Since good wetting manifests in a low wetting angle, the wetting angle can be a measure of the wetting characteristics. When a primer is used to bond the TIM with the surfaces, the primer can improve the wetting characteristics and adhesion with the surface.

For commercial applications, TIMs are characterized per ASTM D5470 [4]. A test apparatus based on the ASTM D5470 measures the steady-state thermal impedance and the bond line thickness of a TIM while applying a controlled amount of pressure. However, the ASTM D5470 method only evaluates steady state thermal resistance and does not account for the actual situation where the electronic assemblies are exposed to shock, vibration, and thermal cycling.

### 2.3 Adhesive Strength

Reworkability and shock/vibration reliability of a TIM are strongly related to the adhesive strength. The adhesive strength of the TIM over the entire use temperature range needs to be considered when selecting a TIM. In addition, the adhesive strength of the lid adhesive material also needs to be taken into account. As shown in Figure 1-1, the die and the lid (heat spreader) are bonded to each other with the lid adhesive material (TIM1), and the lid and the heat transfer device are bonded to each other with the TIM. The lid adhesive material of the V5 CF package (IBM's material code name: ATI) has a low glass transition temperature ($T_g$, ~60°C) and its lap shear strength reduces from ~2060 psi at room temperature to ~630 psi at 125°C [5]. This is a low adhesive strength for an epoxy material, and it creates risk of lid detachment when stress is exerted on the heat transfer device at an elevated temperature. If an epoxy material with an adhesive strength greater than the lid adhesive material is used as the TIM, the lid will likely delaminate instead of the TIM when a high enough stress is applied to the heat transfer device. In addition, if the TIM has to be reworked at an elevated temperature where the lid adhesive material will exhibit reduced adhesive strength, there will be an increased risk of lid delamination during the rework process. The mechanical properties of the lid adhesive material used in the V5 CF package are well understood through a FY12 NEPP task. The CF package, however, has now been discontinued and been replaced by the CN package. The CN package uses a different lid adhesive material; the lid adhesive material of the CF package is an electrically conductive material, but the lid adhesive of the CN package is an electrically non-conductive material. Properties of the new lid adhesive material need to be known to use the new CN package more reliably.

Since spacecraft electronics are often subjected to rework, the possibility of potential rework needs to be considered when selecting a TIM. The heat transfer device will need to be removed to rework the V5 or other electronic parts under the heat transfer device. If the V5 has to be kept intact and only parts under the heat transfer device need to be reworked, the heat transfer device needs to be removed from the V5 with a small amount of force to not to damage the solder columns of V5. If the TIM has high adhesive strength, a large amount of stress will be required to remove the heat transfer device, and the large stress applied during the removal process can be transferred to solder columns or lid, causing damage. Conversely, a TIM with low adhesive strength may be easier to rework, but it may also have an increased risk of potential delamination by shock and vibration. If delamination or cracking take places at a microscopic level, the thermal contact resistance will increase without exhibiting any visually observable indication.

## 2.4 Reworkability

TIMs also need to be reworkable. Spacecraft electronic assemblies are often subjected to rework, and a heat transfer device may need to be removed to rework parts under the heat transfer device. If an excessively large amount of stress is used during the removal of the heat transfer device, the stress may cause delamination of the lid adhesive material or may induce deformation or microcracking to device solder columns that could manifest as premature failure during temperature cycling and shock and vibration tests. The reworkability depends on the properties and the bond line thickness of TIM and the geometry of the heat transfer device. If a TIM has a high adhesive strength, the TIM will be difficult to rework. If the bond line thickness of the TIM is too low or the contact area between the heat transfer device and the CCGA's heat spread is too large, it will be difficult to cut through the TIM.

Figure 2-2 depicts the apparatus developed at JPL during the FY14 task to evaluate the reworkability of TIMs. A six-axis force torque transducer is attached to a structure that can simulate the heat spreader of a V5. A heat transfer device is attached to the heat spreader equivalent material with the TIM. The heat transfer device is removed with the actual tooling and procedure. The six-axis force torque transducer records stress and torque in the every directions. The measured force and torque are then applied to a finite element analysis (FEA) to calculate the maximum stress within solder columns.

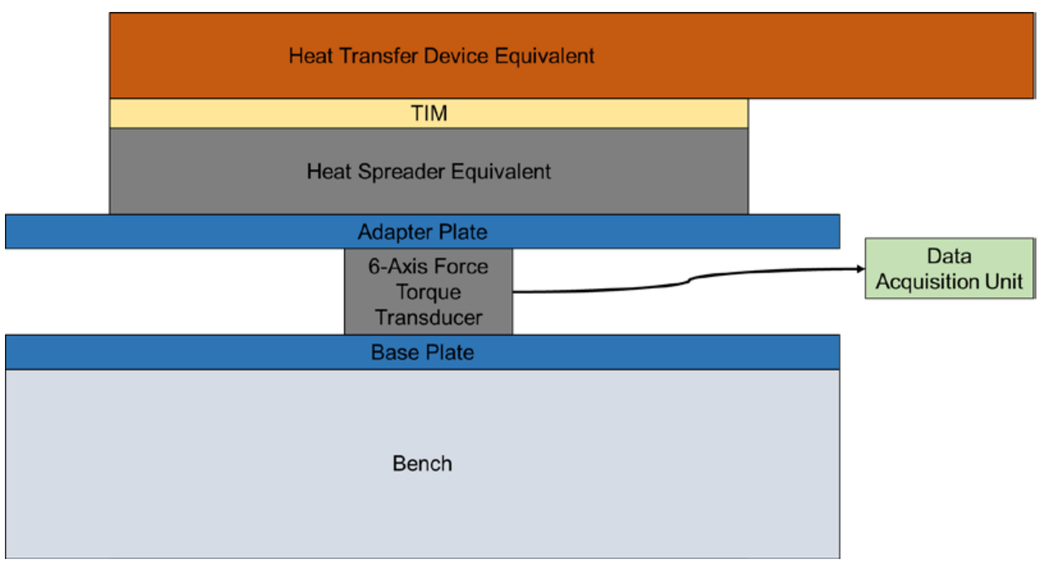



**Figure 2-2.** Schematic diagram of the reworkability test apparatus developed at JPL during the FY14 NEPP task.

The current task focused on developing the reworkability test setup. The reworkability test will be performed in other future programs. The variables of the reworkability test are as below.

1) TIM properties

The stress required to rework will depend on TIM properties such as adhesive strength and the elastic modulus. TIMs with different mechanical properties will be tested. Complete removal of TIM residue is also important; TIM residue will be analyzed with an image-analysis software.

2) TIM bond line thickness

   The bond line thickness of the TIM affects the reworkability. If a cutting tool, such as a hot knife, is utilized to cut through the TIM along the bond line, the cutting action will be progressively more difficult as the bond line thickness is reduced.

3) Evaporator plate geometry

   As explained in the Section 2.6, the evaporator plate geometry will affect the stress concentration within the TIM during shock and vibration tests. Different evaporator plate geometries may be used depending on mission requirements. From the reworkability standpoint, a small evaporator plate would enable good reworkability, but a large circular evaporator plate would minimize the stress at the high stress concentration region. Reworkability of the TIM will be tested using evaporator plates with different sizes and shapes.

The stress measured by the reworkability test apparatus will be later applied to FEA to calculate the level of stress on the solder columns and lid adhesive material.

## 2.5 Device Power Dissipation and Property Changes of the Thermal Interface Material

Properties of a TIM depends on the TIM's temperature, which depends on the ambient temperature, the power dissipation of the device, and the configuration of the heat transfer device. The power dissipated from the device will increase the TIM temperature above the ambient temperature. The effect of the device power dissipation on the TIM temperature was investigated through a finite element analysis (FEA). The finite element model (FEM) is based on a 6U electronic assembly, with a heat pipe attached to a V5, and an aluminum frame. FEA was performed to investigate the relationship between power dissipation, junction temperature, and TIM temperature of the electronic assembly using a heat pipe. The electronic assembly also had other components dissipating heat. Components dissipating power greater 40 mW were all included in the model. The thermal conductivity of the heat pipe was assumed to be 118 W/cm·K. Initially the FEA was performed for the case when the V5 dissipates ~5.7 W. Due to the high thermal conductivity of the heat pipe, the heat pipe was observed to transfer ~7.3 W to the frame, indicating that ~1.6 W of heat generated from components other than the V5 was removed through the V5 and heat pipe to the frame.

The junction temperature and the TIM temperature were calculated as functions of the device power dissipation. In this model, the thermal contact resistance of the TIM was not taken into consideration; instead, 20% of margin was applied to the bulk thermal conductivity of the TIM. The temperature of the chassis mounting surface was set to 65°C. The power dissipation was modeled from 1 W to 20 W. The FEA results describing the relationship between power dissipation, junction temperature and TIM temperature are shown in Figure 2-3. The temperature of the TIM is only several degrees lower than the junction temperature, due to the low thermal resistance of the package lid. The TIM properties, such as adhesive strength and elastic modulus, depend on the TIM's temperature. Therefore, the TIM property changes according to temperature must be taken into account when selecting a TIM. For example, if a TIM exhibits a large drop in adhesive strength at temperatures above 80°C, the TIM may not be suitable for the case in Figure 2-3 when the V5 dissipates 10 W.

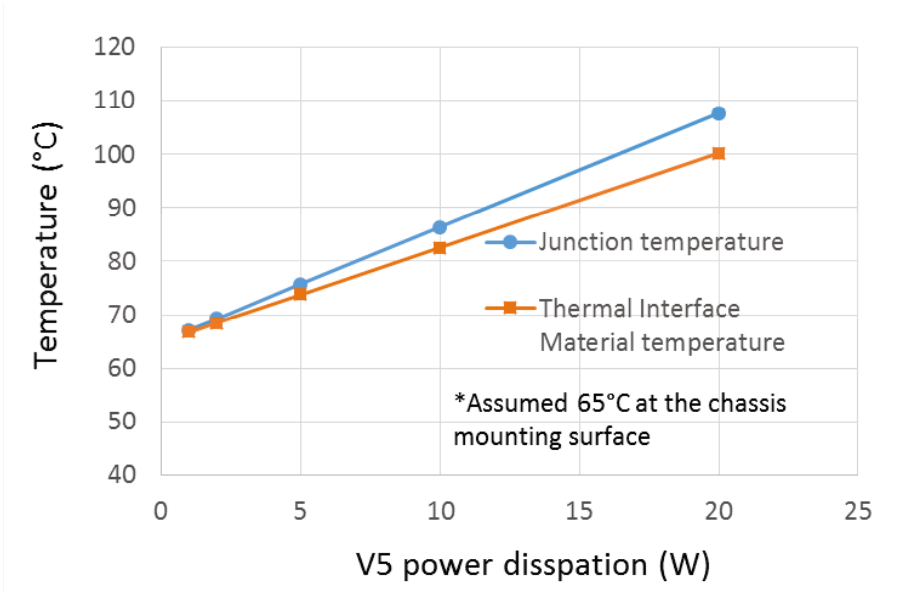



**Figure 2-4.** Plot of the FEA result on the relationship between power dissipation of a V5, junction temperature, and TIM temperature in an electronic assembly using a heat pipe.

The V5 package used in the model is the currently discontinued CF package. The lid of the V5 CF package has greater thermal conductivity and thickness than the lid of the CN package. According to the Xilinx datasheet, the difference in the thermal specification of the two packages is small. More detailed discussion is provided later in this report in Section 3.3.

## 2.6 Elastic Modulus

Figure 2-4 (a) and (b) are FEA results showing how shear stress distribution within a TIM changes according to the TIM's elastic modulus during a random vibration test. The purpose of the simulation was to see how stress distribution would evolve as the elastic modulus increases. When a TIM's elastic modulus was 1 kpsi, the maximum shear stress in the TIM was 33 psi. When the TIM's elastic modulus was assumed to be 10 Mpsi as an extreme case, the maximum shear stress increased to 627 psi. If the maximum shear stress exceeds the adhesive strength of the TIM, delamination of TIM will initiate from the location with the maximum stress and may propagate during vibration. It must be also noted that the geometry of the heat pipe evaporator plate will also affect the stress distribution. The current finite element model was based on an evaporator geometry designed to achieve a good reworkability. The dimension of the evaporator plate was around $1.5 \times 0.5$ inch$^2$ such that the heat pipe can be easily removed if needed; a larger evaporator plate would better distribute the stress but would be more difficult to rework. If excessively high stress concentration on a certain region of the TIM is expected, the risk of TIM delamination can be reduced by using a larger, circular evaporator plate or staking the plate near the high stress concentration region.

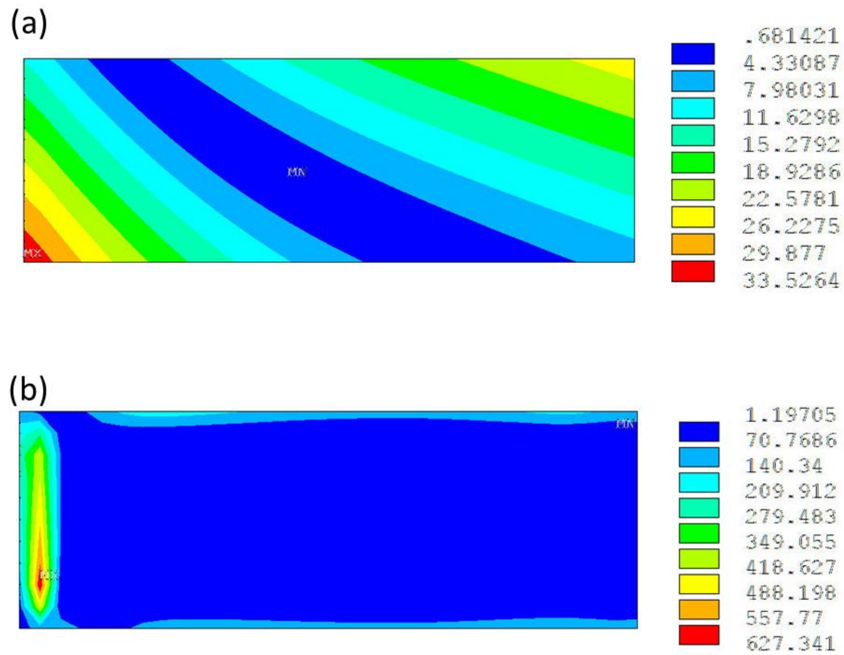



**Figure 2-5.** FEA results showing shear stress distribution in TIM with different elastic moduli shown in (a) 1000 psi and (b) 10 Mpsi.

The effect of a TIM's elastic modulus on the amount of stress on solder columns during vibration was also investigated. The V5 package did not have any corner supports in the model. The FEA result indicated that the elastic modulus of the TIM would not affect the vibration test life of solder columns. TIM's elastic modulus had negligible effect on the solder column loads, printed wiring board (PWB) deflection, and vibration modal frequencies.

The FEM assumed a 5-mil bond line thickness. Investigation of the effect of bond line thickness on the stress distribution within the TIM and the solder columns will be done in future tasks along with actual experiments.

## 3.0 RELIABILITY OF THERMAL INTERFACE MATERIALS

Properties of the TIM, such as thermal conductivity and adhesive strength, should not degrade beyond an acceptable level after long term exposures to harsh environments. More importantly, thermal impedance of the TIM should remain high enough after reliability tests such as thermal cycling, shock, and vibration, and highly accelerated stress test (HAST). The CTE mismatch between the package lid and the heat transfer device will create stress within the TIM and potentially cause the delamination of TIM during the thermal cycling. Since the stress from the CTE mismatch decreases as the TIM bond line thickness increases, increased TIM bond thickness can improve the thermal cycling reliability, though it will increase TIM's thermal impedance. The effective contact between a surface and the TIM is critical for achieving a good thermal contact resistance. Thermal contact resistance can be compromised if microscopic delamination or cracking take places during shock, vibration, and thermal cycling. To prevent delamination or cracking, the TIM needs to have an adhesive strength high enough to prevent delamination but low enough to be reworked. TIM's both mechanical and thermal properties have to be considered when determining the bond line thickness, so that the TIM can be both mechanically reliable and thermally effective.

### 3.1 Apparatus for Evaluating the Performance of a TIM

Delamination or cracking can take place in a TIM during shock, vibration, and thermal cycling tests. Damage in a TIM will result in increased thermal impedance in the TIM. One of the challenges in evaluating the reliability of a TIM is that delamination or cracking may not be detectable through visual inspection. Therefore, in addition to visual inspection, the thermal performance of a TIM has to be characterized before and after reliability tests.

Figure 3-1 schematically depicts a test setup developed to characterize overall thermal performance of a heat pipe assembly. The setup comprises heaters, temperature sensors, a data acquisition unit, and a vacuum chamber. The heaters are attached to a side of the V5 substrate and powered to generate heat. The temperature sensors are attached to various locations, such as package lid, heat transfer device, and chassis. The test is performed in a vacuum chamber to simulate the space vacuum. This test is performed on an electronic assembly before and after shock, vibration, and thermal cycling tests. If there is a delamination or cracking of TIM, the temperature difference between the V5 heat spreader and the heat pipe evaporator will increase. It must be noted that this test does not aim to precisely determine the thermal impedance change of a TIM; the purpose of this test is to determine whether the TIM's performance will remain within the acceptable level after the reliability tests. If damage in the TIM is minor such that the performance of the TIM remains within the acceptable level, the damage will not be of concern.

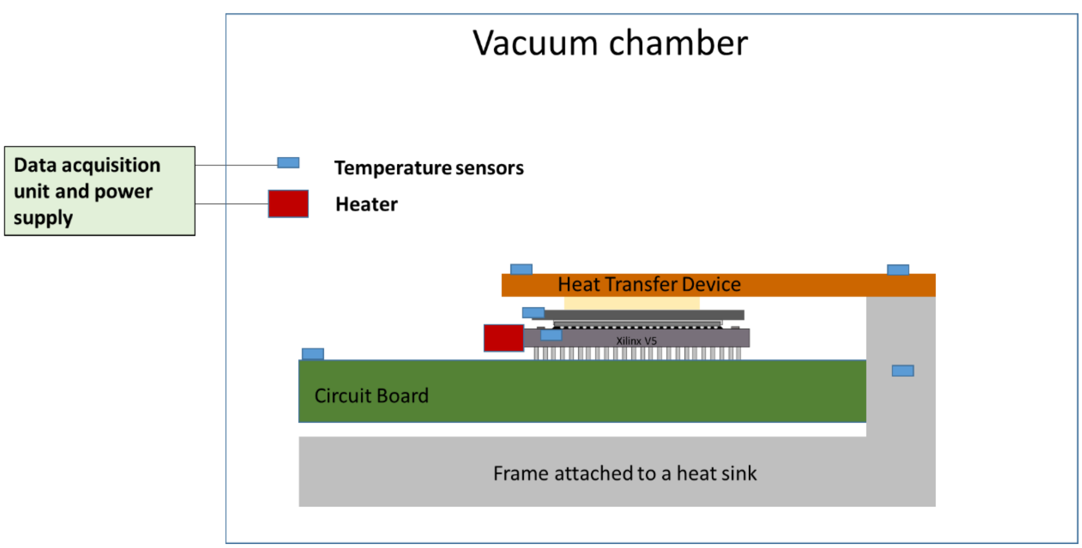



**Figure 3-1.** Schematic diagram of TIM performance test setup developed during the FY14 NEPP task.

The heat generated from the heaters is dissipated through the heat transfer device and the board. The amount of heat flow within the electronic assembly can be characterized by temperature evolution in different regions of the electronic assembly. For example, if the thermal impedance of the TIM increases after the reliability tests, the temperature difference between the lid and the heat transfer device will increase. Heat dissipation through the board will also increase if the TIM thermal impedance increases.

## 3.2 Temperature Cycling Reliability of TIM

As discussed previously, the stress due to the CTE mismatch between the package lid and the heat transfer device can potentially cause delamination of the TIM during thermal cycling. If the circuit board and the heat transfer device have different CTEs, their CTE mismatch can also cause delamination of the TIM and premature failure of solder columns. However, if the heat transfer device is made of copper, it is considered to be sufficiently CTE matched with the circuit board along the length of the circuit board. However, the asymmetric loading from the heat transfer device can potentially affect the temperature cycling reliability of solder columns.

The CTEs of the materials involved in the thermal cycling reliability of TIM are summarized in Table 3-1 below. The Xilinx CF package uses SiC as the package lid. SiC has a CTE close to the CTE of silicon (2.6 ppm/°C) and a high thermal conductivity (~250W/m·K), so that SiC functions as a high thermal conductivity material while producing minimum CTE mismatch stress to the lid adhesive material and the Si die. If a copper heat pipe is attached to the SiC lid, the CTE mismatch between the SiC and copper generates CTE mismatch stress that can potentially cause delamination or cracking of the TIM. The CTE mismatch stress at the edge of the heat pipe evaporator plate increases as the area of the evaporator plate increases and the TIM bond line thickness decreases. The Xilinx CN package uses Al–SiC as the lid material. Al–SiC has a larger CTE than SiC; and therefore, the CTE mismatch stress with heat pipe will be less than in the case of SiC lid. Although the risk of TIM delamination by thermal cycling is low, this type of test would be necessary to eliminate the risk for high reliability applications.

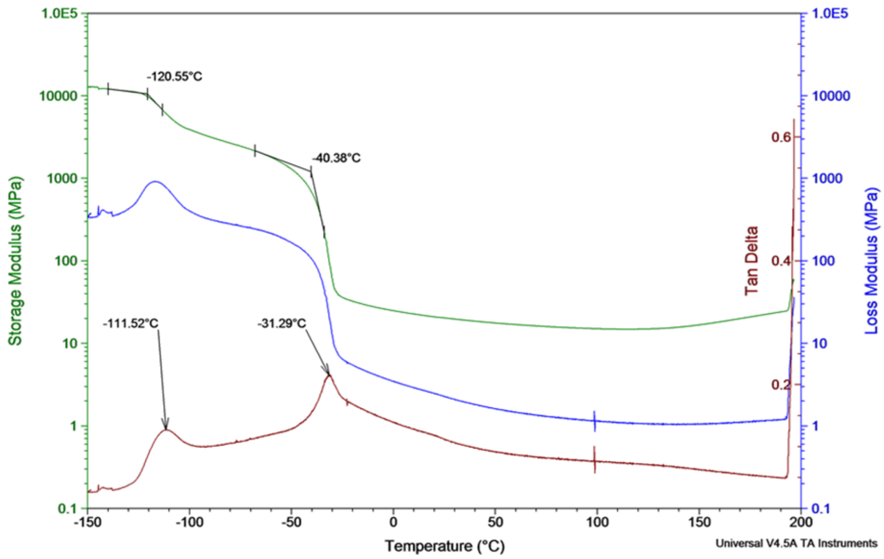
**Table 3-1.** CTEs of materials to which TIMs are bonded.

| Material | CTE (ppm/°C) | Application |
|---|---|---|
| SiC | ~2.8 | CF package lid |
| Al-SiC | 8~12 | CN package lid |
| Copper | ~17 | Heat pipe |

## 3.3 TIM Materials Properties Measurement

The mechanical properties of the candidate material need to be characterized over a wide temperature range. During the FY14 task, dynamic mechanical analysis (DMA) was performed on candidate materials. The candidate materials were thermally conductive low outgassing silicones. Figure 3-2 shows DMA thermograms of two thermally conductive silicones. DMA was performed on a TA Q800 DMA instrument configured in a single-cantilever mode and a gas cooling accessory (GCA) and run from –150ºC (equilibrated and then held isothermal for 5 minutes) to +200ºC using a ramp rate of 3 ºC/min, at a constant frequency (1 Hz) and constant amplitude (25 µm). Both materials exhibit fairly consistent storage and loss modulus above the $T_g$. However, the first silicone in Figure 3-2 (a) exhibited two distinct drops in storage modulus at –120°C and –40°C, whereas the second one in Figure 3-2 (b) produced a more classical DMA thermogram, with a single storage modulus drop at –110°C, and a distinct $T_g$ (tan delta) of 101.17°C.

(a)




(b)

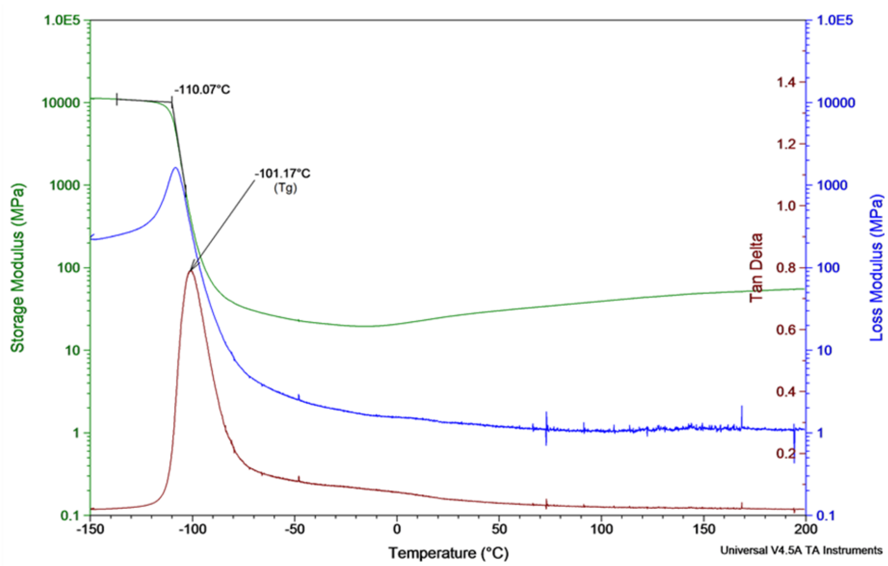



**Figure 3-2.** DMA thermograms of thermally conductive silicones.

It will be useful to know the adhesive strengths of TIMs at the entire range of the operating temperature to use TIMs reliably. The adhesive strengths of TIMs over broad temperature range will be measured in future tasks when opportunity is available.

## 3.4 Status of Studies on V5 Thermal Management and TIM Reliability Tests at JPL

The current FY14 NEPP task focused on setting up test apparatus and performing FEA. The FY14 task also leveraged on-going flight projects at JPL. During the FY15, various reliability tests on electronic assemblies with TIM and heat pipe were performed under different flight programs at JPL. Shock, random vibration, and temperature cycling tests were performed. The test setup for evaluating the thermal performance in the Figure 3-1 was utilized during these tests. The temperature evolution in the electronic assembly was measured before and after random vibration tests and temperature cycling. The effect of heat pipe on solder column reliability was also investigated.

## 3.5 Comments on the Package Assembly Changes of Xilinx V4 and V5, from CF Package to CN Package

Xilinx discontinued the CF package and released the CN package in calendar year 2014. This task mainly focused on the thermal management of the CF package. To address the future use of the CN package, it will be necessary to review the thermal characteristics of the two packages. Table 3-2 summarizes characteristics relevant to thermal performance of the two packages. The thermal conductivity of the lid adhesive material is not known yet, except that the material an electrically non-conductive material. The 1.5 W/m·K thermal conductivity was taken for the typical thermal conductivity of an electrically non-conductive epoxy. The thermal resistances, $\theta_{JC}$, $\theta_{JB}$, and $\theta_{JA}$, are from the Xilinx datasheet [1]. There are only little differences in the thermal resistances, especially the junction-to-case ($\theta_{JC}$) and the junction-to-board ($\theta_{JB}$), which are the relevant parameters for removing heat from a V5 in space vacuum. The lid of the V5 CF package is made of 2-mm thick SiC, which has a high thermal conductivity of 200~270 W/m·K. The lid of a V5 CN package is made of Al-SiC. The lid of the CN package has a lower thermal conductivity (180 W/m·K) than the lid of the CF package, but its smaller thickness compensates for the lower thermal conductivity. A calculation based on the material properties of the package showed a thermal resistance increase of 0.01°C/W through the lid attach material of the CN package than the CF package.

Since the lid-attach material of the CN package is an electrically non-conductive material, the Al–SiC lid is electrically floating and has to be electrically grounded. Using an electrically conductive material as a TIM to provide both thermal and electrical path could be an option for the CN package. However, caution has to be taken since electrically conductive silicone may generate flakes during random vibration, which can cause electrical short.

**Table 3-2.** Physical parameters of Xilinx CF and CN packages related to thermal management.

| | CF package (old) | CN package (new) |
|---|---|---|
| Lid thickness (mm) | 2 | 0.85 |
| Lid area ($mm^2$) | 38.5 x 38.5 | 44.1 x 44.1 |
| Lid material thermal conductivity (W/m·K) | 200~270 (SiC) | 180 (Al-SiC) |
| Lid-attach material thermal conductivity | 3~4 W/mK (Electrically conductive) | ~1.5 W/mK (Electrically non-conductive) |
| $\theta_{JC}$ (°C/W) | 0.06 | 0.07 |
| $\theta_{JB}$ (°C/W) | 2.0 | 1.9 |
| $\theta_{JA}$ (°C/W) | 7.2 | 6.4 |

## 4.0 SUMMARY

The heat from high-power microdevices for space, such as Xilinx Virtex 4 and 5 (V4 and V5) FPGAs, has to be removed mainly through conduction in the space vacuum environment. The class-Y type packages are designed to remove the heat from the top of the package. Therefore, the most effective method to remove heat from the class-Y type packages is to attach a heat transfer device on the lid of the package and to transfer the heat directly to the frame or the chassis. When a heat transfer device is attached to the package lid, the surface roughnesses of the package lid and the heat transfer device reduce the effective contact area between the two. The reduced contact area results in increased thermal contact resistance, and a TIM is required to reduce the thermal contact resistance by filling in the gaps between the surfaces of the package lid and the heat transfer device.

The FY14 task studied the properties and requirements of TIMs and the impact of TIM properties on packaging reliability. The task also developed experimental setups to investigate the performances of TIMs in mission environments. Several candidate TIM materials were selected based on their thermal conductivities and reworkability.

## 5.0 ACKNOWLEDGEMENTS

Mike Blakely performed FEA. Peter Dillon led the selection of the candidate TIM materials evaluated in the current task. Kevin Hischier designed the reworkability test apparatus. Don Hunter led the implementation of a heat pipe. Steve Tseng provided consultation on general issues in thermal management of the V5. The current study leveraged works done under two JPL flight projects, Orbiting Carbon Observatory -3 (OCO-3) and Surface Water Ocean Topography (SWOT).

## 6.0 ACRONYMS AND TERMS

| | |
|---|---|
| BLT | bond line thickness |
| CCGA | ceramic column grid array |
| CPU | central processing unit |
| CTE | coefficient of thermal expansion |
| DMA | dynamic mechanical analysis |
| FEA | finite element analysis |
| FEM | finite element modelling |
| FPGA | field programmable gate array |
| FY | fiscal year |
| GCA | gas cooling accessory |
| GPU | graphics processing unit |
| HAST | highly accelerated stress test |
| JPL | Jet Propulsion Laboratory |
| OCO-3 | Orbiting CarbonObservatory-3 |
| PCM | phase change material |
| PWB | printed wiring board |
| SWOT | Surface Water and Ocean Topography (spacecraft) |
| $T_g$ | glass transition temperature |
| TIM | thermal interface material |
| TIM1 | TIM that bonds a Si die with the heat spreader |
| TIM2 | TIM between the heat spreader and the heat transfer device |
| U | size of 10 × 10 × 10 cm used for roughly describing sizes of electronic assemblies |
| V4 | Xilinx Virtex 4 field-programmable gate array |
| V5 | Xilinx Virtex 5 field-programmable gate array |

## 7.0 REFERENCES

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The heat from high-power microdevices for space, such as Xilinx Virtex 4 and 5 (V4 and V5), has to be removed mainly through conduction in the space vacuum environment. The class-Y type packages are designed to remove the heat from the top of the package, and the most effective method to remove heat from the class-Y type packages is to attach a heat transfer device on the lid of the package and to transfer the heat to frame or chassis. When a heat transfer device is attached to the package lid, the surfaces roughness of the package lid and the heat transfer device reduces the effective contact area between the two. The reduced contact area results in increased thermal contact resistance, and a thermal interface material is required to reduce the thermal contact resistance by filling in the gap between the surfaces of the package lid and the heat transfer device.

The current report describes JPL's FY14 NEPP task study on property requirements of TIM and impact of TIM properties on the packaging reliability. The current task also developed appratuses to investigate the performances of TIMs in the actual mission environment. Several candidate TIM materials were selected based on their thermal conductivities and reworkabilities.

**15. SUBJECT TERMS**

class-Y, thermal management, thermal interface material, Virtex 5, Heat Pipe

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