# MULTICHIP MODULE DIE-ATTACH WITH LOW STRESS, THERMALLY CONDUCTIVE EPOXIES

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## INTRODUCTION

Since the introduction of multi-chip modules for main-frame computers by IBM(1), there was a period of 5 years before major activities were revived for the use of the technology for microelectronic packaging. IBM's approach requires flip-chip and water-cooling through intimate contact with the die, which represents different technology and tends to be too costly for most other manufacturers.

The introduction of a different multi-chip packaging approach by DEC, in its VAX 9000 series of high performance main-frame computers, proved much more amicable to most computer manufacturers(2). Both the cost and technology are more manageable. The performance in terms of circuit speed and thus, instructions per second also proved to be outstanding with a simpler air-cooled system.

The advantages of higher circuit speed, and drastic reduction in size and weight are the main attractions for manufacturers in pursuing such technology. Almost all of the companies involved in high performance computers from work-station, main-frame, to super-computer are actively developing their MCM packaging approaches(3,4).

In this paper, we will address one very important aspect of MCM packaging, namely stress and thermal management in the die-attachment of these complex devices.

## THERMAL CONSIDERATIONS

In order to fully utilize the technological advantages in MCM, die used are normally highly integrated, with sizes over 1 square centimeter and power up to 30 watts. Any die of such size with power of over 2 watts per square centimeter involves some re-thinking of packaging schemes.

In order to channel away the heat generated by such dice, the substrates that are used are normally maximized in terms of thermal conductivity. Thus, it is also very important that the adhesives being used are also as effective a heat transfer medium as possible. It has been proven that the reliability of electronic devices improves by 10 times if the junction temperature of such a device can be reduced from 100°C to 50°C. In addition, excessive temperature increases caused over 55% of all failures in electronic devices(5,6).

It is the size and the power density of the die used in MCM packaging that dictates a new approach to die-attach and thermal management for these modules.

## SUBSTRATE MATERIAL CONSIDERATIONS

In order to maximize the thermal transfer characteristics of the total package, the thermal conductivity of the substrate materials are carefully engineered. Conventional substrates such as FR-4, Polyimide multi-layer, or alumina are seldom used. Instead, silicon, aluminum nitride, copper, and even aluminum are generally used or considered.

The ramification of this type of change is that the thermal expansion coefficient of the substrate can be substantially different that of the traditional packaging material. The TCE difference between silicon die and copper can be as much as 14 ppm/C. These type of TCE differences along with the increase in die size, require a total engineering change in packaging such device.

Another consideration of these new substrates is the fact that the substrates, such as copper or aluminum, and an interconnection, such as polyimide, cannot be processed in the high temperature range of silver-glass adhesives. Lower temperature curing adhesives must be used in these cases.

## SIZE AND TCE CONSIDERATIONS

Almost all packages requiring multi-chip modules will include some high functionality die which are generally very large; over 1 square centimeter. In fact, die in the range of 1 square inch are on the drawing board for higher performance applications.

Traditional IC packages of size close to 1 square centimeter can be made functional and reliable using traditional adhesives and encapsulation. It is generally proven that when size approaches 1 square centimeter, stress becomes excessive for such a method to be used reliably.

Full stress calculation and consideration requires a three dimensional model with various stress and strain assumptions which tend not to be available. The magnitude of the stress issue can be easily visualized with a simple 1-dimensional elastic model.

Figure #1 is an illustration of stress generation due to differences in TCEs of adherends (substrates, components or die) and adhesive. In this particular model, both the die and component are assumed to have the same TCE and thus the only stress contribution is due to that of the adhesive/adherends assembly. Curing the adhesive at 150$^{o}$C, (as most the electronic assembly is performed), and cooling the assembly down to 25$^{o}$ C or ambient condition is assumed. Adhesives such as epoxies are generally of a planer zig-zag conformation and expand and contract at approximately 60 ppm/$^{o}$C below glass transition and approximately 200-300 ppm/$^{o}$C above glass transition temperature. As most adhesives are filled with functional fillers such as silver, alumina, etc., to enhance electrical and thermal properties, the TCE tends to be reduced somewhat proportionately to the volume percentage of the fillers in the adhesive being considered. The TCEs of most of the adhesives available are roughly in the range of 40-45 ppm/C. The adhesive being in the liquid state during part of the curing time, we can roughly assume that being the equilibrium condition and therefore at zero stress. This is somewhat optimistic because the epoxy, or any polymer adhesive, generally will shrink during cross-linking and thus exert a compressive stress along its XY plane.

During the cooling cycle after the adhesive "curing", the adhesive contracts at @45 ppm/C, much faster than silicon which contracts at @3 ppm/C. The difference in TCEs and the temperature excursion of 125C will contribute to a strain of 125 x 42 ppm along the XY-plane. The stress exerted on the die/component can then be calculated as the strain X modulus of the adhesive. Most adhesive systems tend to be high strength epoxies with moduli in the range of 1,000,000-10,000,000 psi. Similar moduli are observed in of high Tg thermoplastics. The modulus of silver-glass systems tends to be high, in the range of 10,000,000 and beyond. Thus if one assumes the modulus to be at the low end (1,000,000 psi), then compressive stress on the die/component will be roughly 5000 psi. Other moduli materials can be simply calculated and are normally much higher in stress. If the assembly is further cooled to -55C for the thermal cycle or shock test, then the temperature excursion is further increased by $80^{\circ}C$ and thus the stress can be as high as 8500 psi. The internal stress due to Newton's 3rd Law will be tensile stress along the XY-plane with a magnitude of 8500 psi.

Thus, it is clear that the stress can be as high as the bond strength of the adhesive and delamination has been observed frequently for the larger area die/component bonding. This stress level, when concentrated, can also cause cracking of IC's and components or substrates. These kinds of failure modes have also been observed frequently in the thin and weaker die/components or substrates.

This kind of stress level is also observed with assembly warp in the case of TCE difference between the die/component and that of the substrate. This is most prominent if one tries to bond an alumina hybrid onto an aluminum carrier when they are not very thick.

## STRESS MANAGEMENT

There are basically two ways to address this stress problem in the assembly. The first being matching not only the die/component material to that of the substrate, but also of the adhesives. However, the difficulty of this approach is obvious from the tabulation of some of the TCEs of some of the adhesives and substrates in Table #1.

TABLE #1: THERMAL EXPANSION COEFFICENTS OF SOME COMMON SUBSTRATES AND ADHESIVES.

| MATERIAL TYPE | TCE(ppm/C) |
|---|---|
| SILICON | 3 |
| Ga/As | 3 |
| MOLYBDENUM | 5 |
| ALUMINA | 7 |
| ALUMINUM NITRIDE | 4 |
| KOVAR | 6 |
| STAINLESS STEEL 316 | 17 |
| COPPER | 17 |
| ALUMINUM | 27 |
| FR-4(XY-PLANE) | 16 |
| POLYIMIDE MULTI-LAYER(XY-PLANE) | 12 |
| TIN/LEAD SOLDER | 26 |
| INDIUM SOLDER | 42 |
| GOLD EUTECTIC | 15 |
| SILVER-GLASS | 17 |
| SILVER-EPOXY | 45 |
| ALUMINA-EPOXY | 33 |
| SILVER-POLYIMIDE | 40 |

The second method of stress management in this type of "adhesive" assembly is by reduction of the modulus of adhesive rather than the reduction of strain in the first method.

Moduli or modulus of adhesives, or any material in general, can differ as much as 2 to 4 orders of magnitude. They are primarily dependent on the glass transition temperatures and cross-link densities of the materials.

Table #2 is a tabulation of the moduli of various materials that are commonly used in electronic applications. While some of the materials might seem usable, because of various limitations, their applications are also limited. Silicones are generally good for some applications, but their weak solvent and chemical resistance and their well-known molecular "migration" cause bonding and soldering problems. Polyurethanes are generally good in terms of stress reduction, but because of a lack of temperature stability for use above 125C, sensitivity in handling and their isocyanate's toxic as well as carcinogenic potential, they are limited in their applications in electronic sectors.

TABLE #2: MODULI OF VARIOUS ADHESIVE MATERIALS(TYPICAL ONLY)

| ADHESIVE MATERIAL | TENSILE MODULUS (1,000,000 psi) | POISSON RATIO |
|---|---|---|
| TIN/LEAD SOLDER | 10.0 | 0.35 |
| INDIUM SOLDER | 5.0 | 0.35 |
| GOLD-EUTECTIC | 10.0 | 0.35 |
| SILVER-GLASS | 12.0 | 0.35 |
| SILVER-EPOXY(Tg @100C) | 1.0 | 0.35 |
| ALUMINA-EPOXY(Tg @100C) | 2.0 | 0.35 |
| SILICONE | 0.015 | 0.45 |
| POLYURETHANE | 0.020 | 0.45 |
| "STRESS-FREE" EPOXY (e.g AIT's ME 7159) | 0.017 | 0.45 |

THERMAL CHARACTERISTIC CONSIDERATIONS

Most of the metallic adhesives such as tin/lead solder, gold eutectic and indium solder tend to be very high in bulk thermal conductivity, in the order of 200-1000 Btu-in/sq ft-hr-$^{o}$F. Most of the thermal impedance due to this kind of adhesive is due to the thermal interface of the bonding only. In the case of solder pastes, it is further complicated by the voids generated in the reflow process.

Most electrically conductive and thermally conductive silver epoxies, are quite a bit less thermally conductive than metallic adhesives; in the range of 45 Btu-in/sq ft-hr-$^{\circ}$F. In the total assembly system they are roughly the same as that of the soldered assembly in terms of thermal resistance when the bondline thickness is thin and in the range of 1-3 mils(10, 11).

In the case of higher thicknesses, the thermal resistance becomes more dependent on the bulk thermal conductivity of the adhesive. For electrically insulating adhesives, the most common filler used is alumina. The thermal conductivity of most of these adhesives is in the range of 4-6 Btu-in/sq ft-hr-$^{\circ}$F(12). Even though they are quite a bit better than the virgin polymer, which is in the range of 0.2 Btu-in/sq ft-hr-F.

With the advance of material technology, the thermal conductivity of epoxy adhesives can be improved significantly. Figure #2 is an illustration of some thermal conductivite that have been achieved with the improvement of these materials. Thermal conductivities as high as 80 Btu-in/sq ft-hr-F have been achieved and with proper heat draining and air-cooling, thermal power of over 30 watts/sq cm has been shown to be able to cool to below 50$^{\circ}$C.

## TAB AND BRIDGING CONSIDERATIONS

Even though silver epoxies have good thermal conductivity, they are electrically conductiv~~it~~e. In the case of fine-pitch TAB configurations, silver epoxies have been shown to cause potential bridging problem between pitches. Even in the more established surface mounting of the components for hybrid circuits, the use of silver-epoxies has been demonstrated to cause occasional bridging problems when the conductive traces are close together.

In order to address this problem when there is no requirement for electrical conductivity, a thermally conductive, electrically insulating adhesive is used. This is often the case in TAB based die-attach applications.

When electrical drain is required with or without thermal conduction requirements, bridging can also be avoided in materials with Z-axis conductive properties only. In this type of technology, the Z-axis conductive adhesive will provide for XY electrical isolation even if the adhesive has been "smeared" between conductive pads.

In MCM packaging, close pitch with either wire-bonding or TAB configuration is fact of life. The availability of "stress-free" bonding with both thermal and electrical conductivity in Z-axis can prove to be useful not only for die-attach but also for outerlead bonding for TAB. In the case of TAB OLB, most common approaches use heat-bar or laser heating for soldering if solder pastes are used. But the limitation due to bridging between pitches poses one of the most difficult processing steps in MCM fabrication. Z-axis conductive adhesives can prove to be a process advantage.

## SUBSTRATE-ATTACH CONSIDERATIONS

While there is no requirement for component level thermal management, there is a definite need for thermal management on the substrate level. While dice are packed in MCM in much higher density than conventional packages, they also tend to be higher power density die. This also increases the need for proper thermal transfer to a thermal base and the outside world.

Substrate attach with proper thermal management consideration will provide much more reliable devices. It has been established that more than 55% of electronic failures can be attributed to thermal problems(5). Because of the fact that the cost effective thermal base is typically aluminum which is very different than most of the typical MCM's substrates, the "stress-free" substrate attach epoxies have been proven to be extremely effective in this level of packaging.

Because of the fact that the thermal energy of each device has been distributed onto the larger areas of the substrate, the power density is much lower than in the die attach level. In most of the applications with power of less than 1 watt/sq.cm, users have found products with 12 Btu-in/sq.ft-hr-F to be adequate. From 1 to 5 watts/sq. cm., 25 Btu-in/sq. ft.-hr-F adhesive was found to be adequate. For power density above this level, novel diamond-based adhesives have been found to be effective.

## SOME EXAMPLES OF THERMAL MANAGEMENT OF MCM

The most prominent example of all MCM packaging is that of the MCM unit in DEC's VAX 9000 main-frame computer(2). The packaging approach can be illustrated schematically in Figure #3. There are typically over 30 silicon dice on each module with a power level in the range 300 watts per module of 4"X4". The highest power die generate energy in the range of 30 watts/sq. cm. The substrate in this case is copper which is substantially different than that of the silicon in terms of CTE( 17 ppm/$^{o}$C vs 3 ppm/$^{o}$C). When conventional silver die-attach materials are used, they pose two main problems: bridging for the TAB device, stress induced delamination or die cracking. A novel flexible, stress-free epoxy with a special diamond filler was developed and provided extreme reliability. If one was to look at the packaging scheme proposed and adopted by DEC, it is rather revolutionary. This novel approach allowed them to air cool their main-frame computer, and while also being able to achieve much higher MIPS than otherwise. This is in part made possible by this rather novel epoxy system.

Another example of MCM packaging can be illustrated in Figure# 4. This particular application,a high frequency communication module MCM, is ideal for high frequency applications in the Microwave range because of controlled impedance and ability to handle higher power density. In this case, both the die-attach and substrate-attach are using the "stress-free" epoxy. Both film and paste silver filled adhesive; the film-format reduces the probability of bridging,compared to conventional paste products. Substrate-attach uses a thermally conductive paste which allows extreme distortion of the co-fired ceramic substrates over the area of 2"X5".

The reworking of these "stress-free" epoxies has also been proven to be extremely useful and effective. ~~Figure#~~ 5 is an illustration of bond-strength vs temperature. Reworking is generally performed in the temperature range of 80-120$^{o}$C. The bond strength is typically in the range of 300 psi. While direct lift-off is not recommended, torque, twisting, tilting are all effective mean of using minor force of a few pounds to provide stress-concentration of over 300 psi to initiate and delaminate the assembly. The bond strength is still relatively strong for reliability of the devices when operating at temperature around and above 150$^{o}$C. The fact that these stress-free epoxies are cross-linked polymers allows them to maintain reasonable bond-strength even up to 300$^{o}$C. In contrast, thermoplastics will normally flow under those condition if Tg is low(18).

## CONCLUSIONS

Multi-chip module packaging has become one of the most advanced packaging schemes for computer and communication applications. The major advantages are the speed of the circuits and the controlled impedance of the modules besides the ability to be much denser and lighter. In order to fully utilize this novel packaging, the dice are typically highly integrated and large in size, along with higher in power density.

Stress and thermal management are the key issues in die- and substrate-attach. Novel flexible and stress-free adhesives in the forms of both pastes and films have been proven to work very effectively in some of the most prominent examples.

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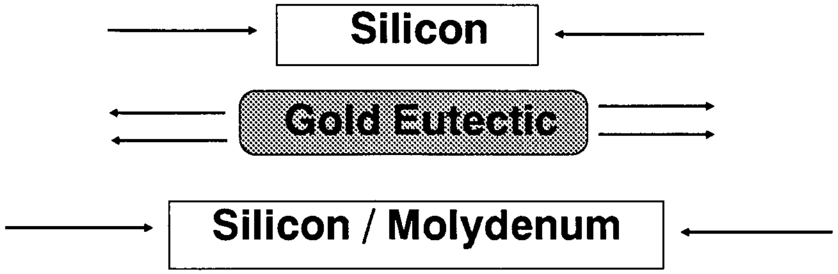
| | | |
|---|---|---|
| $TCE_{Si} = 3$ ppm/°C | $TCE_A = 20$ ppm/°C | $TCE_{Si} = 3$ ppm/°C |
| $E_{Si} = 60 \times 10^6$ psi | $E_A = 10 \times 10^6$ psi | $E_{Si} = 60 \times 10^6$ psi |

**Soldering Temperature = 225°C; Ambient Temperature = 25°C; Low Temperature Exposure = -55°C.**



**Potential Tensile Stress in "Adhesive" / Solder Cool To Ambient:**

$$\begin{aligned}
\sigma_{Si} &= \varepsilon_A \times E_A = \sigma_A \\
&= (\alpha_A - \alpha_{Si})\, \Delta T \times E_A \\
&= 17 \times 10^{-6} \times 200 \times 10 \times 10^6 \text{ psi} \\
&= 34{,}000 \text{ psi} \\
&\text{when } T = 25^{\circ}\text{C}
\end{aligned}$$

**Figure #1: Stresses for device assembled with CTE matched substrates but CTE mis-matched adhesive**

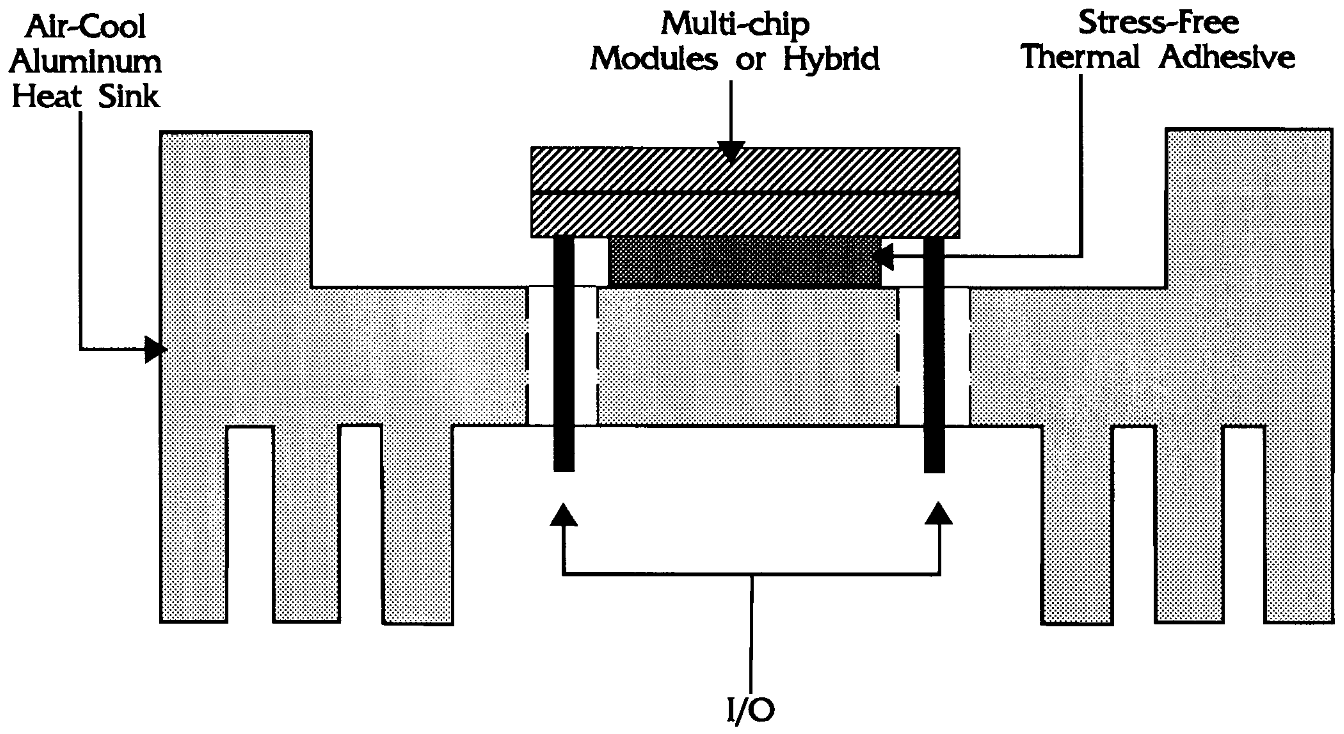


Figure #4: Thermal Management for communication multichip modules

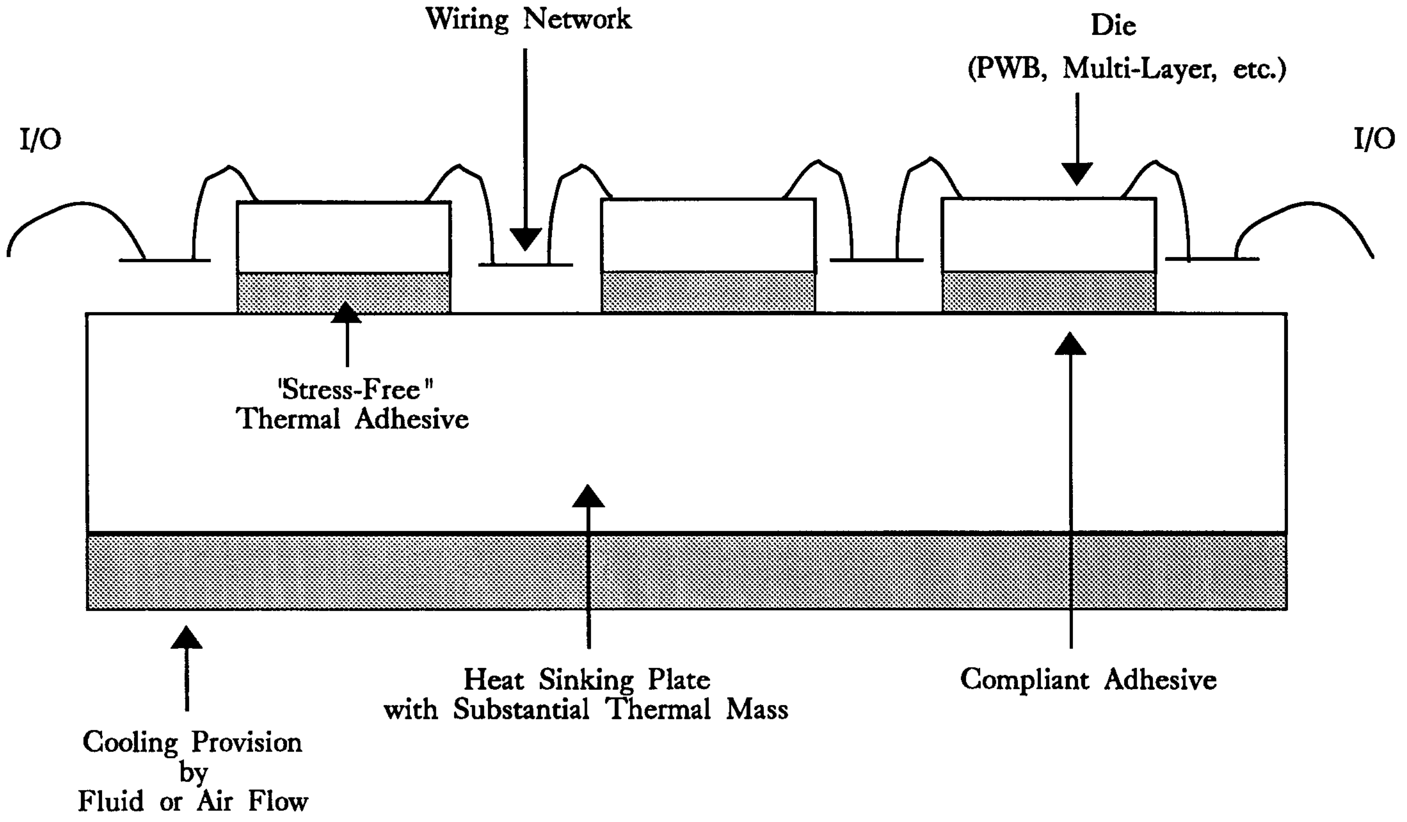


Figure #3: Thermal Management for VAX 9000 MCU module

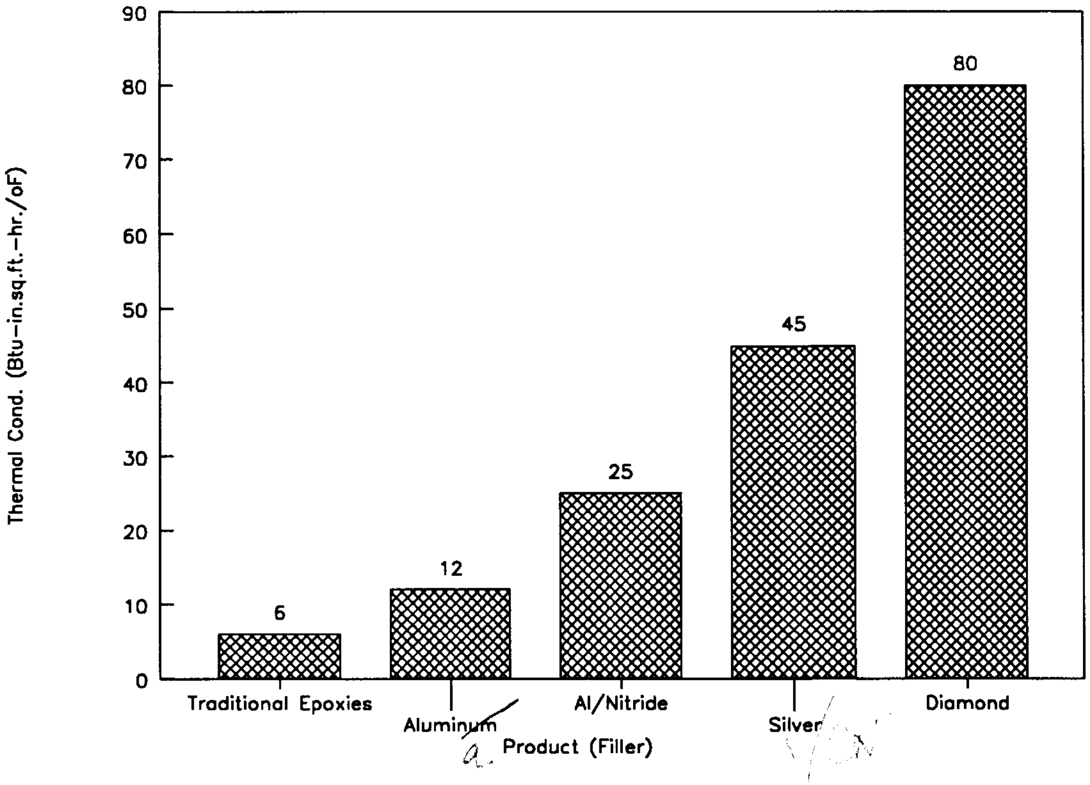


Figure #2: Thermal Conduction Characteristics of Filled Epoxy Adhesives