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APPLICATIONS OF HEAT PIPES TO COOL PWBS AND HYBRID MICROCIRCUITS

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ABSTRACT

Increases in microcircuit power density and closer packing of chips in hybrid packages to meet high-frequency or high-speed circuit requirements has resulted in higher component temperatures, which results in reduced reliability performance. Improved thermal management techniques, such as heat pipe cooling, must be used to lower component temperatures. This paper describes some of the advanced thermal management techniques, developed at Hughes, to reduce operating junction temperature under extreme environmental temperature conditions. Heat pipes in electronic component packaging provide many advantages over conventional cooling methods by reducing component temperatures, eliminating hot spots, and providing design flexibility. We are beginning to find heat pipes cooling components inside hermetically sealed enclosures, removing heat from flat packs, serving as an isothermal mounting plate for an amplifier on a spacecraft, or doubler as a structural member and thermal conductor to cool a solid-state module. Developments are even under way to integrate heat pipes into circuit cards, and to build heat pipes into power transistors. Heat pipes in actual electronic packaging applications, and those under development, will be discussed. Performance characteristics of heat pipes will be given, and examples of how thermal problems in electronic packaging were solved through the use of heat pipes will be described.

Heat pipes were incorporated in the high power transistors and successfully tested under power levels as high as 40 watts. Several prototypes were subjected to 1,000 hour testing at high temperature. Chemical compatibility of the heat pipe fluid with the semiconductor chips was tested by immersing uncapped transistors in the fluid and operating them at high power over an extended period of time. Electrical effects of the wick and fluid on the high frequency operation of the transistors were also determined as a part of this study. During this study, transistor junction temperature was determined both by measuring electrical properties and by infrared microscope techniques. A major breakthrough in this work has been the development of the Hughes high performance Powder Wick (U.S. Patent 4,047,198) concept, which can be applied to the transistor chip by mass production methods. The Powder Wick has much higher performance than the fiber bundle wicks used in the earlier study and is electrically compatible with the microwave transistors.

Heat Pipe for PWB was invented (U.S. Patent #4,11,8,756) and developed at Hughes Aircraft Company, Fullerton, California. This heat pipe, which accommodates 50 DIP devices was designed to fit into existing Hughes equipments which use aluminum or copper thermal mounting plates for

conduction cooling of circuit card components. The circuit card heat pipe shell is made of beryllium copper. This material was selected for its high yield strength, high thermal conductivity and ease of manufacture. Use of beryllium copper results in a rugged heat pipe not requiring special handling and without sacrifice of thermal conductivity. Beryllium copper is easily fabricated and can be joined by brazing, soldering, or welding. The circuit card heat pipe uses stainless steel screen wicks in the evaporator and condenser in combination with sintered-fiber stainless steel artery wicks. The thin screen wicks provide a short heat transfer path from the shell of the heat pipe to the vapor space, providing a low thermal resistance and resulting in a low temperature drop. Since the thin, tightly woven mesh will have a high resistance to liquid flow, the artery wick is utilized to provide a low resistance path for fluid flow. The artery wick is a sintered-fiber metal with an open structure for fluid flow but with a pore size consistently with capillary pumping requirements. Methanol was selected as the heat pipe fluid for the circuit card heat pipe because it has a high surface tension, high latent heat of vaporization, and low viscosity. In addition, it has a relatively high vapor pressure at the operating temperature which minimizes problems with sonic velocity, entrainment, or any inert gases in the heat pipe. Compatibility of heat pipe fluid and materials is essential to reliable heat pipe operation. Incompatibility between the fluid and the wick and shell materials may lead to heat pipe failure from a number of causes. Selection of all material used was based on experimental life test data developed by Hughes and data from the technical literature on heat pipes. The results illustrate that thermal resistance on the PWB can be reduced to one half by utilizing circuit card Heat Pipe. Test data will be presented in this paper.

INTRODUCTION

A heat pipe may be defined as any device that transfers heat by evaporation of liquid from heated areas and condensation on cooler areas, with continuous return of the condensation to the heated area by capillary action. The simplest form of heat pipe consists of a sealed tube lined with a wick which is wet with a suitable volatile liquid. No gas other than the pure vapor of the liquid is present. If flow of the vapor through the tube is not at too high a velocity, pressure will be nearly uniform throughout the vapor space. The temperature along the wick surface will then be essentially constant at the equilibrium temperature for the liquid-vapor interface at the given pressure.

Addition of heat any point along the tube wall will cause the temperature all along the wall to rise through local evaporation and condensation on all cooler areas. Regions of the pipe where heat is introduced into the system are evaporator sections, and those where heat removal takes place are condenser sections. The mechanisms affecting the flow of heat axially along the pipe are all extremely rapid and the adjustment o temperature consequently occurs almost instantaneously. The primary thermal resistance of the pipe is usually caused by the conduction of heat through the tube wall and wick structure.

The most important non-electrical parameter in the prediction of electronic system reliability is the maximum operating junction temperature of the system semiconductor devices. The maximum junction temperature of the device may be computed from equation (1) as follows:

$$T_{jmax} = T_a + Q_{chip} (\theta_{jc} + \theta_{ca}) + (Q_{sub} - Q_{chip})\theta_{ca} \tag{1}$$

Where

T_{jmax} = junction temperature of hottest chip

T_a = ambient air temperature

Q_{chip} = power dissipation in the hottest chip

Q_{sub} = total power dissipation on the package

θ_{jc} = thermal resistance from junction to case for the hottest chip (internal thermal resistance)

θ_{ca} = thermal resistance from case to ambient or ultimate sink (external thermal resistance)

It can be seen from equation (1) that the only thermal variables which play an important role in thermal packaging are θ_{jc} and θ_{ca}. At Hughes-Fullerton, a number of studies have been conducted over the past ten years to develop heat pipes to minimize θ_{jc} and θ_{ca}. They included three different studies on the development of heat pipes for Standard Electronics Modules and circuit cards. These studies demonstrate the application of heat pipes to enhance the reliability of electronic components by reducing their operating junction temperatures. This paper will also include the results of Independent Research and Development in the development of heat pipe for microcircuits. Reductions in junction temperatures up to 50°C have been achieved by incorporating heat pipe concept in a standard package.

The reliability of a semiconductor device is a function of its normalized junction temperature. The normalized junction temperature is given by:

$$T_n = \frac{T_j - T_s}{T_{jmax} - T_s} \tag{2}$$

Where

T_n = normalized operating junction temperature

T_j = junction temperature (collector junction for transistors)

T_s = temperature at which power derating begins (usually 25°C)

T_{jmax} = maximum rated junction temperature determined from the device specification

At Hughes-Fullerton, a number of studies have been conducted to develop heat pipes to minimize θ_{jc} and θ_{ca}. This paper summarizes the results of these studies.

HEAT PIPE DEVELOPMENT TO REDUCE THERMAL RESISTANCE

In the cooling of high power solid state devices, such as power transistors, the overall thermal resistance from the device junction to the surrounding ambient environment may be considered in terms of a series of thermal resistances. In devices designed for higher operating frequencies, the internal resistance from junction to case will establish the limits of device performance.

Changes in chip design, to limit collector-to-base capacitance and to distribute the power dissipation more uniformly over the chip surface, have raised the upper frequency limits for high power transistors by allowing the thermal dissipation area to approach the total chip area. Current trends in transistor design involve the use of overly emitter electrode construction and built-in diode compensation to permit higher power and higher temperature operation. The particular techniques used vary widely from manufacturer to manufacturer, even for what is nominally the same transistor. However, all of the techniques used involve distribution of the transistor junction over the surface of the chip while controlling the collector-to-base capacitance. This generally means placing limits on the chip size which, in turn, causes thermal limits on device performance. Elimination of this frequency power limit within the restrictions of present chip design required application of heat pipe cooling methods directly at the chip surface to provide a mechanism for minimization of temperature irregularities over the chip surface and reduction of the junction-to-case thermal resistance. The objective of the program was the development and demonstration of heat pipe techniques for power transistors operating in the VHF range with dissipation power of 25 watts or more. Program goals were to reduce θ_{jc} by 33% at a given power level over conventionally packaged devices without significant change in electrical characteristics.

The most fundamental capability offered by heat pipes to the cooling of electronic components is the achievement of extremely high values of thermal conductance. Heat pipes have an additional advantage as thermal conductors in that they may utilize non-metallic, non-electrically conductive materials in order to maintain electrical isolation while retaining high thermal conductance. Another useful characteristic is the capability for acceptance of widely varying thermal fluxes without variation in temperature. Power density variation of 10 to 1 is possible in the evaporator area of a heat pipe without appreciable variation of evaporator surface temperature. This insensitivity to local variations to input power may be exploited in the reduction of local temperature variation or hot spotting.

Of the various characteristics of heat pipes, the one of most concern in power transistor cooling applications will be the high limiting values of local heat. The wick surface nearest the junction of the transistor will be exposed to extremely high values of heat flux. As the heat input in this evaporator section of the heat pipe is increased, the temperature at the liquid-wick-wall interface will rise to the point where nucleate boiling occurs in the adjacent liquid. The heat pipe will continue to operate if the capillary and buoyancy forces are great enough to cause convection of the vapor bubbles through the wick and into the vapor core. The high limiting values of local heat flux permit application of heat pipes to solid state device cooling. A schematic of a heat pipe configuration for the above-described application is shown in Figure 1.

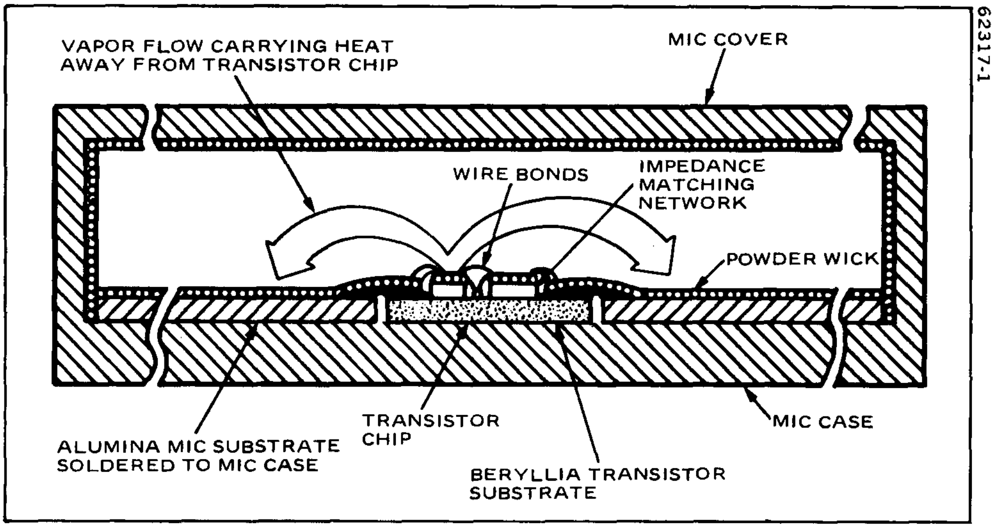

Figure 1. Section of Heat Pipe Cooled MIC RF Transistor. Heat is absorbed by the evaporating heat pipe fluid and carried to the alumina substrate where it is released by the condensing fluid and transferred through MIC case to the heat sink.

A glass fiber (Refrasil) wick was used in the heat pipe tests. The wick consists of fiber glass stand bundles 0.01 cm (0.004 inches) in diameter spaced 0.041 cm (0.02 inches) apart over the chip surface. The open configuration was chosen because of the high heat flux density at the chip surface and low thermal conductivity of the dielectrical wick material. The individual strand bundles served as a means of transferring fluid from the region alongside the chip which served as a condenser when the device was base cooled to the chip surface. Surface forces distributed the fluid over the chip surface providing a flow distribution to the largest part of the chip surface while maintaining a minimum thermal path to the vapor space.

Work to date has demonstrated the feasibility of the Hughes approach by: 1) significantly lowering the junction temperature of RF transistors by heat pipe cooling; 2) demonstrating heat pipe cooling at high junction power density; 3) demonstrating that the electrical performance of the transistors was not affected by the heat pipe fluid and wick materials used; and 4) development of a high performance powder wick concept which can be applied to RF power transistors on a production basis. (See Figures 2 and 3.)

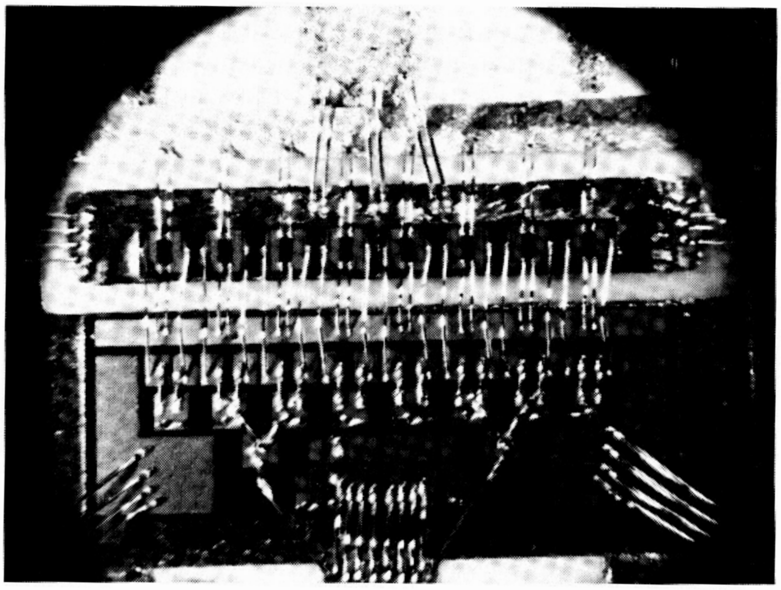

Figure 2. Multicell RF Power Transistor. Typical microwave bipolar power transistors are too complex to incorporate conventional heat pipe wick construction.

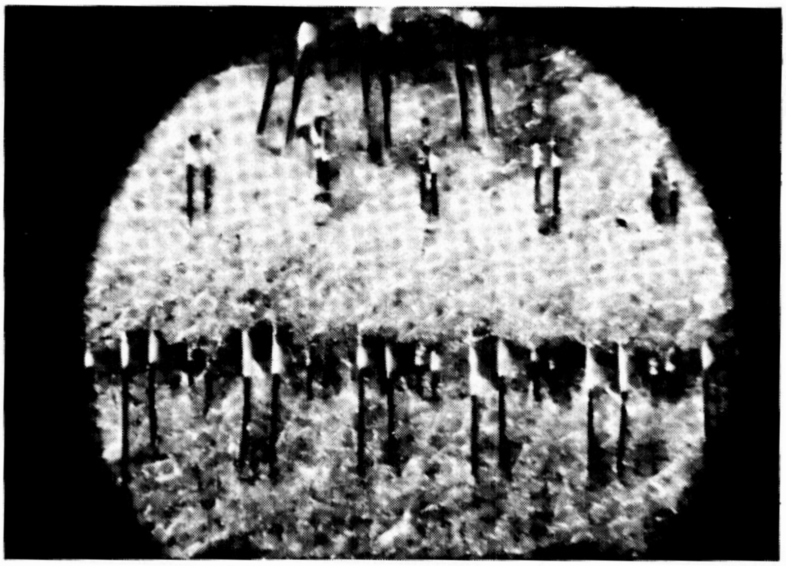

Figure 3. Hughes 'Powder Wick' Applied to a Multicell Transistor. The 'Powder Wick', designed to give high fluid flow and heat transfer performance, is applied without disturbing the transistor bond wires.

Reduction in thermal excursion during high power applications has two obvious benefits: either (1) increased reliability, or (2) increased power output for the same peak junction temperature and associated reliability. This phenomenon is basically true regardless of the type of solid state power generating device employed or the chosen frequency of operation. Figure 4 demonstrates transistor junction temperature reductions of up to 60°C or (alternatively) 33 percent higher power levels with the same junction temperature with the application of heat pipe cooling. The transistor was eutectically bonded to provide good heat transfer across the bond.

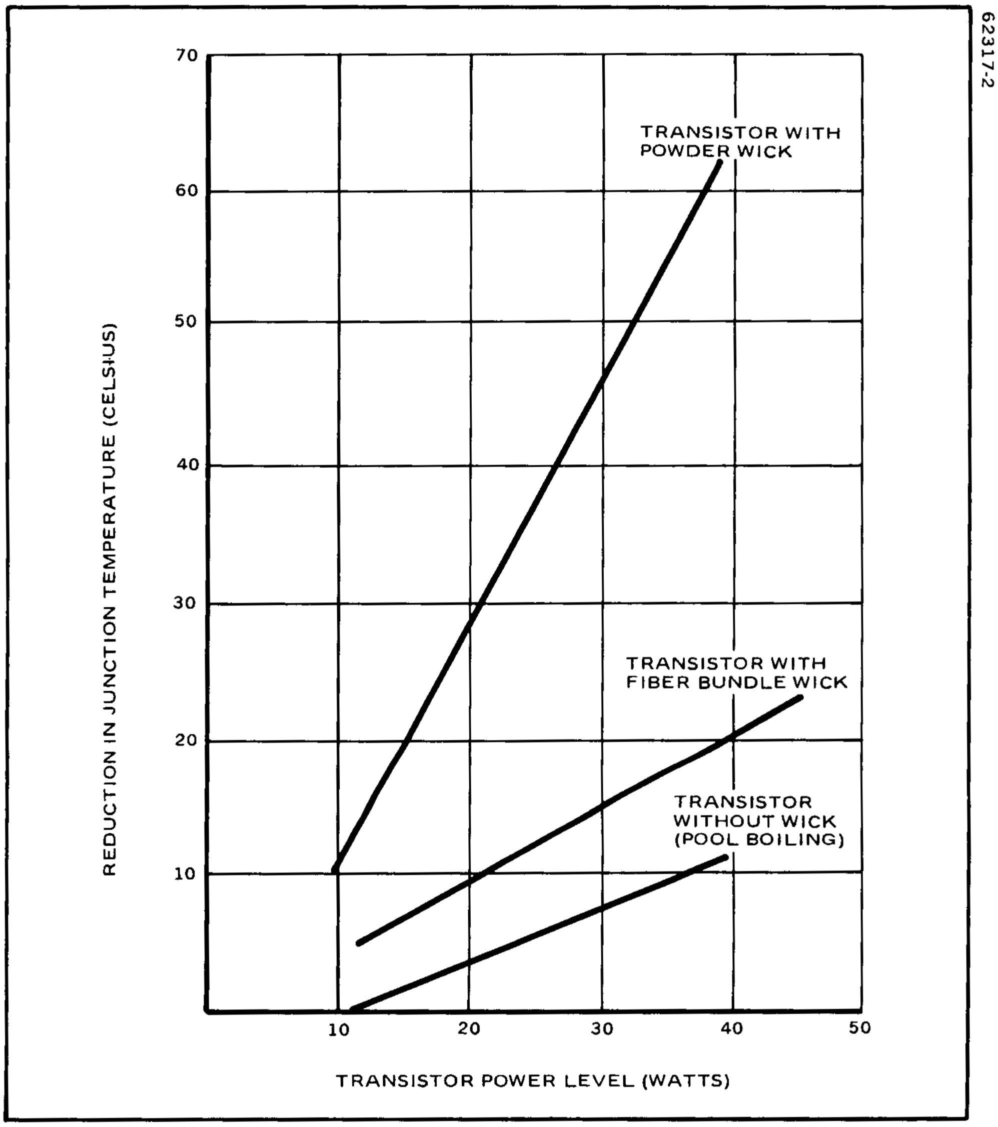

Figure 4. RF Power Transistor Temperature Characteristic. Junction temperatures are compared for a transistor (TRW-2N5071) with and without the application of a heat pipe.

Advanced model of a circuit card heat pipe, developed by Hughes, is shown in Figure 5. This heat pipe, which accommodates 50 DIP devices was designed to fit into existing Hughes equipments which use aluminum or copper thermal mounting plates for conduction cooling of circuit card components. The circuit card heat pipe shell is made of beryllium copper. This material was selected for its high yield strength, high thermal conductivity and ease of manufacture. It is also corrosion resistant and compatible with the heat pipe fluid. Use of beryllium copper results in a rugged heat pipe not requiring special handling and without sacrifice of thermal conductivity. Beryllium copper is easily fabricated and can be joined by brazing, soldering, or welding.

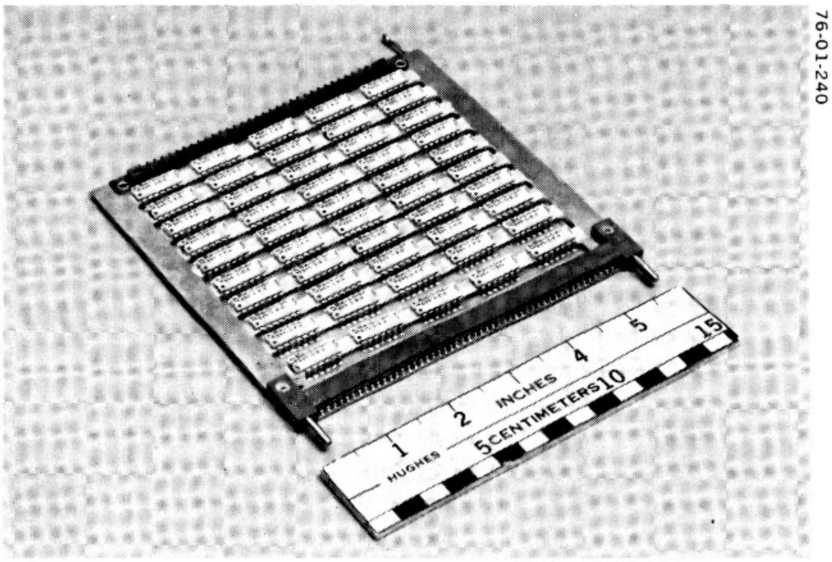

Figure 5. DIP Circuit Card with Heat Pipe Thermal Mounting Plate. The heat pipe is designed to accommodate up to 50 DIPs and has a very high heat transfer capability.

The circuit card heat pipe uses stainless steel screen wicks in the evaporator and condenser in combination with sintered-fiber stainless steel artery wicks. The thin screen wicks provide a short heat transfer path from the shell of the heat pipe to the vapor space, providing a low thermal resistance and resulting in a low temperature drop. Since the thin, tightly woven mesh will have a high resistance to liquid flow, the artery wick is utilized to provide a low-resistance path for fluid flow. The artery wick is a sintered-fiber metal with an open structure for fluid flow but with a pore size consistent with capillary pumping requirements.

Methanol was selected as the heat pipe fluid for the circuit card heat pipe because it has a high surface tension, high latent heat of vaporization, and low viscosity. In addition, it has a relatively high vapor pressure at the operating temperature which minimizes problems with sonic velocity, entrainment, or any inert gases in the heat pipe.

The experimental results of testing the heat pipe with a 30 watt load are shown in Figure 6, where a comparison is made with analytical data for similar metallic thermal mounting plates. The data demonstrates the superior performance of the heat pipe in lowering both the maximum component mounting surface temperature and the temperature gradient between components.

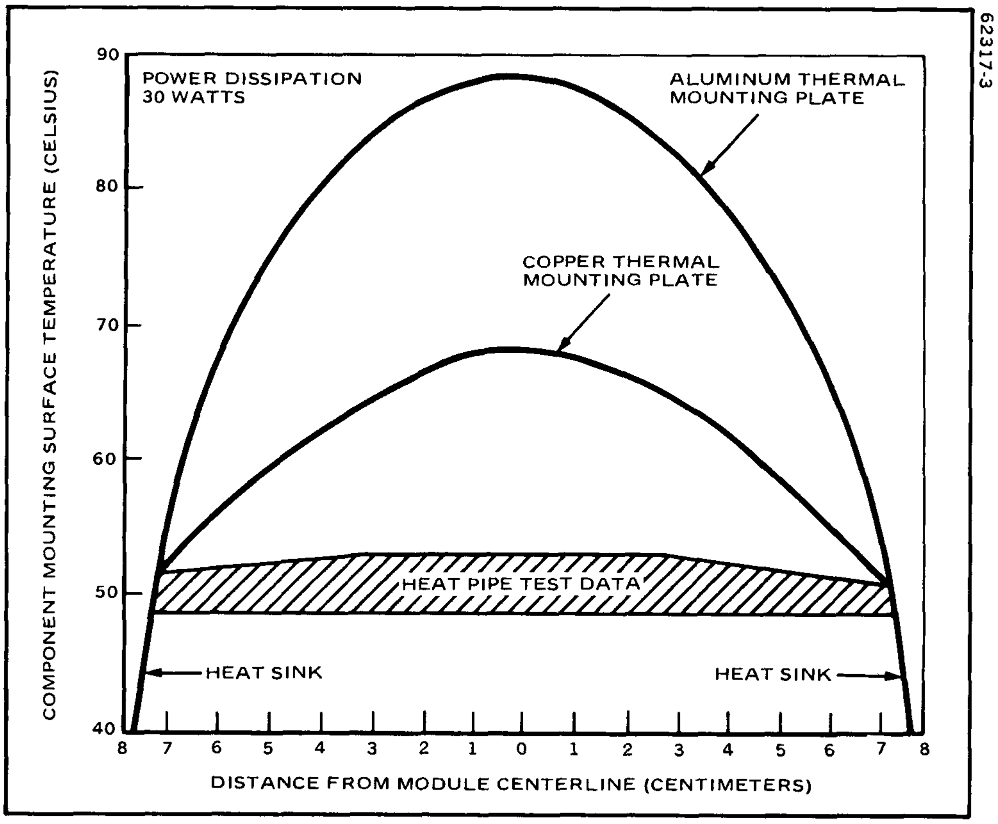

Figure 6. Performance Comparison of Heat Pipe Thermal Mounting Plate with Copper and Aluminum Thermal Mounting Plates. Heat pipe thermal mounting plate shows markedly superior performance.

In addition to thermal testing, the circuit card was qualified for use on jet aircraft by being tested to random vibration per MIL-STD-810C, Method 514.2, Procedure 1A Modified, and Shock per MIL-STD-810C, Method 516.2, Procedure 1. The circuit card was operational during the vibration testing and no degradation of performance was observed. No degradation of performance was noted following the shock testing.

CONCLUSIONS

Heat pipes have been successfully used in several applications in packaging electronic components. New developments with heat pipe devices show even more promise to improve electronic component performance. The design data and device technology are sufficiently reduced to practice. In many instances, electronic package designs are limited only by the imagination and ingenuity of the packaging engineer. As with any device, the heat pipe will not solve all problems; but if the packaging engineer understands heat pipes and their limitations, and considers operating conditions and subsystem and system requirements, heat pipes can solve many complicated thermal problems, and can remove limitations that are imposed by conventional designs.

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