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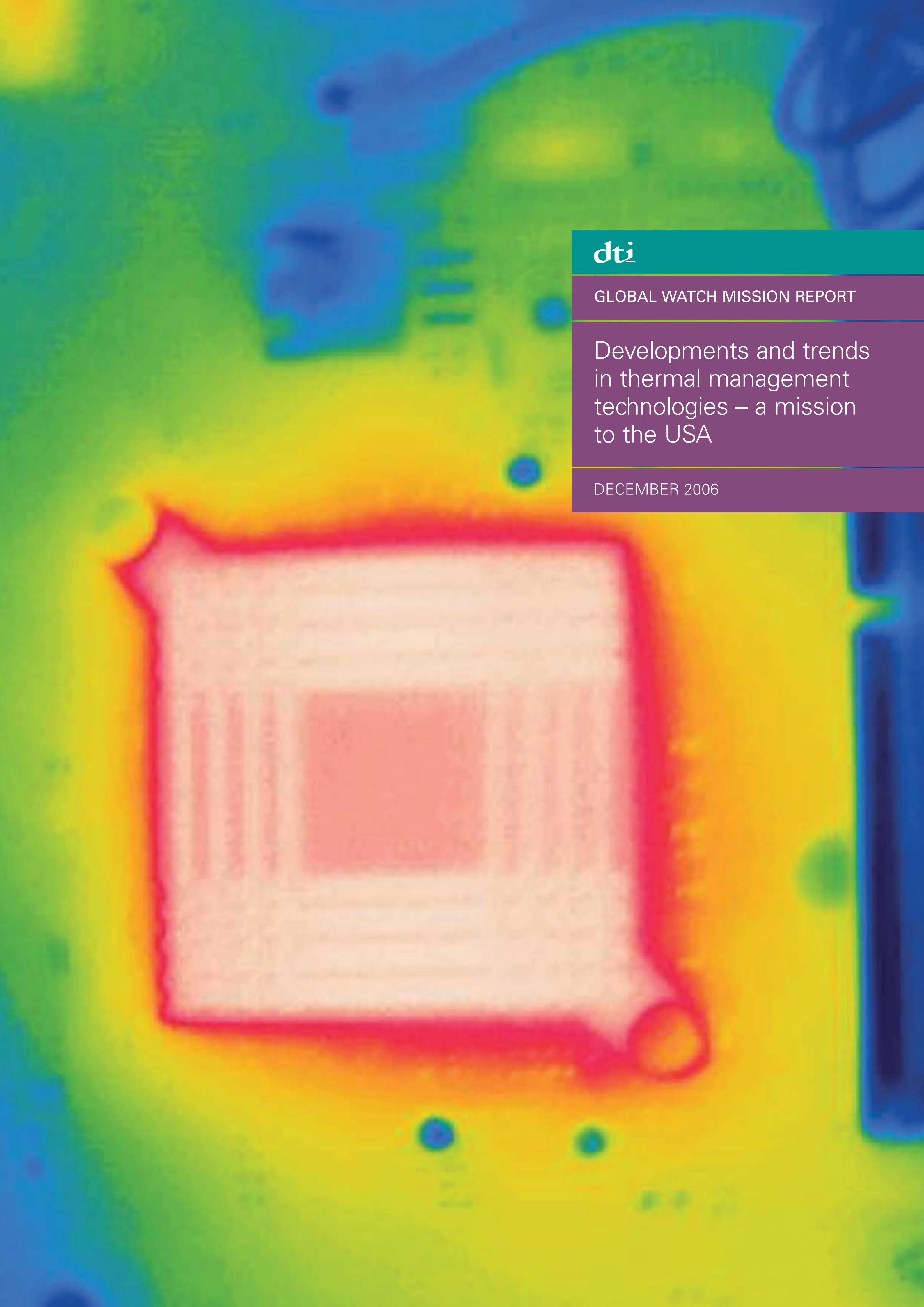
GLOBAL WATCH MISSION REPORT

Developments and trends in thermal management technologies – a mission to the USA

DECEMBER 2006



Global Watch Missions

DTI Global Watch Missions have enabled small groups of UK experts to visit leading overseas technology organisations to learn vital lessons about innovation and its implementation, of benefit to entire industries and individual organisations.

By stimulating debate and informing industrial thinking and action, missions have offered unique opportunities for fast-tracking technology transfer, sharing deployment know-how, explaining new industry infrastructures and policies, and developing relationships and collaborations.

Disclaimer

Cover image: A thermogram of a hot computer chip. The temperature range goes from hot (white) to cold (blue). Thermography is a technique for visualising the temperature of surfaces by recording the emission of long-wavelength infrared radiation. This heat radiation is detected electronically and displayed with different colours representing different temperatures. TED KINSMAN/SCIENCE PHOTO LIBRARY

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– a mission to the USA

REPORT OF A DTI GLOBAL WATCH MISSION

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FARADAY ADVANCE

Materials

Knowledge Transfer Network

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EXECUTIVE SUMMARY

The relentless increase in electronics capability enabled by rising device density and clock speeds has led to increasing demands for dissipation of the waste heat generated by the active devices. If thermal management is inadequate, premature device failure can be expected either by direct failure of the semiconductor or more likely by progressive accumulation of thermomechanical damage and eventual cracking of interconnect structures. The risk is real: the US National Aeronautics and Space Administration (NASA) has estimated that 90% of mission failures can be attributed to thermally induced interconnect failures.

At the same time, market expectations for reducing overall size, weight and cost of electronic systems are leading to design constraints which are leading to a conflict between the growing thermal loads and the capacity of existing thermal management solutions to dissipate the heat. This is resulting in increasing problems for designers tasked with the need to maintain device junction temperatures within safe limits.

This situation is not new and industries have developed solutions to meet the particular needs of the electronics industry. These include materials for heat sinks and heat spreaders, interface materials or joints for efficient assembly of devices. These solutions have allowed an extension of the range of passive cooling. However, continuing demands for power density in some applications have driven the development of new active cooling systems.

Thermal management technologies in the USA continue to evolve to meet the demands of the high-technology and defence industries, and cost-effective thermal management is seen to be a very important factor that can influence competitive edge.

This DTI Global Watch Mission to the USA took place during 4-8 December 2006 and was coordinated by Faraday Advance.

The high-level aims were to:

- Evaluate the US state-of-the-art in terms of both materials technologies and their implementation
- Assess use of modelling with both passive and active cooling scenarios
- Assess market uptake
- Identify potential collaboration partners

It has been established that considerable research and development (R&D) activity has been undertaken and is continuing, funded by internal investment, regional or government funding and especially through support measures for small companies. Geographical constraints in visiting the USA meant there were some companies of key interest which it was not possible to visit but constructive dialogues contributing to the mission were established using internet conferencing

The main findings of the mission were:

- Extensive development of carbon materials
- Higher state of market readiness for active cooling than expected
- Strong interest in diamond composite systems driven by reducing cost of diamond
- Modelling being used extensively both for design optimisation and as a marketing tool
- New developments in thermoelectric cooler device technology

1 INTRODUCTION

1.1 Significance of thermal management

NASA: 90% of mission failures are attributable to thermally related interconnect failure

Japan Space Agency (NASDA): 50% of mission failures result from overstressed solder joints between boards and devices

US Air Force: 55% of failures in defence-related electronics are due to thermal effects

***Exhibit 1.1** Significance of thermal management*

Thermal management of electronics is a significant issue because of increasing volumetric power densities and the harsh environments in which they are deployed.

This includes almost all application fields: defence, aerospace, automotive, oil and gas, remote sensing as well as computer processors. Other significant applications exist in photonics – light-emitting diode (LED) displays and semiconductor lasers.

The increased volumetric power densities are a result of increasing functionality and reducing die feature size allowing more processing to be packed into a smaller area or volume.

Data server centres are an example where heat management becomes problematic. High-availability systems are required and the density of computing power generates significant amounts of heat which has to be removed by a cooling system. The total thermal management system has to consider junction through die to package, package to board, board to enclosure and then thermal management of the room containing the enclosure. An excessive thermal resistance at any point may lead to processor overheating. Systems installed to remove heat can themselves consume significant amounts of energy.

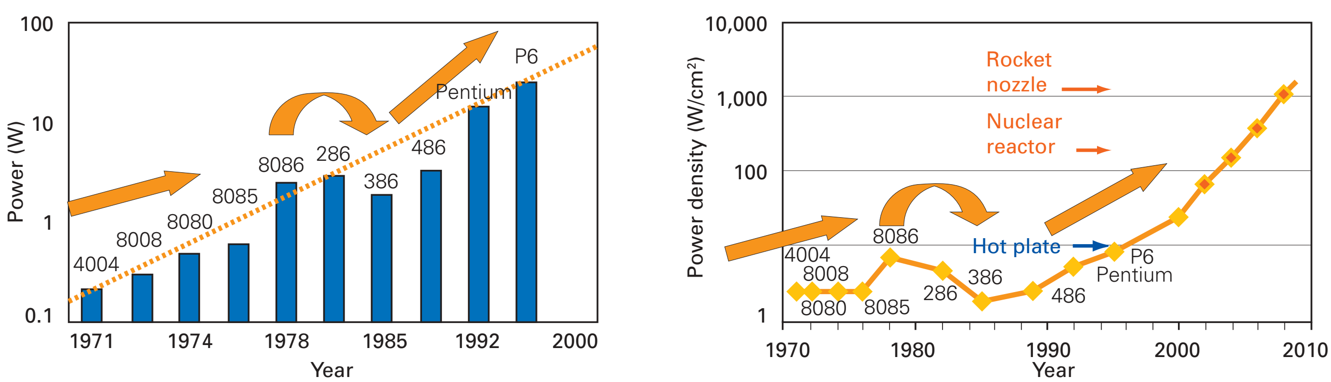

***Exhibit 1.2** Intel microprocessor trends*

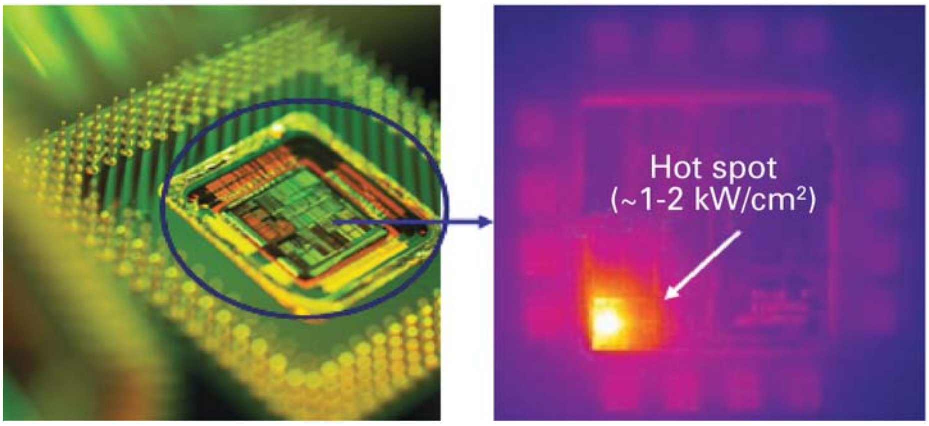

Exhibit 1.3 *Local hot spots in a semiconductor device (courtesy Nextreme Thermal Solutions Inc)*

Exhibit 1.2 is a useful starting point in considering the thermal management problem and challenge. As predicted by numerous technology roadmaps such as ITRS (International Technology Roadmap for Semiconductors) and iNEMI (International Electronics Manufacturing Initiative), the absolute power levels in microelectronic devices will continue to increase above and beyond 100 W.

For Intel Corp and Advanced Micro Devices (AMD) Inc and their move towards multicore technology, this trend will continue and is driving the need for thermal management technologies that can dissipate heat at significant heat fluxes in the range 10-50 W/cm^2 and beyond. For power electronic devices and laser semiconductors much higher heat fluxes are required – above and beyond 100 W/cm^2.

Further, temperatures at the chip surface must be maintained at low values (ie for silicon devices ~100°C) to ensure good operating performance and overall product reliability.

Even for devices that can be operating in the region of 100 W there can be local hot spots which have local power densities in the order of kW/cm^2. This is illustrated in Exhibit 1.3 and requires thermal management technologies that have very high local heat flux removal capabilities. Again this is to ensure that locally on the chip the temperature does not climb to levels which will affect chip performance and reliability.

Reliability is defined as the probability that a product will survive for a particular period of time. In electronic systems reliability is dependent on the stresses imposed onto the materials, resulting from a number of factors. Temperature is generally taken to be one of the most important drivers for stress and this is due to the different coefficients of thermal expansion in the materials. Exhibit 1.4 illustrates the importance of temperature on electronic system reliability.

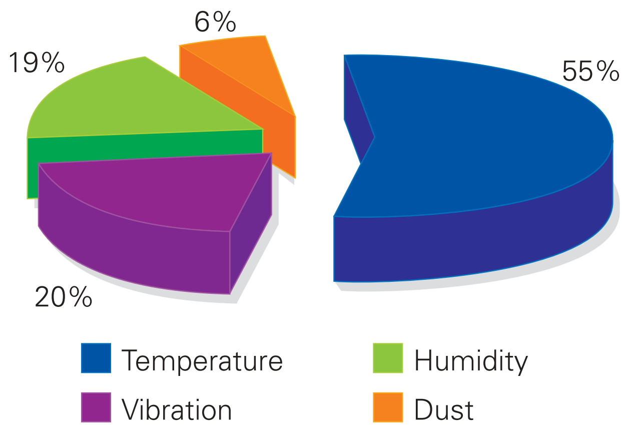

Exhibit 1.4 *Environmental causes of failure in defence-related electronic systems (courtesy US Air Force)*

Given the above market condition and technology trends many companies are adopting modelling and simulation tools to complement their materials development and physical prototyping and testing programmes.

Exhibit 1.5 *VME format graphics card showing aluminium heat sink and thermal plugs contacting the top of high-power devices via a flexible interface material (courtesy Radstone Embedded Computing, part of GE Fanuc Embedded Systems)*

What was clear from the mission is that many US organisations are using the results from modelling to optimise materials formulation and product design and to also use these results in their marketing activities.

1.2 Future needs

Future electronic systems will require improved thermal management to sustain customer expectations of reliability levels. Customer expectations must be satisfied in an environmentally friendly manner and meet the volume, weight, cooling requirements, manufacturability and reparability of future systems. An area often causing problems is the build-up of mechanical tolerances in the thermal path requiring thermal management materials with some compliance or flexibility.

To provide lower thermal interface resistances, updated jointing materials are required that prevent the formation of voids, often a cause of increased thermal resistance. The materials used in assemblies must have similar coefficients of thermal expansion to avoid thermal stress failures.

The joining techniques must also take account of the wider range of materials being used and be able to form a low-resistance path between dissimilar materials. There is also pressure to reduce thickness of interface layers in order to reduce thermal resistance.

Common materials used for device-to-heat-sink interfacing are flexible polymeric films or greases loaded with thermally conductive particles. The filler materials may be metallic or thermally conductive ceramic particles such as alumina or boron nitride if electrical insulation is required.

The most common material used for heat sinks is currently aluminium as shown in Exhibit 1.5.

Aluminium has the advantage of low cost, easy machining and forming and a corrosion resistant surface which can be further enhanced by anodising. Its thermal conductivity at ~180 W/m·K is low compared to copper (~379 W/m·K) but aluminium is often preferred on cost and weight factors unless the thermal load is very high.

Interfaces between materials have a significant impact on the thermal impedance of electronic systems and in practice they can be the dominant factor in achieving effective thermal transfer. Interface materials and processes are the methods used to join an electronic device to the thermal transfer medium (eg substrate, heat pipe, heat sink), including coatings and bonding techniques. In this respect they may need to perform the tasks of attachment, stress/strain relief and thermal transfer over a wide range of temperatures.

1.3 Trends

From the visit to the USA it became apparent that the main thrusts are carbon-based materials and active cooling techniques using a liquid. The visit did not address improved thermal efficiency of electronics. The carbon materials usually in the form of graphite or diamond may be combined with metals to give materials that are easier to process into manufactured items. The graphitic materials are lower density than copper or aluminium and can offer higher thermal conductivities. The carbonaceous materials can also be processed to form low-density thermal insulators to protect electronics from heat sources, or to shield parts of the assembly from excessive temperature rise, eg in laptop computers and telephone handsets.

In active cooling systems phase change is often used to remove heat from electronics. All of the active cooling systems seen required a subsequent heat exchanger to transfer the thermal energy to the external environment.

Passive cooling techniques are generally preferred to active cooling for reasons of cost, complexity and reliability. The available performance of passive systems is still extending. This is enabled both by improvements in the materials engineering and also by the opportunity for improved design which comes from system-level modelling. However, developments in active cooling are addressing many of the issues which have limited its scope in the past.

1.4 Barriers to technology implementation

1.4.1 Commercial barriers

Advanced materials have to offer substantial improvement relative to mainstream materials in order to have a realistic possibility of being specified. Even if materials do have sufficient technical merit there is a massive investment and lead time required in order to move towards market readiness with appropriate qualification approvals aligning with matched production capacity and downstream integration.

For UK industry some of the cooling technologies may be export controlled, so limiting the rights to worldwide distribution.

1.4.2 Technical barriers

Surfaces

Historically, uptake of advanced materials in thermal management has been held back by difficulties in cost-effective production processes. These problems seem to be mitigated by evolution of technologies involving machinable composites or technologies for net shaping where machining is difficult, as is the case with aluminium silicon carbide (AlSiC). Surface engineering of metal diamond composites is still problematic. Metallisation by plating of advanced materials now appears to be almost routine.

Gap management

A barrier to successful implementation of any thermal management strategy is the management of gaps which can accumulate as a result of a build-up of manufacturing tolerances. Highly conductive but compliant gap-filling materials are required in order to provide a thermal path with low thermal resistance. The highest performance passive technologies are the high-conductivity graphitic materials but these require mechanical support or encapsulation to be reliably integrated into a system. Although many different gap-filling solutions were presented to the mission with a wide range of costs, there is no general solution to the problem and engineering judgment is required to select gap fillers that perform within budget constraints.

The use of phase-change systems requires careful control of the boiling systems to maintain an effective and stable cooling system.

Design awareness

Design awareness may also constitute a barrier for uptake of the newer technologies. This includes the awareness of the cost implications of specifying costly high-performance elements in a thermal management scheme. It is important to undertake these calculations at a system level since the method of thermal management may well impact on system complexity elsewhere, with a strong bearing on overall cost and reliability. This is an excellent opportunity for computer modelling and simulation. The mission noted that simulation is now being used as a marketing tool, as well as an engineering tool, to demonstrate how selection of particular thermal management solutions can lead to reduced overall system cost and complexity.

1.5 UK position

Providing the UK can assimilate best practice in thermal management materials and techniques it is well placed to consolidate and strengthen its position. Key attributes include:

- Strong materials R&D base including some unique capabilities at TWI (eg Surfi-Sculpt)

- Established industries in some thermal management materials including:
  - Morgan Crucible – advanced carbons and diamond chemical vapour deposition (CVD) technology (Diamonex)
  - Element Six for diamond heat-spreader products
  - CE alloys (aluminium-silicon alloys) (Sandvik)
  - Copper powder for powder injection moulding of thermal management components (Sandvik)
  - Strong intellectual property (IP) and know-how for integration of advanced graphitic materials (TMS Ltd)

- Leading modelling and simulation capabilities already harnessed to co-modelling for reliability modelling in the thermal management context

- Strong competences in heat flow science, especially two-phase flow

- Strong metrology capabilities, especially determination of heat-transfer coefficients under high heat flux conditions

- Extensive knowledge of interfaces and increasing research into nanotechnology

However, in the UK, uptake of active cooling systems has been limited by a lack of awareness of state-of-the-art capability and know-how for implementation. Full exploitation of modelling and simulation is also hampered by data gaps and lack of standards.

Furthermore, the UK lacks cohesion within the thermal management community and could benefit from improved coordination and network development.

1.6 Report structure

Chapter 2 of the report describes the materials and materials processing discussed during the mission, with a particular focus on high-conductivity graphite and composite materials. A complementary set of materials having ultralow thermal conductivity are also discussed.

Materials for thermal management in electronics fall into two main groups which include interface and bulk materials. Interface materials are formulated to provide a low thermal resistance path between the heat-producing device and the second group of materials which move the thermal energy of the device over a larger area and deposit it into a thermal sink. The interface group are usually relatively flexible and are required to overcome the surface irregularities between the device and the heat-sink surfaces for the lowest thermal resistance. In addition to good thermal transfer these materials may also serve to perform mechanical attachment and offer compliance to provide stress/strain relief, so this group is also considered to include coating and bonding techniques.

The materials into which the device thermal energy passes require high thermal conductivity to move the power effectively. Other factors which may be significant for these materials include fast thermal response (high thermal diffusivity) to control thermal transient behaviour, low weight and acceptable material and fabrication cost. The lowest device temperature (and hence reliability!) will be achieved when the lowest device-to-sink thermal resistance is achieved.

Chapters 3 and 4 discuss passive and active cooling devices and techniques. These can often make use of materials considered here. The application of thermal and multiphysics modelling is of increasing importance in the field and this is discussed in Chapter 5. Chapter 6 discusses the funding mechanisms, research and trade networks germane to thermal management in the USA. Finally, Chapter 7 summarises the key findings and recommendations from the mission.

Further details on host organisations and the mission team are presented in the appendices as well as a compilation of data for the main relevant materials encountered in the mission or elsewhere.

2 MATERIAL TECHNOLOGIES AND PROCESSES

A large number of materials are being produced or are in development for thermal management applications. Exhibit 2.1 displays available thermal conductivity and thermal expansion data for the material classes of interest in electronics packaging. Materials having high thermal conductivities are carbons or composites containing carbons.

2.1 Carbon allotropes

Thermal conduction in metals is by energy transfer via the free electrons and the highest value is ~420 W/m·K for silver. To achieve higher values we must turn to carbon which occurs naturally in two forms, graphite and diamond as shown in Exhibit 2.2.

The thermal conductivity of various forms of carbon is shown in Exhibit 2.3. Diamond, graphite in-plane, HOPG and CVD fibre were encountered during the mission, processed in some form into a thermal management solution.

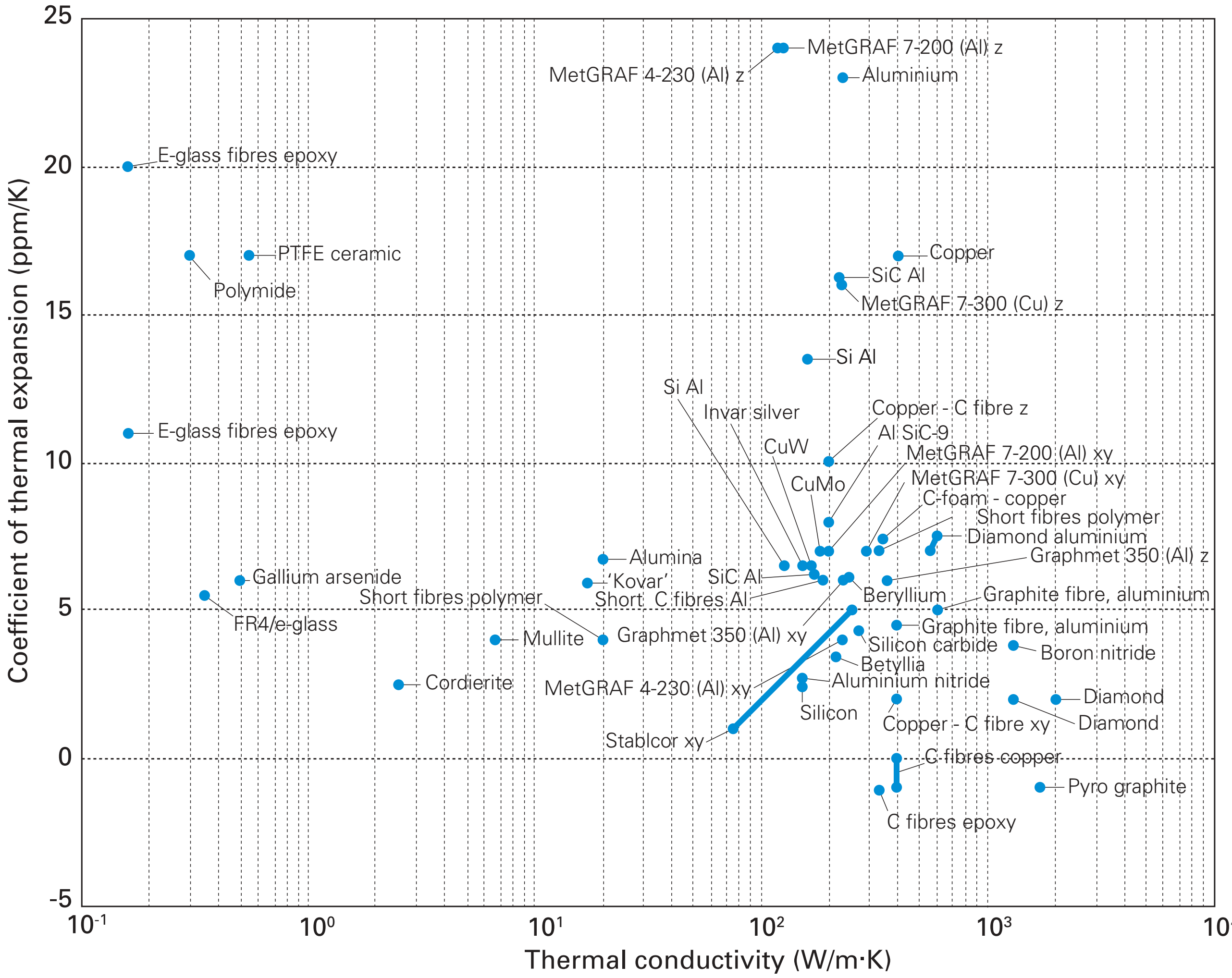

Exhibit 2.1 Thermal conductivity and expansion data for materials of interest in electronics packaging

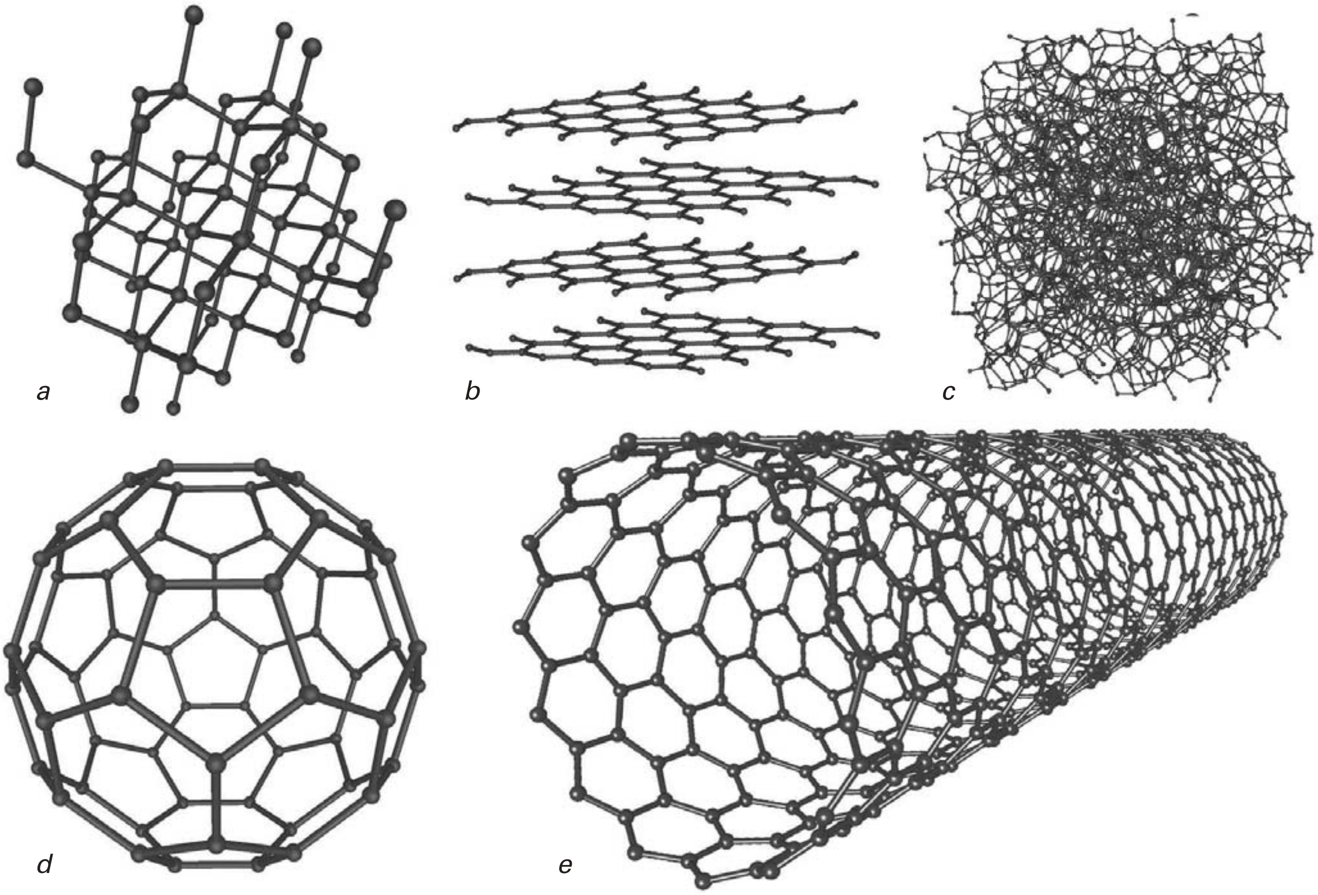

Exhibit 2.2 *Allotropes of carbon: (a) diamond, (b) graphite, (c) amorphous carbon, (d) spherical 'Buckyball' C60 fullerene, (e) cylindrical carbon nanotube*

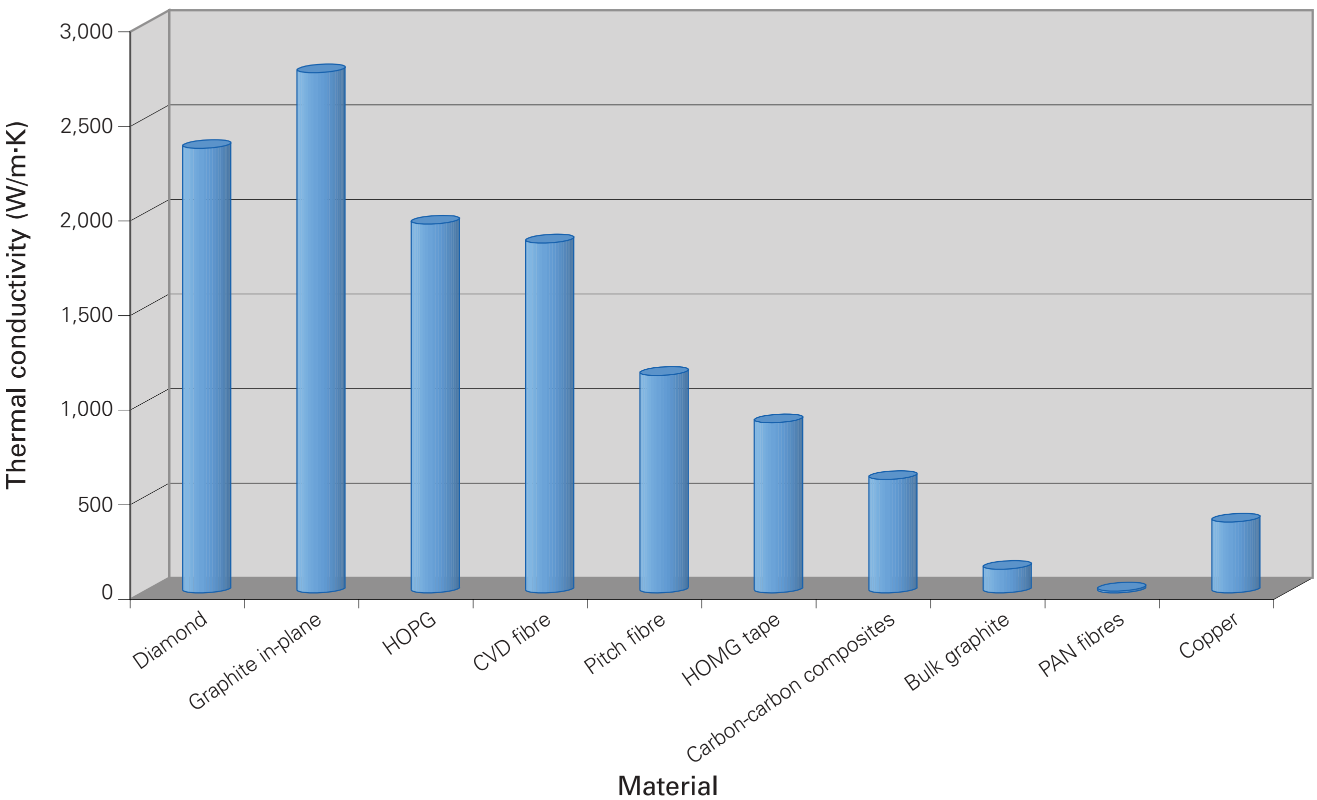

Exhibit 2.3 *Thermal conductivity of graphitic (sp2) and diamond (sp3) forms of carbon*

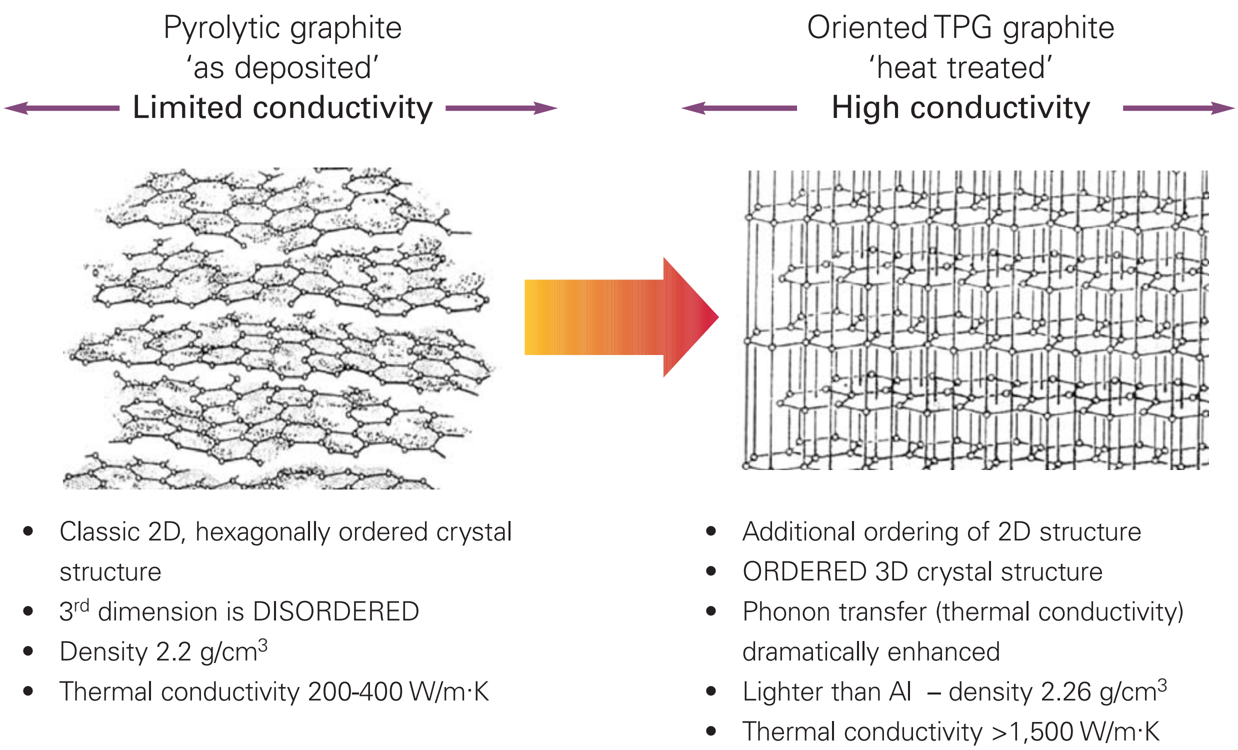

Exhibit 2.4 Production of hyperconductive graphite (courtesy Momentive Performance Materials Inc)

The nanotube form can occur as single or multiwall structures with the single wall having very high thermal conductivity along its axis. There is a challenging problem in materials engineering in usefully harnessing the high values available. In contrast the spherical structure can act as a very good thermal insulator. Both of these properties can be used to advantage in designing materials for thermal management.

Nearly all of the companies visited or contacted are involved with carbon-based materials.

2.2 High-conductivity carbons

Thermal conductivities in graphite (if properly ordered) and in both natural and synthetic diamond (high pressure, high temperature (HPHT) and CVD processes) can range between 1,000 and 2,000 W/m·K. In noncomposite form only CVD diamond grown in thin sheets and highly oriented pyrolytic graphite (HOPG) offer practical possibilities for passive thermal management.

2.2.1 Diamond

CVD diamond has been used for many years, mainly in small-scale chip cooling applications, and no additional developments with this material were seen during the mission. Particulate diamond is being used in composite structures and these are covered in Section 2.3.5.

2.2.2 Hyperconductive graphite

The main US manufacturers of very high thermal conductivity carbon are Momentive Performance Materials Inc (formerly GE Materials) and Minteq (Pyroid™). The material is produced by CVD of cracked methane (CH_4) followed by a combination of pressure and thermal treatment at very high temperatures to produce a material with >1,500 W/m·K in the plane of the sheet and ~10 W/m·K across the thickness of the graphite layer.

The process is illustrated in Exhibit 2.4 and the base material is shown in Exhibit 2.5.

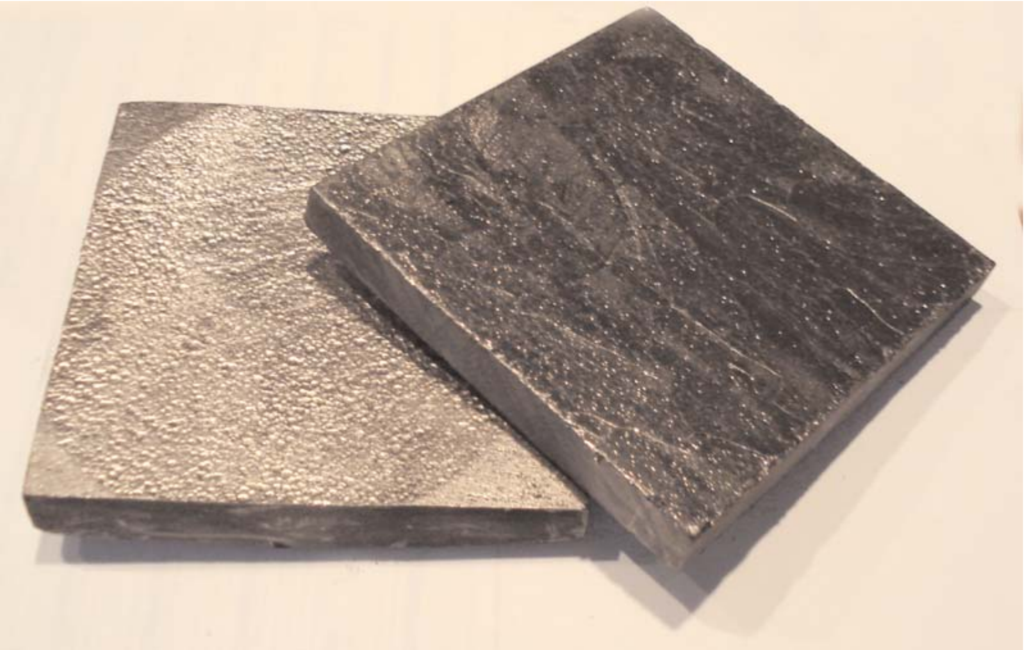

Exhibit 2.5 *Base HOPG 1050 material from Momentive Performance Materials Inc*

Parameter	Value
In-plane thermal conductivity (XY)	>1,500 W/m·K
In-plane electrical resistivity (XY)	3x10^{-3} Ω/cm
Thru-plane thermal conductivity (Z)	10 W/m·K
Thru-plane electrical resistivity (Z)	3x10^{-2} Ω/cm
In-plane coefficient of thermal expansion (CTE)	-1 ppm/K
Maximum thickness (Z)	3/8 in
Typical size (X x Y x Z)	10 x 5 x 3/8 in
Maximum size (X x Y x Z)	12 x 5.5 x 3/8 in
Piece part cost	15-30 \$/in^2

Exhibit 2.6 *Properties of hyperconductive graphite (courtesy Momentive Performance Materials Inc)*

Material parameters as quoted by Momentive are given in Exhibit 2.6.

HOPG was first produced over 40 years ago and the 1050 material was originally developed for US military use in the 1960s and remains subject to US export control although Momentive is hoping to have this relaxed in the future.

2.3 Composite materials

2.3.1 Metal-graphite

This section is concerned with composites of carbon with metals in contrast to carbon fibre metal composites. The most common method of combining the graphite is by squeeze casting or pressure casting with aluminium or copper.

The most well-established material encountered in this study is the family of Graphmet materials from Materials and Electrochemical Research (MER) Corp which are produced by squeeze casting into porous graphite preforms. For Graphmet350, thermal conductivity is rated in the range 220-360 W/m·K (some anisotropy) with a thermal expansion in the range 6.0-8.5 ppm/K with a density of 2.1 g/cm^3. The material is machinable and is also capable of being net shaped into packages. The main advantage of the material is its low cost, but the main issue with the material is its low mechanical strength (30 MPa bending strength) which may limit some applications.

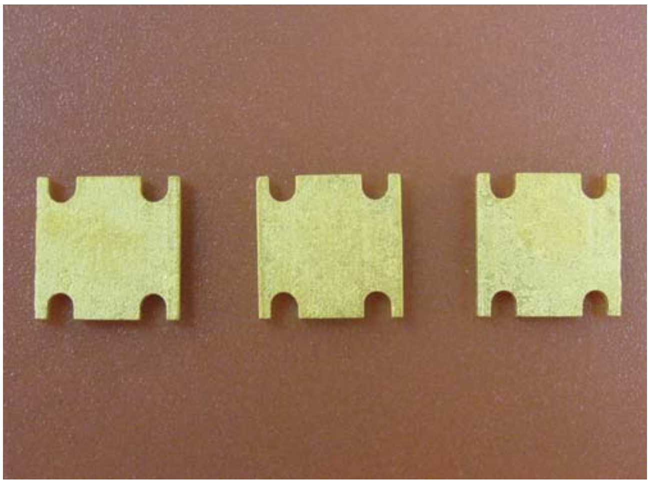

Exhibit 2.7 GraphMet 350 components (courtesy MER Corp)

MER Corp utilises a plasma transfer arc which allows for large-volume metal deposition so giving a quick route to manufacture. The graphite percentage is typically of the order 25%. This leads to a lower mass density material, sometimes with an enhanced thermal conductivity. Depending upon the process used to manufacture and the design, the composite thermal highways may be formed in one, two or three dimensions. Composites can be machined but care is required because of the laminar structure of the graphite. In some cases the resulting material needs to be plated to prevent corrosion.

2.3.2 Metal-graphite fibre

Metal Matrix Cast Composites (MMCC) LLC (not visited during the mission) also manufactures materials using high-pressure squeeze casting – MetGraf aluminium loaded with 30 or 40% by volume of carbon fibre, and one copper matrix product. MMCC has many projects with aerospace and defence primes for development and qualification of packages, many of which are installed on various satellites and defence platforms. JW Composites LLC approaches copper-graphite composites differently to other suppliers by utilising technology for CVD coating graphite fibre with a thin layer of molybdenum. This is for three reasons:

1. It produces a surface which is wettable by infiltrant metal (compared with untreated) without requiring application of pressure
2. Molybdenum is effectively insoluble in copper so the intrinsically high conductivity of oxygen-free copper is not degraded
3. Molybdenum coating is required in order to develop a carbide interface which has low interfacial thermal resistance – this is important for 'coupling' the graphite and the matrix for optimised thermal performance

The resultant copper-graphite composite has typically 25 to 30% graphite, with a maximum size of 10 x 13 x 0.25 inch which is built from layers of 10 x 13 x 0.020 inch. Meeting flatness specifications in thinner sheets is a challenge. By adjusting the construction the coefficient of thermal expansion and thermal conductivity can be set to predefined values within a range. The main benefit is the provision of a material with low expansion with enhanced in-plane conductivity and good through-thickness thermal and electrical conductivity with reduced density compared to copper.

Using this technique, fibres having an axial conductivity of 600 W/m·K are combined with the copper matrix to deliver a material with thermal expansion controllable within the range 2-10 ppm/K with in-plane thermal conductivity substantially equivalent to copper (400 W/m·K) and Z-plane conductivity of 200 W/m·K.

This combination is of particular interest in power electronic applications and especially as substrates or base plates for large-area die attach. Trials undertaken by Harris Semiconductor indicated no degradation after 500 thermal shock cycles (-50 to +125ºC). Testing by Omnirel indicated significantly improved thermal performance compared with Al-SiC and demonstrated increased power density capability allowing reduction of die size for a given rating from 1,000 x 1,000 mil to 500 x 500 mil for insulated gate bipolar transistors (IGBTs).

Support technologies required for implementation are metallisation, soldering, eutectic bonding and conductive adhesive. Potential applications include IGBT base plates, thermal caps, heat sinks and cores for co-fired ceramics. Very low loss factors – below Cu-Mo-Cu low-temperature co-fired ceramic on metal (LTCC-M) – also suggest some radio-frequency (RF)/microwave/THz applications.

The current size envelope is within 325 x 250 mm and thickness in the range 0.5 to 6 mm.

2.3.3 Metal-graphite foam

JW Composites has also developed a graphite foam/copper composite as a replacement for copper-tungsten (Cu-W). Carbon foams (Exhibit 2.8) are an attractive alternative to fibre composites as it is easier to control volume loadings, and high conductivity values – 600-1,200 W/m·K – are available in the ligaments, so should also be substantially lower cost. An important difference is that the material is substantially isotropic.

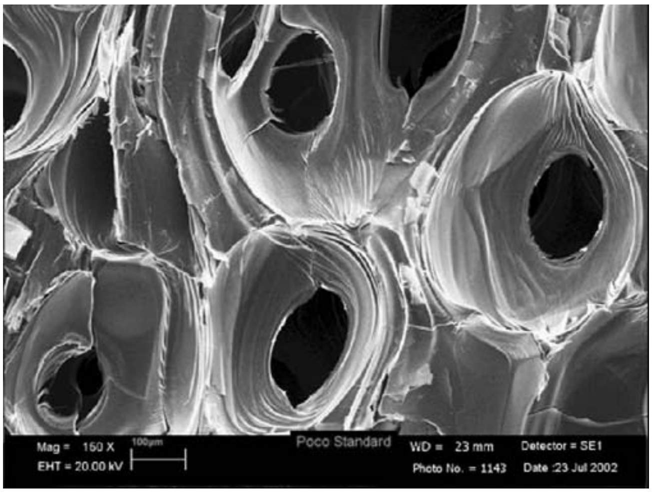

Exhibit 2.8 *PocoFoam structure (courtesy Poco Graphite Inc)*

Developmental materials have thermal conductivity of ~342 W/m·K and CTE 7.4 and 5.7 ppm/K. Compared to baseline Cu-W composites, improved thermal management is expected with easier machining and lower mass. Applications targeted include LDMOS microwave power transistor substrates, high-power laser diodes, various power applications and high-power transmit-receive module (TRM) packages (Exhibit 2.9). Control of surface roughness can be a problem on machined surfaces.

2.3.4 Metal-silicon carbide

Aluminium-silicon carbide (Al-SiC) metal matrix material[1] technology is well established by Ceramics Process Systems (CPS).[2] CPS uses its net-shape fabrication process for high-volume manufacturing of Al-SiC components including flip-chip lids (microprocessor, heat sink, flip-chip, digital signal processing (DSP) application),[3] power applications (IGBT base plates,[4] power substrates),[5] optoelectronic[6] and microwave packaging.[7]

Metallising and packaging technologies are now well proven. Different variants are offered with different thermal expansion coefficients to suit application requirements. Typical ratings (isotropic) are CTE 8 ppm/K, thermal conductivity ~200 W/m·K and density 3.01 g/cm^3. The high loading of silicon carbide imparts high modulus and forms a strong interface with the matrix, and the resulting high strength-to-weight ratio suits it for many weight-critical applications. It is also used commercially for power (IGBT) base plates.

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2 www.alsic.com
3 www.alsic.com/page4a.html
4 www.alsic.com/page4c.html
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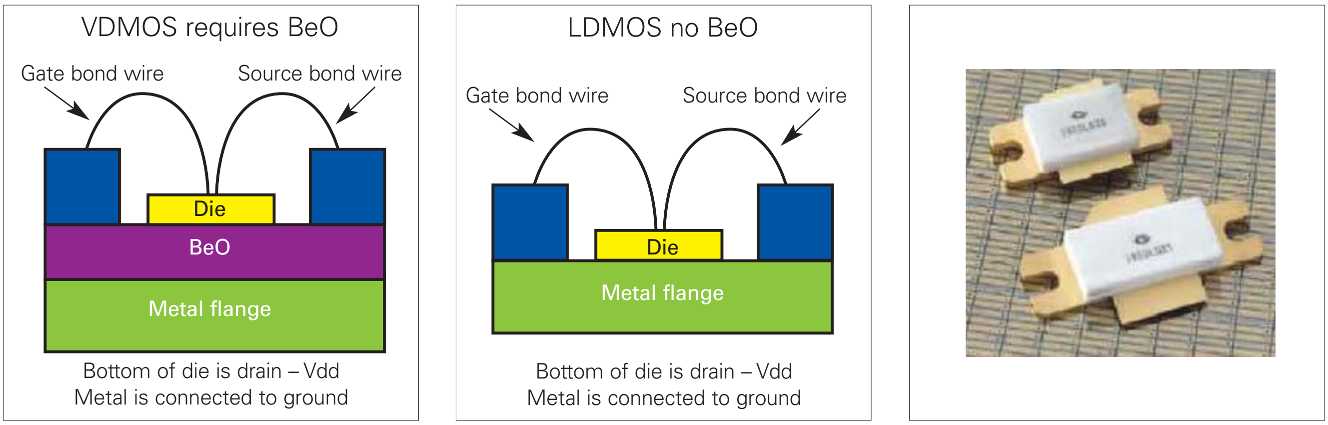


Exhibit 2.9 Thermal applications LDMOS for high-power microwave (courtesy JW Composites)

2.3.5 Metal-diamond

Diamond-aluminium or diamond-copper composites provide an isotropic high thermal conductivity material. Interest in diamond composites is growing as a result of the falling price of both synthetic and natural diamond, largely driven by sources in China. MER Corp indicated diamond costs are in the range $140-500/lb (~£157-560/kg) depending on quality.

Both MER Corp and JW Composites are developing diamond-metal composites for high-performance applications.

JW Composites is applying its patented Mo coating technology to coat diamond (see Exhibit 2.10) for subsequent melt processing with copper or silver matrices, building on its current position in the tool market (Moly-bonded Diamond™ – capacity is 10,000 carat/day). Diamond loadings for development projects are 50% volume fraction (V_f) and it is estimated that this could be increased to 75-80% if necessary. JW Composites estimates that materials with thermal conductivity of 600-800 W/m·K (isotropic) can be produced with CTE in the range 5-8 ppm/K.

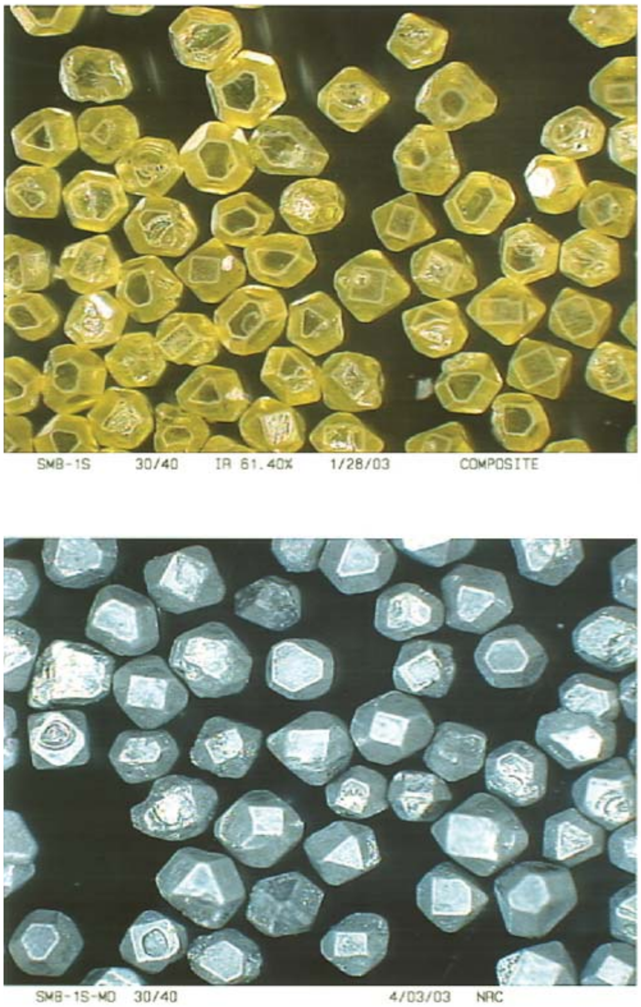


Exhibit 2.10 As received and coated synthetic diamonds (courtesy JW Composites)

The major disadvantage is the difficulty of machining the composite. This problem is being addressed by development of net-shape processing routes.

MER Corp is using high-pressure squeeze casting to manufacture near net-shape diamond-aluminium and diamond-magnesium substrates and enclosures (Exhibit 2.11). Much of this development work has been in collaboration with NASA.

Unlike many other materials, the thermal conductivity of diamond-aluminium composites rises with increasing temperature: values are in the range 350 (ambient) to ~520 W/m·K at 150ºC and thermal expansion rising from 7.5 to 10 ppm/K over the same range. Properties obviously scale with diamond V_f loading: another data set for diamond-aluminium rates it at thermal conductivity 650 W/m·K, CTE ~7.5, density 3.2 g/cm^3.

The measured thermal conductivity of the composite is in agreement with theoretical predictions. Exploitation is hampered by surface roughness (10 µm and 1.3-5 Ra for electro-discharge machining (EDM) and diamond wheel cutting respectively). MER Corp has been exploring applications of this technology in IGBT base plates which are engineered to eliminate direct bond copper (DBC) by co-casting aluminium with AlN isolation and aluminium-diamond material to deliver extremely high diffusivity and conductivity values through the stack. Modelling studies indicate that it is only possible to exploit the high conductivity of these materials at die/junction level if water cooling or extended surfaces are engineered to increase available heat transfer coefficient.

2.3.6 Carbon nanotube composites

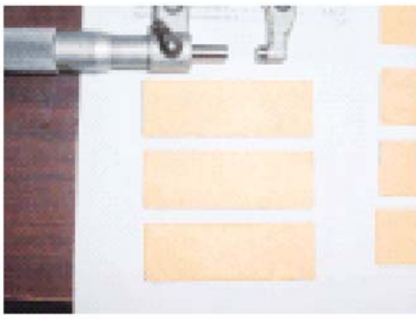
Carbon nanotubes (CNTs) offer very high thermal conductivities (>1,000 W/m·K) and most companies were at least considering thermal conducting material using CNTs. Some of the small or medium-sized enterprises (SMEs) had limited production, usually outsourced. A limiting factor in the use of CNTs is the transfer of heat flux from one nanotube to another in an efficient manner. Butt joints give poor thermal resistance, and research into devising a low thermal resistance joint was taking place. CNTs can be woven into mats to produce a low density, high thermal conductivity material. This can be put into a metal composite by pressure or squeeze casting, or epoxy added as a filler to give rigid mats. These approaches are still at an early stage.

2.3.7 Polymer composites

Laird Technologies manufactures soft polymers which can be used as gap fillers. These polymers are ceramic loaded to enhance thermal conductivity to 9 W/m·K. One material used as filler is boron nitride. This is an alternative to graphite but is expensive to process.

2.3.8 Carbon composites

Carbon-carbon materials have been extensively developed and manufactured for aircraft brakes and it is surprising that these materials have not found more applications in electronic systems. One application area



3 x 1 x 0.05 in Ni/Au metallised diamond/Al substrate

6 x 6 x 0.5 in diamond/Al enclosure with through holes

4 x 4 in diamond/Al inserts in heat sink case

Exhibit 2.11 *Diamond-aluminium substrates and enclosures (courtesy MER Corp)* which exploits carbon-carbon properties is cores for printed circuit cards which use the combination of material properties including high thermal conductivity, high stiffness and low CTE to offset expansions of other (FR4) layers in the stack. This allows the CTE of the board to be tailored to match the surface mount devices and thereby reduce interconnect stress while allowing an increase in dissipation.

2.3.9 Carbon foams

Depending on the precursor materials and the manufacturing process carbon foams can have a wide range of interesting thermal properties: from highly insulating materials (<1 W/m·K) such as the well-established vitreous carbon foams and more recently-developed GRAFOAM product from GrafTech, through to highly conductive materials such as the graphitic foam developed at Oak Ridge National Laboratory (ORNL).

The new generation of high thermal conductivity foams emerged from research in the USA during the 1990s with alternative precursors. Precursors derived from pitch and coal allowed the manufacture of foams with highly graphitic ligaments (for the most crystalline ligaments thermal conductivities an order of magnitude greater than aluminium are anticipated). This results in bulk thermal conductivities in excess of 100 W/m·K and specific conductivities four or fives times greater than copper. The foams are commercially available from a number of sources, and with their low densities and high available surface areas the materials show promise for heat sink and heat exchanger applications.

Graphitic carbon is not readily wetted by most molten metals, and though a carbide phase may enhance wetting and bonding, the reaction with infiltrating metal (eg with aluminium) may be undesirable, so attention must be given to the technology of metal bonding and impregnation of the materials. S-Bond Technologies LLC has developed a proprietary process utilising an active-solder technology that allows the bonding of graphite foam to metallic, ceramic and composite sheets without premetallisation, providing a strong and thermally conductive joint. Encapsulation of the foam without excessive penetration is possible and has enabled the use of the foam in heat exchanger applications such as IGBT power module cooling, and lightweight cooling systems for military applications.

MER Corp produces a mesophase pitch-derived graphitic foam with anisotropic thermal properties. The foam has been used in hybrid structures with carbon-carbon composite for mirrors and niche thermal applications. For a laser diode submount the foam may be employed to spread heat to a high-conductivity 1D carbon-carbon composite base.

High-conductivity graphite foams have been available since 2000, and although at present are used in niche applications, the materials show promise for high-power electronics subject to pressure-drop design constraints.

2.4 Low-conductivity materials

2.4.1 Ultralow-conductivity materials

Thermal insulation materials come in a range of forms; primarily they are low-density foams or fibrous materials that restrict conductive and convective heat transfer. Depending on the thermal environment, appropriate materials may be polymers, glasses, ceramics or carbons. An additional benefit (for example with carbon materials) may be a measure of electromagnetic interference (EMI) shielding.

A range of these materials is used in aerospace applications to shield and safeguard electronic components; for protection of control equipment these tend to be bespoke designs.[8] With the introduction of more electronics into demanding environments (eg all-electric aircraft and jet engines) there will be requirements for even higher performance thermal insulation which may require new materials and approaches. The following briefly highlights some recent developments in insulating materials in the USA.

As a space application the reflective insulation/heat radiator combination is key to ensuring that the electronics within satellites are maintained within their operating temperature range. For the Mars Pathfinder Rover, NASA used solid silica aerogel to insulate the electronics and restrict heat loss. Silica aerogel is the lowest density solid material and is a remarkable insulator because silica is a poor conductor and the materials structure restricts convective transfer; typical conductivity is 0.02 W/m·K. Aerogels can be manufactured from a number of materials, and in the early 1990s carbon aerogels were developed.

A major factor in preventing the more extensive use of aerogels has been their cost of production. However, take-up of the materials has been significant in thermal insulation applications such as building and pipelines, and more recently they have been used for automotive 'under-the-hood' thermal management. With the ongoing cost reductions and the development of new materials and composites this class of super-insulator should become very attractive for electronics thermal shielding.

The materials are available from several suppliers in the USA (eg NanoPore Inc, Aspen Aerogels Inc, Marketech International Inc, Cabot Corp). NanoPore[9] believes its products have a role as with the improved thermal performance the insulation volume can be drastically reduced. Its vacuum insulation panels (VIPs) for electronics can be produced with dimensions as small as 40 x 40 x 3 mm or less.

Exhibit 2.12 *Aerogel insulation (courtesy NASA)*

Coatings may have a role, particularly in hybrid constructions. Industrial Nanotech Inc[10] markets Nansulate, an oxide nanocomposite material that because of the nano-sized structure presents tortuous thermal paths and consequently poor thermal transfer. The manufacturers claim a total conductivity of 0.017 W/m·K for a material which may be applied as a liquid coating.

The creation of a high interface density within a nanolaminate material (Universities of Illinois and Colorado) produced a very effective barrier to heat transfer and a material with a thermal conductivity three times smaller than conventional insulator.[11] The heat flow is limited at the interface as the differences in lattice vibration between the materials restrict the transfer of energy across the interface.

8 www.thermalengineering.co.uk

9 www.nanopore.com/thermal.html

10 www.industrial-nanotech.com

11 *Controlling material structure at nanoscale makes better thermal insulator,* February 2004: www.azonano.com

Researchers at the University of Oregon[12] created a new insulation material with the lowest thermal conductivity for a fully dense solid by using a novel approach to produce thin films of tungsten diselenide. The unusual structure is crystalline in two directions but with a rotational disorder in the direction of low heat conduction. Though some way away from immediate application, the researchers believe that understanding of the principles may point the way toward new methods for producing improved insulation.

2.4.2 Carbon foam

Carbon foams can be processed to have high or low thermal conductivity. Low-conductivity foams were tabled by GrafTech. These materials have been developed as heat shields but are also finding applications in composites and lightweight structures. Four variants are supplied having thermal conductivity values in the range 0.3 to 0.06 W/m·K with solid fractions in the range 39% to 1.4% respectively. These foams are produced using a low-cost technology so that these materials may realise higher levels of market penetration, albeit in applications other than mainstream electronics.

2.5 Interface materials

Interfaces between materials have a significant impact on the thermal impedance of electronic systems and in practice they can be the dominant factor in achieving effective thermal transfer.

For the purpose of this report, the interface materials and processes described are the methods used to join an electronic device to the thermal transfer medium (eg substrate, heat pipe, heat sink), including coatings and bonding techniques. In this respect they may need to perform the tasks of attachment, stress/strain relief and thermal transfer.

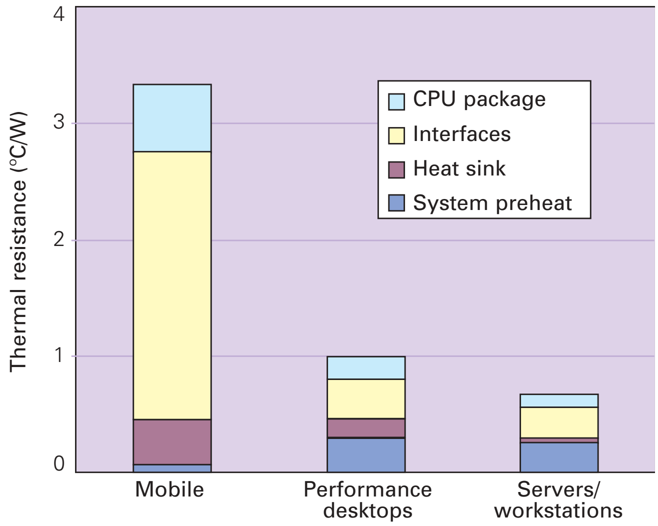


Exhibit 2.13 Partitioning of thermal resistance contributions by market sector (courtesy The EPPIC Eye)

The simplest of all interfaces is a dry joint (two surfaces pushed together). In this case interface thermal resistance can be significant and will be dependent on the surface materials, their hardness, co-planarity, roughness and the applied pressure to hold the surfaces together.

To enhance heat transfer across the interface, thermally conductive materials are introduced to improve surface coupling and conductivity (Exhibit 2.14).

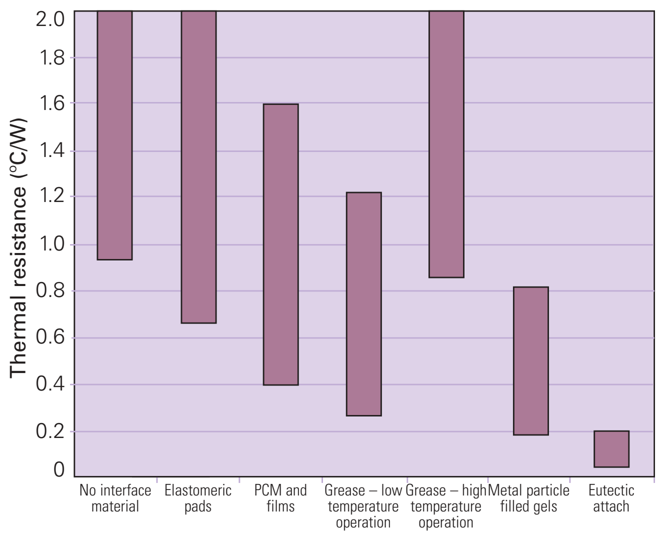


Exhibit 2.14 Thermal resistance of representative interfaces (source: An introduction to thermal management, The EPPIC Eye, 2004)

12 *Researchers produce insulation with lowest thermal conductivity ever,* December 2006: www.physorg.com

Typical interface materials include:

- **Elastomeric thermal pads:** typically loaded with boron or aluminium nitride – primarily for low-power devices

- **Thermal greases:** loaded with particles or unfilled
  – No curing required and good thermal conductivity
  – Less suitable for applications with power cycling or high interface mechanical shock

- **Phase-change films (PCFs):** materials (eg polymer + carrier + thermally conductive filler) that transform from solid to liquid under die operating conditions
  – Wetting properties significantly reduce contact resistances but can be sensitive to 'mechanical forces' during shock and vibration

- **Metal filled gels:** typically silicone polymers with cross-linked density filled with metal (eg aluminium) or ceramic (eg aluminium or zinc oxide)
  – Conform well to surfaces with lower molecules than epoxy materials and can accommodate thermomechanical strains

- **Conductive adhesives:** polymers filled with ceramic (eg alumina or boron nitride, diamond) or metal particles (eg silver, aluminium nickel coated graphite copper)
  – Relatively low process temperatures, relatively wide range of material properties available
  – Lack of reliability data in some areas

- **Soldering and brazing:** metal is melted in a joint in such a way as to wet to the interfaces before solidifying. There are many alloys available which can offer a range of processing temperatures (eg <100ºC to >1,000ºC). Usually need a metal (metallised) surface and flux/reducing atmosphere to enable wetting to take place

- **Diffusion bonding:** a solid phase metal-to-metal joining technique requiring the application of pressure across a joint at elevated temperature in a protective environment (eg inert gas, vacuum)

2.5.1 Active solder

Conventionally, solder attachment requires metal surfaces (eg base material, plated or metallised) and a flux to clean the oxide and contaminants from the interfaces. S-Bond has developed active solders which enable wetting directly to metal and ceramic surfaces without the need for flux. This is achieved through the modification of conventional solders by the addition of titanium (0-5%) and/or rare earth elements. These active elements migrate to the interface and react with the opposing material surface to remove oxides and nitrides and transport them into the bulk of the solder as an inert material. This process can be conducted in an air environment but requires the application of a low-level mechanical shearing action to break a thin oxide (Sn-Ti) layer on the molten solder and initiate the reaction with the component interfaces. The level of shear is claimed to be small and can be delivered by brushing or scraping the surface, sliding the joining surfaces relative to one another, or by the application of high-frequency vibration to the parts to be joined. Once the oxide layer has been disrupted, the bulk solder reacts very rapidly with the substrate surfaces to form either a metallurgical (metals) or atomic attraction/van der Waals bond (eg graphite).

The bonding protocol was described as follows:

- Heat substrate surface to 250ºC (solder material dependent)
- Establish layer of material on surface
  – Ultrasonic tool
  – Mechanical action

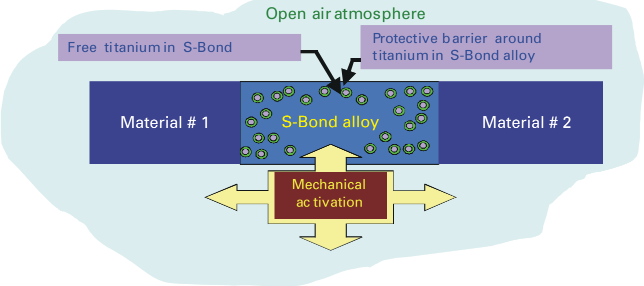


Exhibit 2.15 *S-Bond process*

- Apply enough solder on one surface to fill gap between die and lid
- Bring lid and die together to minimise trapped air and load with ~2 lb/in^2
- Cool to below 190°C

Typically the process is conducted at 10-20°C above the melting point of the solder. The molten active solder retains the ability to self-align components.

S-Bond has focused its activity on the lead-free solder compositions listed in Exhibit 2.16.

Materials that have been successfully active soldered include those listed in Exhibit 2.17.

Examples of active soldered joints are shown in Exhibits 2.18 and 2.19.

In general, ceramics and refractory metals require a proprietary pretreatment (not specified) to improve joint strength.

Exhibit 2.18 *Aluminium joining (courtesy S-Bond)*

Exhibit 2.19 *Al_2O_3 joining (courtesy S-Bond)*

Product	Description	Maximum service temperature	Initial melting point (solidus)	Fully liquid point (liquidus)
SB115*	Indium/tin	~100°C	~115°C	~120°C
SB140*	Bismuth/tin	~125°C	~135°C	~150°C
SB220	Tin/silver	190°C	221°C	232°C
SB220-50	Low-cost aluminium and copper joining	190°C	221°C	232°C
SB400	Zinc/aluminium	390°C	405°C	415°C

* Development products

Exhibit 2.16 *Lead-free solder products from S-Bond*

Metals	Ceramics	Metal-matrix composites	Carbon
Copper Aluminium Titanium Kovar Nickel Silicon	Silicon carbide Aluminium nitride Titanium carbide Alumina/sapphire Zirconia Tungsten carbide	Aluminium-silicon carbide Aluminium-graphite Nickel-titanium carbide	Graphite Carbon-carbon composite Graphite (foamed/TPG) Diamond

Exhibit 2.17 *Materials successfully active soldered by S-Bond*

Alloy	Joining temperature	CTE 25-150°C	Electrical resistivity	Thermal conductivity (intrinsic)	Tensile strength	
					25°C	175°C
220	250-280°C	19 ppm/K	1.6 µΩ·m	48 W/m·K	53 MPa	26 MPa
400	410-430°C	~32 ppm/K	–	~80 W/m·K	69 MPa	54 MPa

Exhibit 2.20 Properties of S-Bond active solder alloys

Joint performance

The optimum bond line thickness for these active solders is 50-100 µm compared with 200-250 µm for conventional die attach solders. Thicker layers result in degraded performance.

The mechanical performance of active solder material is claimed to be similar to comparable conventional solders, although the addition of titanium was claimed to improve the high-temperature creep performance of Sn-Ag-Cu alloys.

Typical stated properties of the two main active solder alloys are shown in Exhibit 2.20.

Mechanical strength will be dependent on the substrate materials and the joint design. In general, metallurgical bonds achieve 20-55 MPa (3,000-8,000 psi), and those employing van der Waals forces 6-12 MPa (1,000-2,000 psi).

Silicon bonded to substrates has been shown to survive thermal cycling tests (1,000 cycles for -55°C to +125°C) and multiple solder reflow cycles (~260°C).

To achieve higher joint strengths in carbon-based substrates (eg diamond, TPG, foamed graphite), stainless steel and Kovar, the initial coating step is replaced with a proprietary heat treatment process that ensures a permanent chemical bond to the material surface.

The ability to join graphite and aluminium foams to metal base plates opens up the potential of replacing some fin-plate heat exchangers. Thermal property (heat transfer coefficient in closed loop water) measurements showed graphite-foam samples to possess

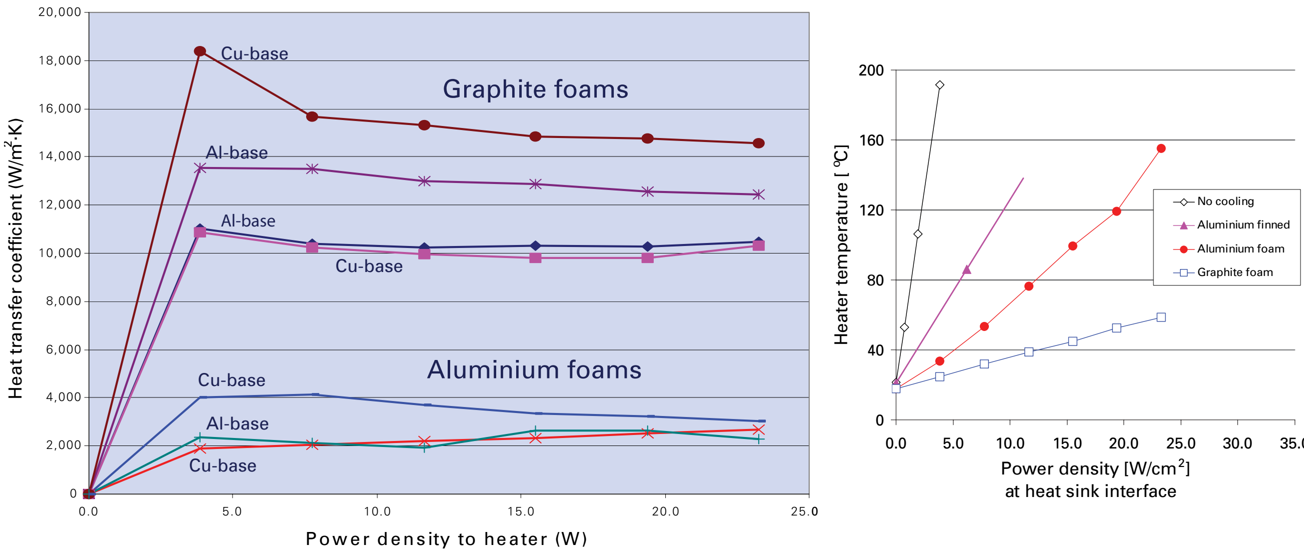


Exhibit 2.21 Thermal performance of foam-plate heat exchangers (courtesy S-Bond)

superior heat transfer coefficients compared to commercial aluminium fin-plate heat exchangers, having heat transfer coefficients between 10,000 and 20,000 $W/m^2 \cdot K$ compared to 500-1,200 $W/m^2 \cdot K$ for commercial aluminium fin-plate designs, thus demonstrating active-solder joined graphite-foam cores to be a factor of over 15 times better. Comparative investigations on active-solder joined aluminium-foam cores resulted in coefficient values of 1,500-2,000 $W/m^2 \cdot K$.

Potential process benefits

The potential benefits of active soldering are:

- No flux
  - – Eliminates cleaning and residual corrosive material
- No pre-plating
  - – Reduction in thermal impedance layers
  - – Reduction in process steps/cost
- Ability to solder a wide range of materials
- Good thermal/electrical joint conductivity
- Reworkable joint
- High surface tension (low flow)
  - – Low penetration into foam materials and pipes/channels

Applications

Active soldering is a relatively new process and consequently is still developing a market presence.

Stage	Application
Commercial	Radiation sensors – Sapphire/Ti/Stainless steel Laser cooling systems – C/Al Electronic thermal management – Al/Cu/C/Al-SiC PVD targets – Si/Quartz/Al/Cu
Scale-up	Electronic packaging – Si/Cu-W
Development	Graphite/metal composites
Research	Photonics – Glass/Au/Ceramic Aerospace – Ti/Al Defence – Ceramics/Ti

Exhibit 2.22 *S-Bond's commercialisation profile for active soldering*

S-Bond's commercialisation profile is shown in Exhibit 2.22.

Potential thermal management applications

Potential thermal management applications include:

- Die attach – eg Si device/MEMS, SiC
- Substrate/thermal back plane/package fabrication – eg Al_2O_3, AlN, SiC, Cu, Al, Al-SiC
- Heat sink fabrication – fin and pipe attachment, graphite foam joining

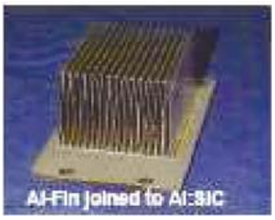


Exhibit 2.23 *Aluminium fin joined to Al-SiC (courtesy S-Bond)*

Exhibit 2.24 *Graphite foam joined to alumina (courtesy S-Bond)*

General comments

The S-Bond active solder is potentially an attractive product for electronic thermal management systems. Two key features are:

- Ability to directly join combinations of high thermal conductivity materials with a reduced number of interface (thermal impedance) layers
- Clean (no-flux) processing

The latter is becoming increasingly important as package density increases, systems become more complex and environments more severe.

The process is relatively immature and consequently new applications will need to be fully tested to establish the performance of the joint and its impact on the application and product reliability. The need to pre-coat materials prior to soldering may limit some high-volume applications unless alternative metallisation techniques (eg sputtering) can be developed.

2.5.2 Carbon nanotube adhesive

Carbon nanotubes (CNTs) are increasingly finding applications in thermal management materials and are also being considered as potential interface and attachment techniques. The following describes work being conducted on CNT 'adhesive/Velcro' by the University of California at Berkeley, Purdue University and MER Corp.

University of California, Berkeley (UCB)

UCB's Department of Mechanical Engineering has been conducting work – funded by NASA and the US Department of Defense (DoD) – on the fundamental thermal behaviour of materials (electrons and phonons) including transport down at the nano level. This has led to research into the development of CNT technology as a novel 'dry adhesive'.[13 14]

When grown on a surface in an array, CNTs can provide an extremely large surface-to-volume ratio and bind to each other and to surfaces through van der Waals (vdW) interactions. When acting collectively, vdW forces can provide significant adhesive strength (~12 N/cm^2) regardless of the hydrophobicity of the surfaces. The above, in conjunction with their electrical and thermal conductivity, makes CNTs potentially attractive as a device or substrate attachment technique.

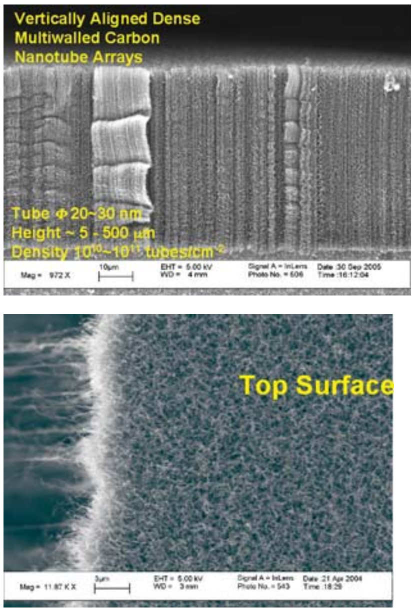


Exhibit 2.25 Vertically aligned dense CNT arrays as interface materials

UCB has produced vertically aligned multiwall CNTs (MWCNTs) by CVD on silicon substrates using thin-film iron as a catalyst and aluminium film as an adhesion layer (Exhibit 2.25).

Nanotube dimensions:

- MWCNT diameter 20-30 nm
- MWCNT height 5-500 µm
- Spatial density 10^{10}-10^{11} tubes/cm^2
- Contact area 4-20 mm^2

To investigate the adhesive properties of the MWCNT arrays grown on silicon, they were pressed against various target surfaces with a preload of <2 kg in the normal direction, then the joint strength measured.

The maximum adhesive forces measured to various target surfaces are shown in Exhibit 2.26. The maximum measured adhesive strength for 5-10 µm height arrays to a glass surface was 11.7 N/cm^2 in the normal direction

13 *Interfacial energy and strength of multiwalled-carbon-nanotube-based dry adhesive,* Yang Zhao, Tao Tong, Lance Delzeit, Ali Kashani, M Meyyappan and Arun Majumdar, Journal of Vacuum Science and Technology, B, Microelectronics and Nanometer Structures – Processing, Measurement and Phenomena, ISSN 1071-1023, 24 (1): 331-335 (2006)

14 *Dense vertically aligned multiwalled carbon nanotube arrays as thermal interface materials,* Tao Tong, Yang Zhao, Lance Delzeit, Ali Kashani, M Meyyappan and Arun Majumdar

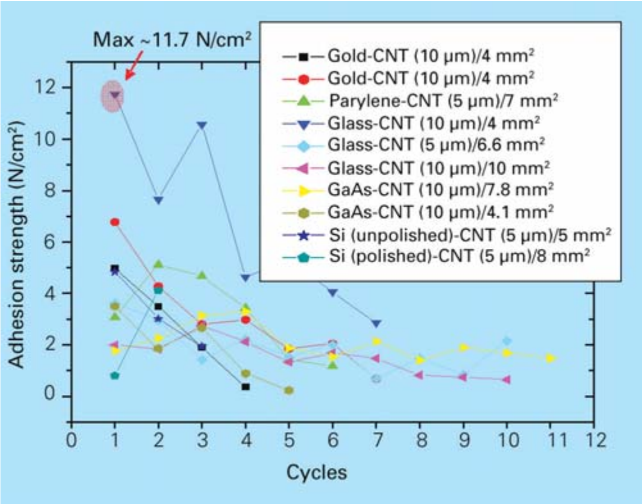


***Exhibit 2.26** Dry adhesive properties of MWCNTs*

(apparent contact area of 4 mm^2) and 7.8 N/cm^2 in shear (apparent contact area of 8 mm^2). The adhesive energy between MWCNT and a glass surface was found to be 20-80 mJ/m^2. The adhesive strength over repeated adhesion and separation cycles degraded, due to the relatively poor adhesion of the MWCNTs to their silicon growth substrate. This was improved significantly by adding molybdenum to the catalyst underlayer.

Thermal interface measurements for the above system (silicon/MWCNT-glass) identified that the dominant interface is between the MWCNT layer and the glass substrate (10^{-5}-10^{-6} K·m^2/W) which is at least one order of magnitude lower than that of the CVD grown MWCNT-silicon interface (Exhibit 2.27).

Main points from research to date

- Vertically aligned MWCNT arrays can be grown on a silicon substrate and act as a 'dry adhesive', joining to various surfaces, disregarding their hydrophobicity
- Adhesive strengths of up to 11.7 N/cm^2 (normal direction) were achieved when joining to a glass surface
- The adhesion strength over repeated removal/attachment cycles degraded and is limited by the relatively poor adhesion of MWCNTs to their growth substrate (silicon) but this was improved by adding molybdenum to the catalyst underlayer
- MWCNT 'adhesives' are electrically and thermally conductive (comparable to commercially available thermal paste)

Issues and limitations

- Adhesion performance is dependent on the tube length – 5-10 µm tubes gave best adhesion
- A relatively large preload (2 kg) is necessary to effect a joint
- Adhesive strengths were related to apparent contact areas (4-20 mm^2) – smaller contact areas had higher strengths, possibly due to coplanarity or surface flatness

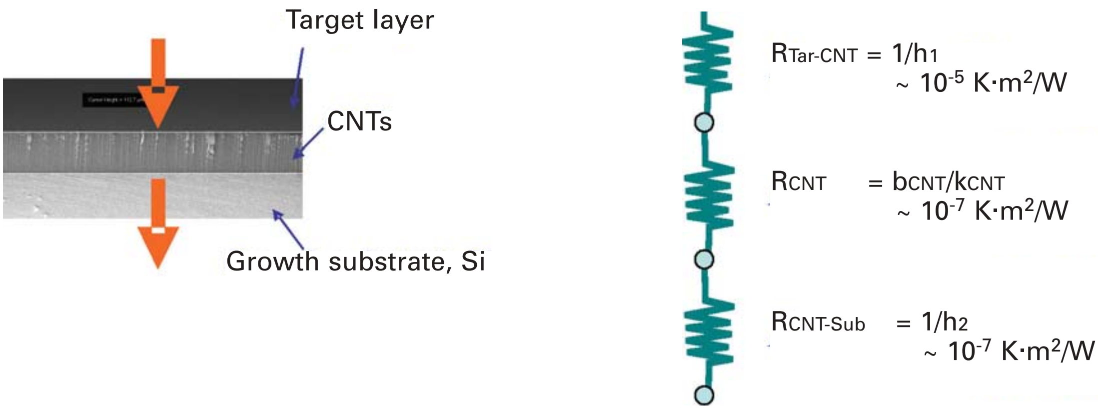


***Exhibit 2.27** Thermal interface properties (courtesy UCB)*

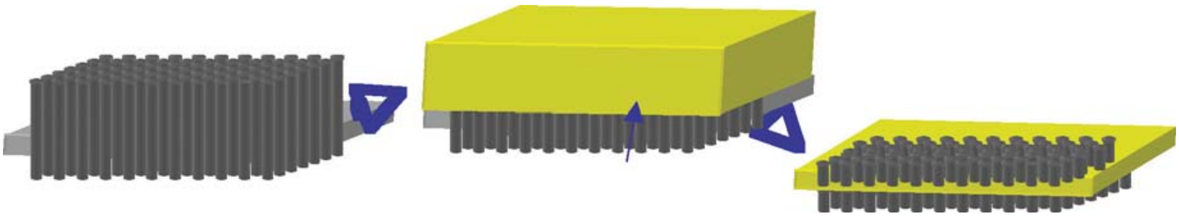


Exhibit 2.28 *Transfer etching (PDMS, polystyrene, PMMA etc) allowing control of the protruding length of tubes for matrix (Yurdumakan et al)*[15]

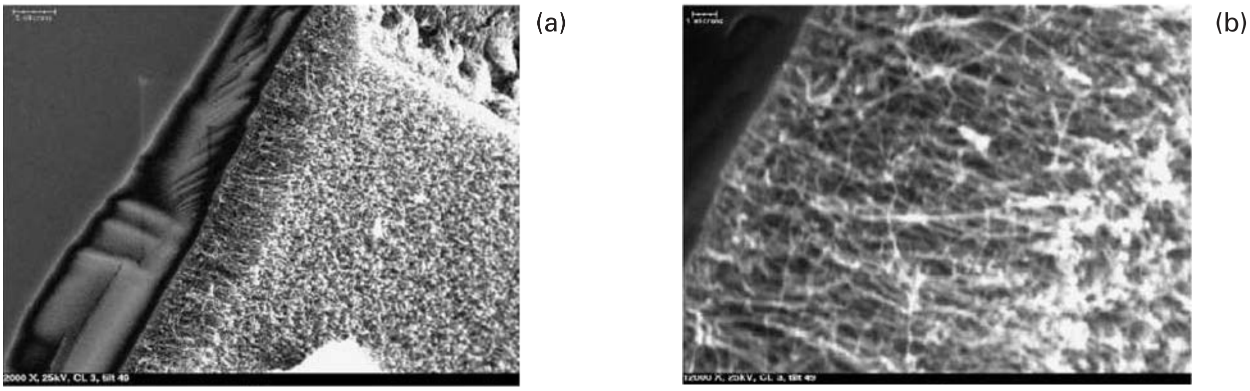


Exhibit 2.29 *SEM images of a CNT array viewed with a tilt angle of 49º – (a) typical appearance of the CNT array on a silicon wafer (scale bar = 5 µm), (b) high-magnification view of a CNT array (scale bar = 1 µm) (Xu and Fisher, 2006)*

Proposed future development

- Embed vertically aligned MWCNT in soft polymer films for improved conformity to surfaces (Exhibit 2.28)
- Increase adhesive energy and strength through the use of conformable substrates, single-walled CNTs, solder coated fibres (eg indium) or adhesive on the target surface
- Investigate the potential of boron nitride nanotubes – similar thermal conductivity to carbon

Purdue University School of Mechanical Engineering

Similar work was reported at Purdue University's Electronics Cooling Laboratory which is developing CNT interfaces for improved thermal and electrical management. The aim is to utilise the inherent excellent heat-conduction properties of CNTs through the development of controlled fabrication techniques. The vertically aligned nanotubes (15-250 nm diameter) were grown using microwave-enhanced CVD on silicon and copper test substrates using a titanium adhesion layer (~10 nm), aluminium buffer layer (~10-20 nm) and nickel or iron catalyst layer (~16-10 nm). Results of three research programmes are summarised below.

1 Multiwalled CNT coated silicon to copper interface: thermal contact resistance[16]

- CNT array height 7-13 µm
- CNT diameter 15-25 nm
- CNT density 20-30 x 10^7 CNTs/mm^2
- Substrate area 10 x 10 mm

15 *Synthetic gecko foot-hairs from multiwalled carbon nanotubes,* Betul Yurdumakan, Nachiket R Raravikar, Pulickel M Ajayan and Ali Dhinojwala, Chem Commun (2005) 3799-3801: www.rsc.org/publishing/journals/CC/article.asp?doi=b506047h

16 *Enhancement of thermal interface materials with carbon nanotube arrays,* Jun Xu and Timothy S Fisher, Int J Heat mass Transfer 49 (9-10): 1658-1666 (May 2006)

Results:

- Thermal interface resistance of 20-37 $mm^2 \cdot K/W$ at a pressure of 0.445 MPa
- A combination of a CNT array and a phase change material (load 0.35 MPa) produced a minimum resistance of 5.2 $mm^2 \cdot K/W$

2 3-Omega measurements of vertically aligned CNTs on silicon substrate[17]

A schematic of the experimental structure is given in Exhibit 2.30, the CNT dimensions being:

- CNT array height 13 µm
- CNT diameter 10-80 nm

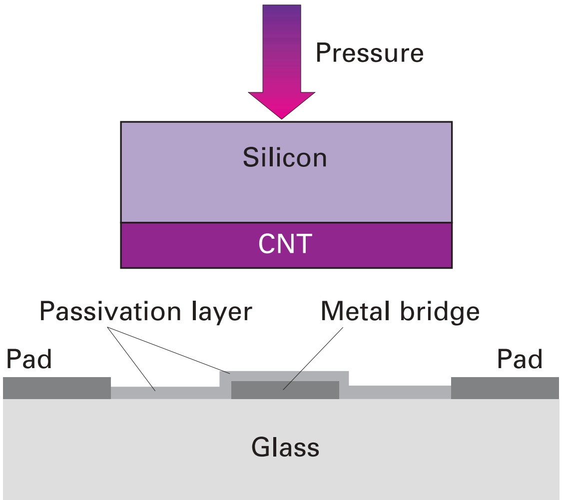


Exhibit 2.30 *Schematic of the experimental structure (X Jack Hu et al, 2006)*

Results:

- Effective thermal conductivity 74-83 W/m·K in the temperature range 295-323 K, one order of magnitude higher than the test thermal greases or phase-change materials

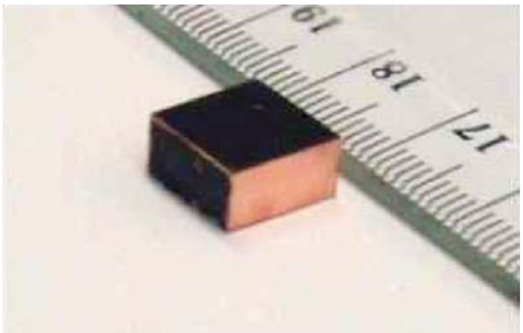


Exhibit 2.31 *As-fabricated MWCNT layer on copper substrate (unit = cm) (Myounggu Park et al, 2006)*

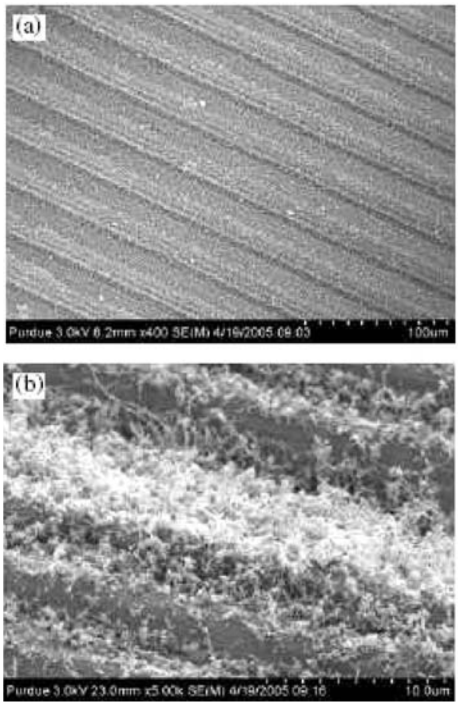


Exhibit 2.32 *FE-SEM images of MWCNT layer on copper substrate – (a) machining lines on copper substrate, (b) MWCNTs on machining line (Myounggu Park et al, 2006)*

3 Electrical resistance of CNT coated tough pitch copper (alloy 110)[18]

- Copper substrate 10 x 10 x 0.5 mm
- Copper probe contact area 0.31 mm^2

17 *3-Omega measurements of vertically oriented carbon nanotubes on silicon,* X Jack Hu, Antonio A Padilla, Jun Xu, Timothy S Fisher and Kenneth E Goodson, J Heat Transfer 128 (11): 1109-1113 (November 2006)

18 *Effects of a carbon nanotube layer on electrical contact resistance between copper substrates,* Myounggu Park, Baratunde A Cola, Thomas Siegmund, Jun Xu, Matthew R Maschmann, Timothy S Fisher and Hyonny Kim, Nanotechnology 17 (9): 2294-2303 (2006)

Results:

- An 80% reduction in contact resistance was observed when an MWCNT layer was used (minimum measured resistance: Cu-Cu 20 Ω, Cu-MWCNT-Cu 4 Ω
- Resistance decreased with increasing contact force

General comments

The research has shown that the major thermal impedance is at the tube tip-substrate interface.

The main issues with the current technique are ensuring that the silicon is kept below 350ºC during CNT processing (this is not an issue with SiC devices) and the need to apply a clamping pressure (1-4 atm) to effect a joint.

Potential applications include microprocessors and power electronics (eg military). Commercialisation is already being pursued by several companies including NanoConduction Inc (Sunnyvale, California).

MER Corporation

MER Corp is developing a CNT interface material with Mitsubishi. The material takes the form of a film on 2 μm thick porous (20% CNT, 80% pores) material which can then be filled/laminated with polyethylene or epoxy resin to improve its mechanical properties. This system produces similar thermal properties to conventional phase-change materials. A condensed hydrocarbon on the nanotubes improves wetting but may limit thermal conductivity.

General comments

The concept of a CNT dry adhesive is very attractive in terms of the potential for a high thermal conductivity interface. Individual multiwalled CNTs have been shown to have very high thermal conductivity (~3,000 W/m·K) at room temperature.[19]

Additionally, the potential for a low insertion force, 'flexible' (stress relieving) and reworkable die and substrate attach system would be of significant benefit for assembly and maintenance.

This work has demonstrated the potential of this new technology; however, there are still significant issues in terms of strength, performance and reliability to address prior to it being acceptable as an attach system industrial application.

2.5.3 Other interface/interconnect materials

This mission primarily visited developers of high thermal conductivity materials. Consequently, other than as described in Sections 2.5.1 and 2.5.2 above, there was less emphasis on interface solutions as they were often being developed by their customers, many of whom did not provide detailed results. The following summarises the information obtained from these discussions.

Laird Technologies

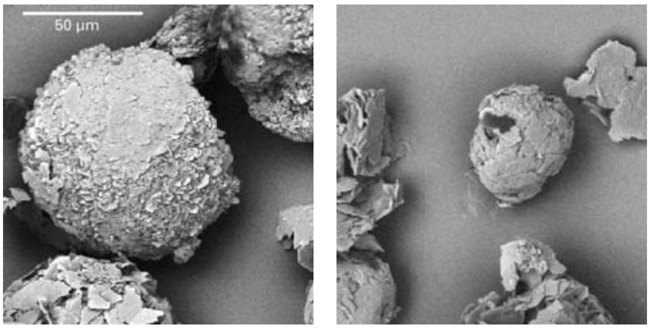
Laird Technologies presented a range of conventional conductive particle filled polymer (soft/hard) thermal interface materials together with phase-change materials and greases. These were primarily for passive cooling systems.

No new interface materials were discussed.

19 *Thermal Transport Measurements of Individual Multiwalled Nanotubes,* P Kim, L Shi, A Majumdar and P L McEuen, Phys Rev Lett 87 (21) 215502 (19 November 2001): www.lassp.cornell.edu/lassp_data/mceuen/homepage/Publications/thermalprl2001.pdf

Momentive Performance Materials Inc (formerly GE Materials)

Momentive Performance Materials Inc produces PolarTherm boron nitride particulates (10-30 μm) in large quantities for conducting fillers for a wide range of greases, gels, adhesive films and potting agents. A new spherical filler material (60 and 25 μm diameter) was presented which was claimed to give a two times improvement in thermal conductivity (eg 6 W/m·K) over conventional particulates, was more isotropic and very durable when compounded.



PTX60 400X *PTX25 ~430X*

Exhibit 2.33 *PolarTherm boron nitride fillers – spherical particles (courtesy Momentive Performance Materials Inc)*

Proposed interface applications include greases, phase-change materials, thin films and conductive adhesives.

Limitations are mainly related to the minimum sphere size. Many customers require a bond line thickness (thermal resistance) of ~12 μm and it is currently difficult to make the particulates small enough.

Ceramics Process Systems (CPS) and Sp3 Diamond Technologies

Ceramics Process Systems (CPS) and Sp3 Diamond Technologies have jointly developed Al-SiC packages incorporating diamond 'pins'. This solution provides high thermal conductivity (>1,000 W/m·K) paths in a tailored CTE package. Strategically placing the pins near hot spots they act as 'vertical heat pipes' and, in conjunction with an encapsulated pyrolitic graphite sheet, promote heat-spreading across the package surface.

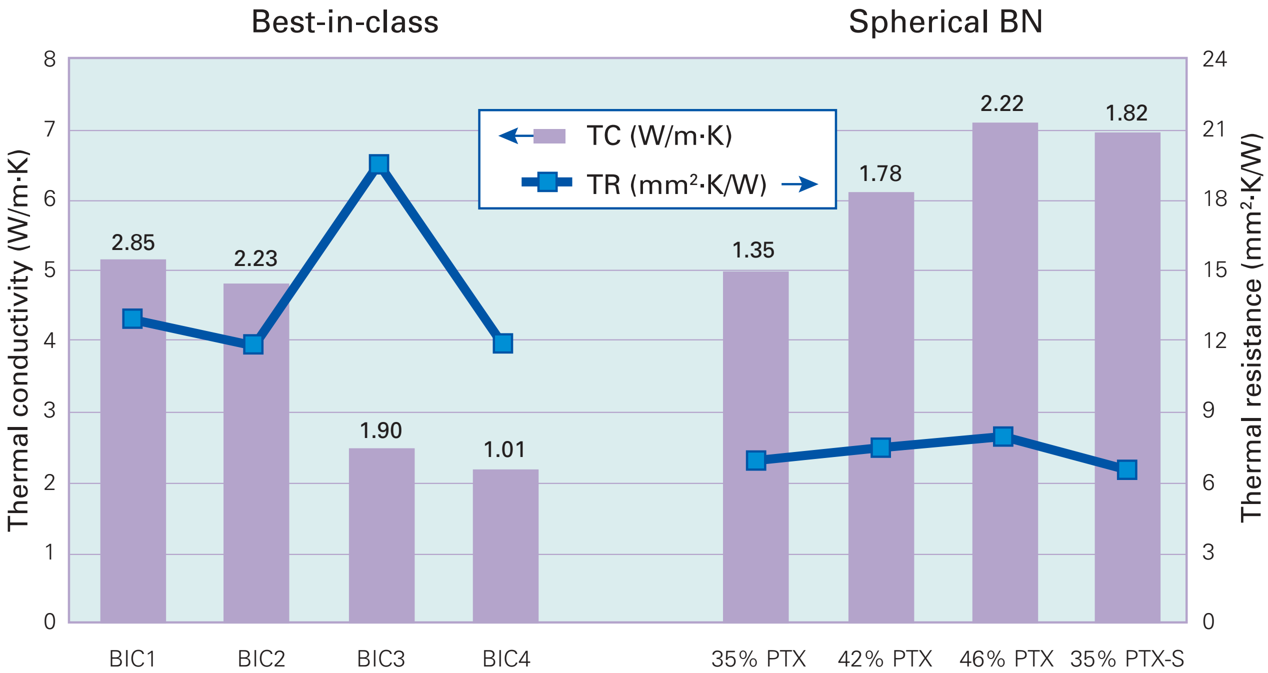


Exhibit 2.34 *Grease results, spherical boron nitride vs best-in-class commercial grades (courtesy Momentive Performance Materials Inc)*

3 PASSIVE COOLING

3.1 Pyrolytic graphite heat spreaders

Highly oriented pyrolytic graphite (HOPG) from Momentive Performance Materials Inc is the most sophisticated large-area thermal management materials technology. This finds applications in premium passive heat transfer applications. Momentive claims that the very high thermal conductivity of its material offers more than five times the power dissipation capability of aluminium.

However, a great deal of materials engineering know-how is involved in realising this, given the inherent fragility and extreme anisotropy. The benefits of using high-conductivity materials are determined by the other thermal resistances in the system. High-quality thermal interfaces are needed to exploit the potential of the material. The parallel development of PolarTherm boron nitride fillers for high-performance interface materials therefore sits well with this.

To date the material has mainly been used encapsulated in a metal casing within which the HOPG material is kept always in compression. Applications have been those where cost is not a driving factor and have included avionic, telecom, power electronics, high-end servers and high-brightness LEDs. Other methods of integrating the material with lower expansion advanced materials are also being developed, for example as an embedded insert in Al-SiC flip-chip lids which offer thermal conductivity of 1,350 W/m·K in the XY plane.

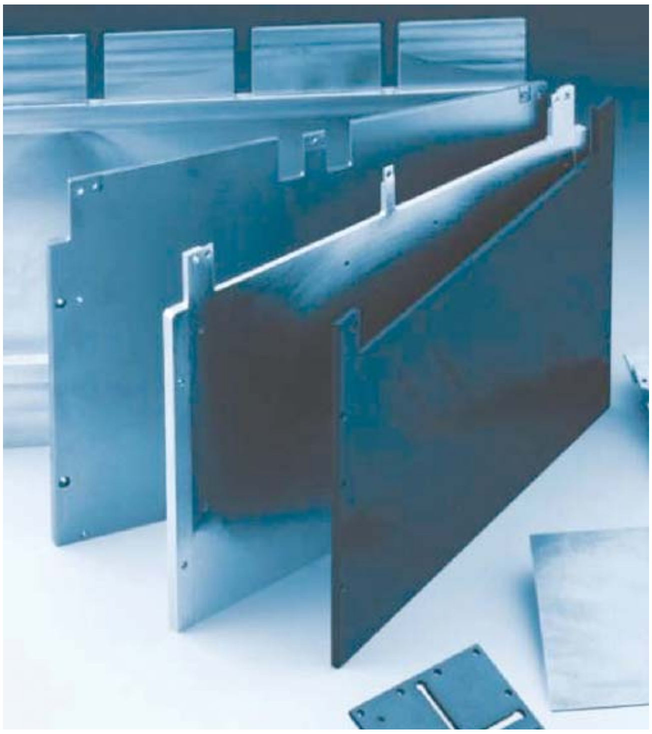


Exhibit 3.1 *TPG embedded in TC1050 (courtesy Momentive Performance Materials Inc)*

Exhibit 3.2 *TPG inserts embedded in flip-chip lid (courtesy Momentive Performance Materials Inc)*

The poor Z-plane conductivity of the material can reduce the thermal coupling efficiency in dealing with hot spots in some configurations. This problem can be attacked using the technique of introducing diamond pin inserts, used for example in one radar module application.

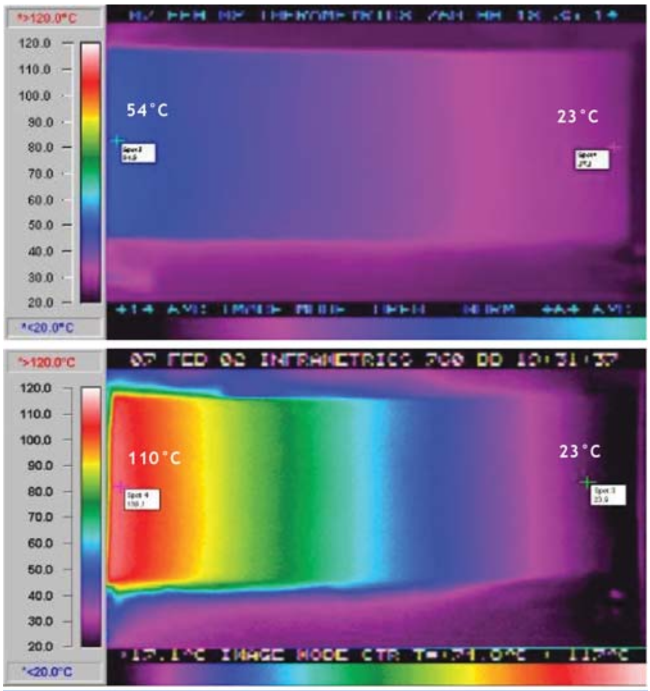


Exhibit 3.3 TC1050 thermal core (top) vs aluminium (bottom) – infrared image (courtesy of Momentive Performance Materials Inc)

Thermal imaging of equivalent thermal loads is shown in Exhibit 3.3 with TC1050 (upper figure) compared to aluminium (lower figure), indicating how effectively peak temperatures can be reduced to 54ºC from 110ºC.

In effect TC1050 appears to offer heat transfer performance commensurate with what might be expected with heat pipe or vapour chamber structures but all in the solid state, with associated reliability and longevity benefits.

3.2 Graphite laminations

Graphite originating from natural sources has been combined with polymers by GrafTech International Ltd. This builds on GrafTech's base in volume manufacture and supply of graphite foil. These processes are already scaled up and the price-performance combination for graphite heat spreaders positions them for use in consumer applications including laptop computers, plasma and LCD televisions (TVs) and mobile telephone handsets.

GrafTech supplies high thermal conductivity flexible graphite-based heat spreaders called SpreaderShield which are now used in a range of laptop computers, plasma and LCD TVs. These types of flexible graphite films are thermally anisotropic, having high in-plane thermal conductivity varying (process dependent) between ~140-500 W/m·K and through-thickness conductivity between 5-10 W/m·K.

The graphite material laminated with polymer material can be can be formed into a number of different shapes and can be used to form heat risers, heat sinks and heat spreaders.

To overcome the poor thermal conductivity in the Z-direction GrafTech fits thermal copper or aluminium studs into the graphite material to improve the Z-plane thermal conductivity. The studs can be coated for electrical isolation or conductivity and act as large thermal vias (Exhibit 3.4).

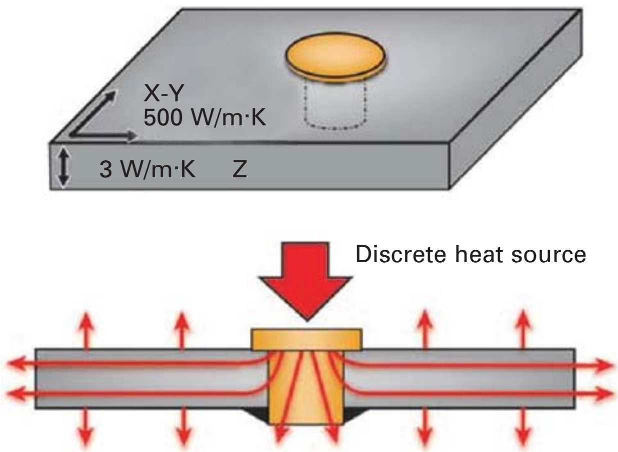


Exhibit 3.4 Use of studs as thermal vias in graphite sheets (courtesy GrafTech International Ltd)

The material can be laminated together to give 3D shapes. The graphite can also be laminated into printed circuit boards (PCBs) as a thermally conductive plane.

Applications of this technology include:

- Sony (Vaio X505) and Panasonic notebook/laptop computers –

SpreaderShield (0.2 mm thick) replaced heat pipe and fan units. The SpreaderShield was placed on the skin of the computers and pressed against the processor, graphic card and memory chips using elastomeric pads bonded to the case. This resulted in a reduction in touch temperature (eg 8ºC) and processor chip operating temperature (>77ºC without SpreaderShield, 60ºC with SpreaderShield), a 50% weight loss and improved battery life

- LCD and plasma displays – in the latter case, SpreaderShield replaced acrylic bonded to aluminium heat spreader. This resulted in improved brightness, life and image quality

Exhibit 3.5 *SpreaderShield thermal management in notebook computer (courtesy GrafTech International Ltd)*

Exhibit 3.6 *Spreader retrofitted in Samsung LCD TV (courtesy GrafTech International Ltd)*

Condition	ΔT_{max}	ΔT_{ave}	ΔT_{sd}
As received	26.3	20.0	2.73
With SpreaderShield 260 W/m·K	21.5	17.8	1.86

Exhibit 3.7 *Temperature data for Samsung 40 in LCD TV (courtesy GrafTech International Ltd)*

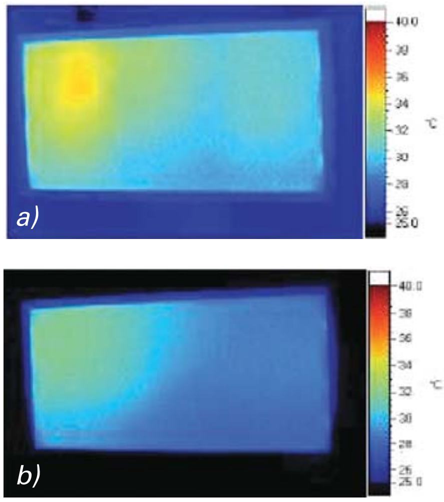


Exhibit 3.8 *Retrofitted NEC PDP panel: infrared images, full-black condition – (a) as received, (b) with SpreaderShield 260 W/m·K (courtesy GrafTech International Ltd)*

Packages such as fully buffered dual in-line memory modules (FBDIMMs) or high-temperature LEDs can be directly attached to these plugs (eg soldered). Trials have shown the zSpreader gives a 5-8ºC reduction in device temperature when compared with aluminium-based heat sink technology.

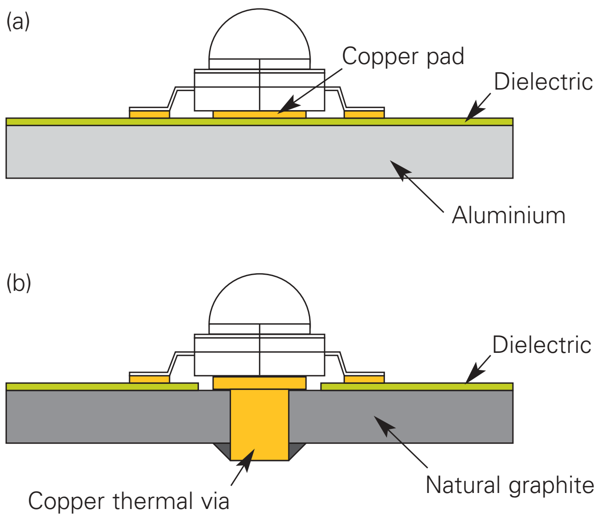


Exhibit 3.9 *Schematic of LED mounted on (a) aluminium, (b) natural graphite with embedded copper via (courtesy GrafTech International Ltd)*

	Experimental			Numerical	
Case	LED power (W)	Ambient temperature (°C)	Thermocouple at slug/TIM interface (°C)	LED junction temperature (°C)	Total weight (g)
Aluminium MCPCB	3.33	21	65.7	97.1	22.5
Natural graphite replacement	3.37	21	61.1	92.2	17.5

***Exhibit 3.10** Experimental and numerical results of the two board configurations (courtesy GrafTech International Ltd)*

3.3 Composite structures

Similar benefits available with composite packages and base plates were presented by MER Corp for its Graphmet350 product, aluminium diamond products, and by JW Composites for its copper matrix fibre and developmental copper-graphite foam products. This also goes for products from MMCC for its MetGraf products. Many of the products tabled were engineered into product forms between flat substrate and highly sophisticated packages. MER Corp indicated structures involving a 2D heat spreader coupled to a 1D heat pipe in the Z plane which are capable of handling highly local dissipation (Exhibit 3.11).

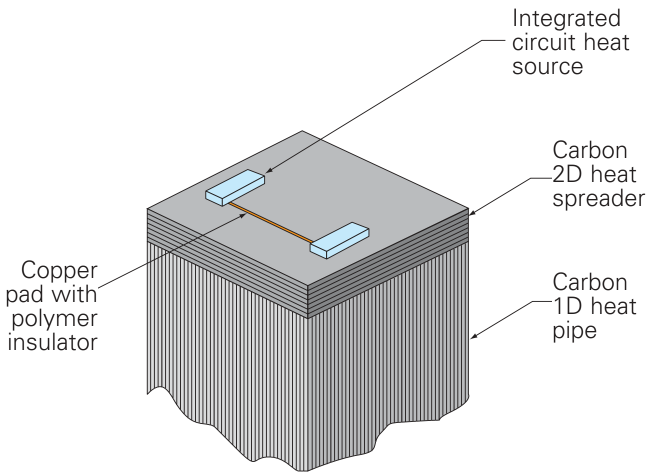


***Exhibit 3.11** Use of carbon-carbon composites in passive cooling (based on figure supplied by MER Corp)*

3.4 Carbon-composite PCB cores

One good example of passive cooling technology is the use of Stablcor carbon-carbon composite technology which addresses heat conduction within a PCB. Stablcor prepreg material is a thermally and electrically conductive material, ideally used as a ground plane. The material is presented as a carbon-composite laminate with copper coating (Exhibit 3.12).

This material has significantly improved thermal conductivity when compared to FR4 laminate and a lower coefficient of thermal expansion (see Exhibit 2.1). Many of the other mechanical properties such as density are comparable or offer an improvement on other prepregs or stiffeners traditionally used in PCB materials. Normally the material is configured to have the same thermal conductivity in both the X and Y direction. To conduct heat into the carbon composite layer thermal vias are used (Exhibit 3.13).

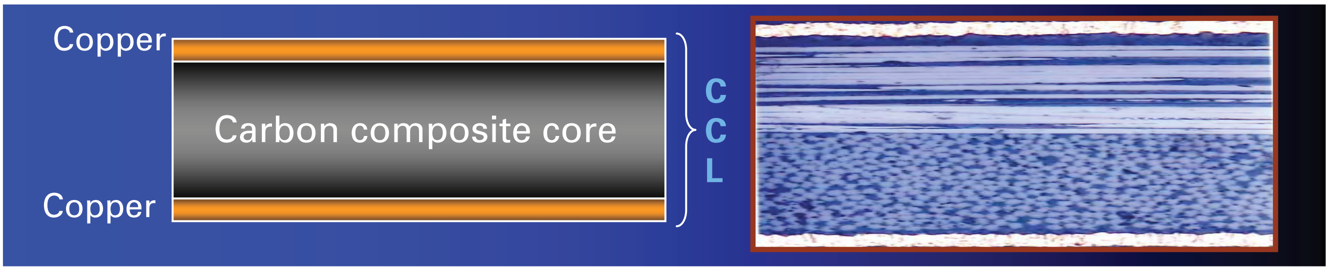


***Exhibit 3.12** Basic construction of Stablcor prepreg (courtesy Stablcor Inc)*

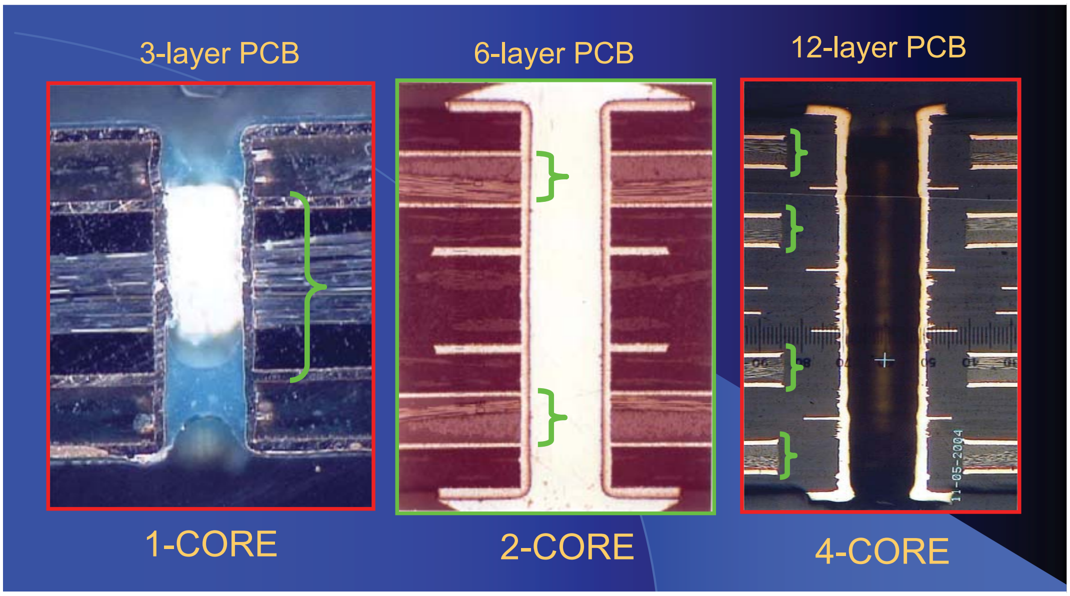


Exhibit 3.13 *Thermal vias for Stablcor material (courtesy Stablcor Inc)*

Exhibit 3.14 *Lay-up for PCBs using Stablcor material (courtesy Stablcor Inc)*

To obtain optimum performance the PCB lay-up must be carefully designed to give a balanced structure, otherwise the material can be processed in traditional fashion (Exhibit 3.14).

For a total thermal management solution a thermal path from the PCB into the chassis is required to provide the thermal sink. This can be achieved in traditional fashion using mounting screws or wedge locks, with ideally an electrical and thermal conduction path to the Stablcor prepreg; for this reason the use of Stablcor as a ground layer is recommended. The material also acts as a heat spreader because of its high thermal conductivity.

4 ACTIVE COOLING

The distinction between active and passive cooling can be difficult to define but for the purposes of the mission microchannel coolers (potential heat exchanger technology in active cooling systems), impingement jets, spray jets and Peltier coolers are active devices. An active cooling system requires energy input to drive the cooling system, and the coefficient of performance (COP) is a measure of its effectiveness:

$$COP = \frac{\text{Thermal power transferred}}{\text{External input power}}$$

Phase change in this context effectively means evaporative cooling. Other types of phase-change system useful in thermal management based on heat flows associated with melting waxes or complex salt hydrates are beyond this discussion.

Because heat transfer processes depend on so many variables it can be difficult to compare different processes at a fundamental level. An important study at Purdue University (International Electronic Cooling Alliance) has benchmarked different heat transfer process ranges under standardised conditions (Exhibit 4.1)

A phase-change system takes advantage of the phase change to dramatically improve the level of heat transfer that can be attained. However, heat fluxes from surfaces in contact with a liquid coolant are bounded by the tendency for vapour films to disrupt the contact with the liquid, as shown in Exhibit 4.2.

The critical heat flux (CHF) represents an instability – further increase in applied heat flux leads to a reduction in the heat transfer coefficient and hence to potentially catastrophic increase in the device temperature.

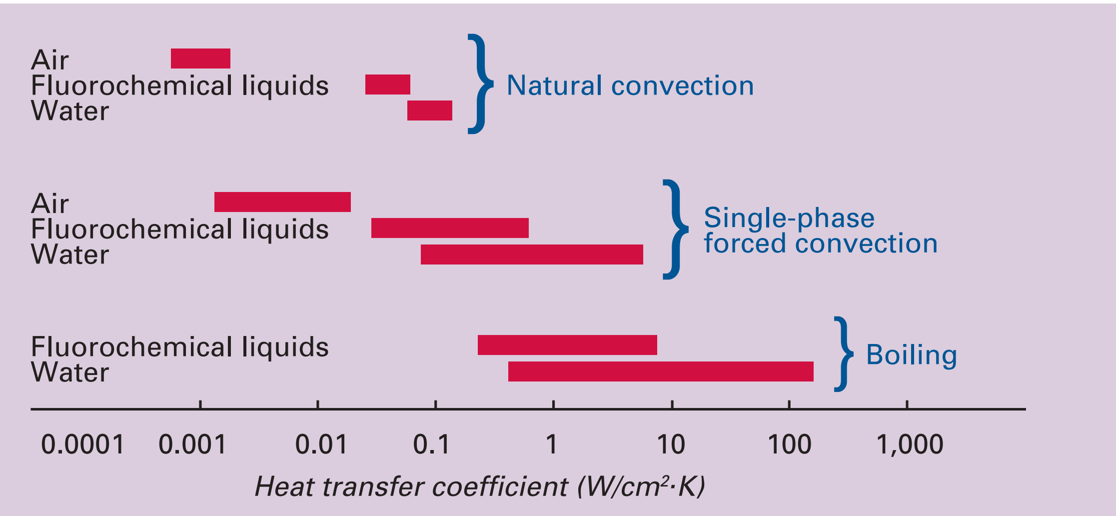


Exhibit 4.1 *Normal heat transfer ranges (courtesy Prof Issam Mudawar, School of Mechanical Engineering, Purdue University)*

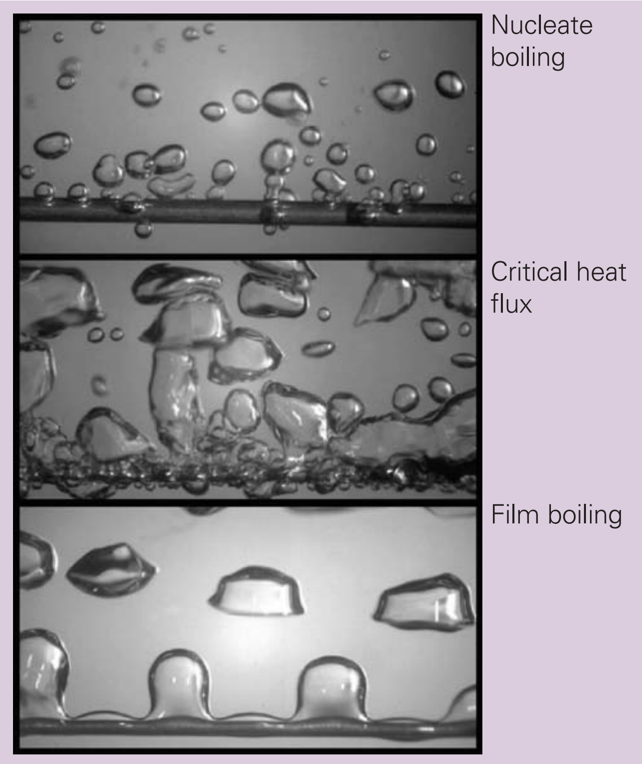


Exhibit 4.2 Different boiling conditions (courtesy Prof Issam Mudawar, School of Mechanical Engineering, Purdue University)

Two-phase systems must be engineered to avoid potential instability associated with the CHF and maintain the correct boiling conditions, often nucleate boiling. Much R&D effort has been invested in identifying configurations and techniques for increasing the CHF.

A single-phase system often needs higher fluid flow rates and subcooling to achieve the same degree of cooling which is available with two-phase cooling. High flow rates and subcooling are both undesirable as higher pressure drops and additional secondary cooling may be required.

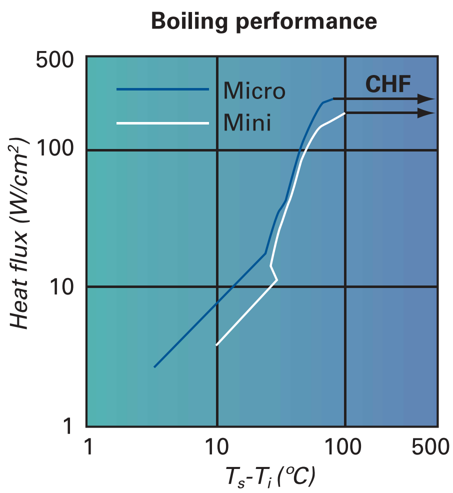
4.1 Microchannel devices

Purdue University has studied high (25-1,000 W/cm^2) and ultrahigh (1,000-100,000 W/cm^2) heat flux in regimes including pool boiling, falling film cooling, and micro- and minichannel boiling.

Indicators for different approaches are:

- CHF in channel flow boiling determined as 361 W/cm^2 (high coolant flow, high subcooling and surface enhancement)
- Ultrahigh CHF of 27,600 W/cm^2 demonstrated in high mass flow, high subcooling in microchannel cooling

Microchannel cooling is frequently used in cooling systems because combined large heat transfer areas and high CHFs lead to high total heat transfer capability. The penalty with microchannels (0.51 mm diameter) compared to minichannels (2.5 mm) is the high pressure drop (Exhibit 4.3).



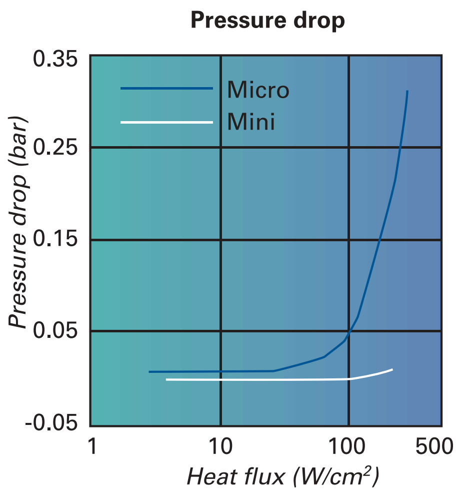


Exhibit 4.3 Performance of micro- and minichannel devices (courtesy Prof Issam Mudawar, School of Mechanical Engineering, Purdue University)

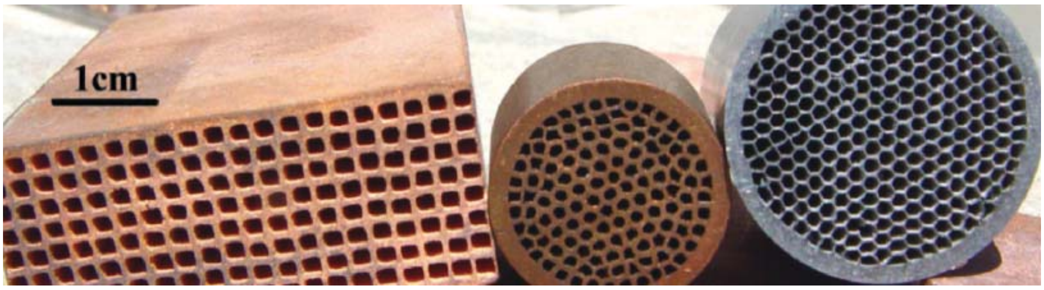


Exhibit 4.4 *Oriented microchannel devices (courtesy MER Corp)*

Devices

The difficulty to date has been the economic manufacture of microchannel devices and the limitation of planar production processes.

Commercial development of microchannel cooling is being undertaken by Cooligy Inc (Mountain View, California) but it was not possible to visit.

However, some technology of interest to micro- and minichannel devices was presented by MER Corp. It has developed a powder metallurgy extrusion process with polymer cores to form microchannel devices which may be an appropriate technology for various classes of heat exchangers. The extrusion process yields microchannel devices with oriented channels with size and shape which can be defined. Minimum wall thickness can be as low as 5-10 μm (Exhibit 4.4).

A variant of the extrusion process creates foams which can be used as the basis for heat exchangers and heat sinks in a wide range of metallic materials. Complex shapes can be formed using near net-shape approaches. If the device can be made of graphite it reduces the weight compared to aluminium or copper heat sinks, and with correct orientation of the graphite layers highly effective heat exchangers can be made.

The parts tabled at the meeting were convincing demonstrators of what can be achieved with this approach. It should be noted that this approach leads to the possibility of producing heat exchangers with integral manifolds.

4.2 Impingement jet and SprayCool

Higher heat fluxes can be attained using impingement jet and spray cooling. For systems utilising jet impingement cooling the effects of liquid velocity, droplet size, delivery

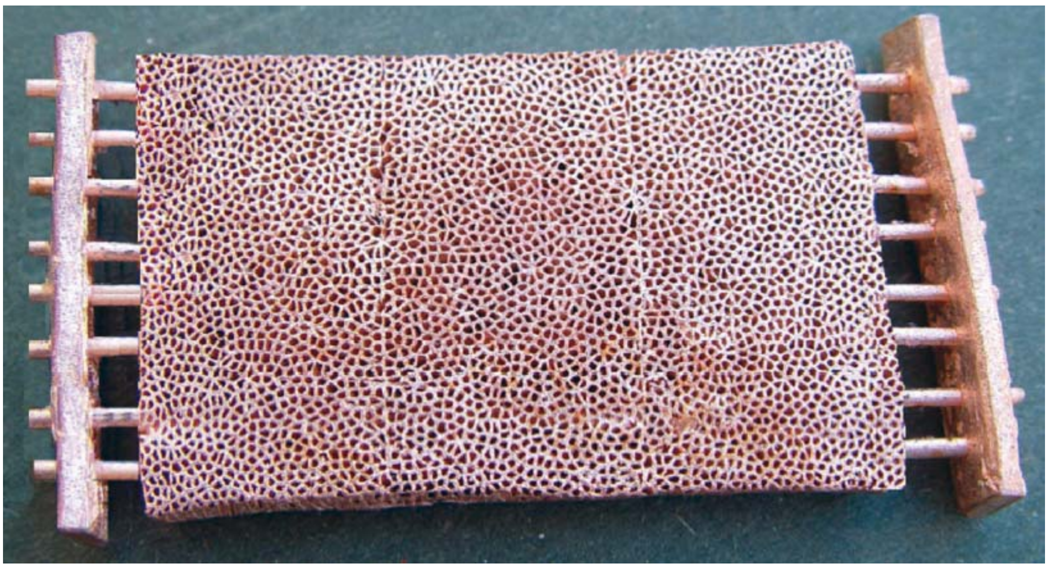


Exhibit 4.5 *Foamed heat exchanger (courtesy MER Corp)*

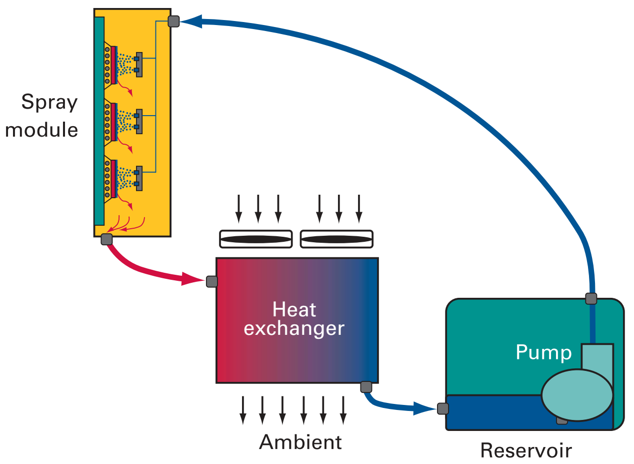


Exhibit 4.6 SprayCool system block diagram (courtesy ISR Inc)

rate and impingement angle on heat flux have been studied extensively by Purdue University.

SprayCool technology developed by ISR Inc uses a partial phase-change system. The technology has been developed for data centre servers and aerospace applications but is applicable to other fields as well. SprayCool's IP is the knowledge of an effective droplet distribution pattern. For effective cooling a fog is formed in the area needing cooling, and the fluid pumped to a remote heat exchanger (Exhibit 4.6).

Active cooling systems require heat exchangers, and microchannel devices provide an effective solution. Another alternative is nanochannel technology but this is unlikely to be used for fluid cooling systems because of the large pressure drop developed.

The formation of a fog allows a degree of cooling to take place around corners. The SprayCool approach requires less fluid than pool boiling. The effective cooling depends upon the droplet size, droplet impingement angle, droplet momentum, thickness of liquid-phase film, amount of splashing and heat flux (Exhibit 4.7).

Apart from the heat flux these parameters can be controlled by design for an optimum solution. The SprayCool system relies upon delivery of sufficient fluid to avoid boiling dry. The fluid and vapour removed is passed through a heat exchanger to remove heat to the external environment. The pressure difference between the high and low side is about 20 psi and the system pressure is set so that the liquid boils on contact with the components being cooled. In some cases warmed liquid is sprayed to ensure the most effective rate of heat removal. Typically the

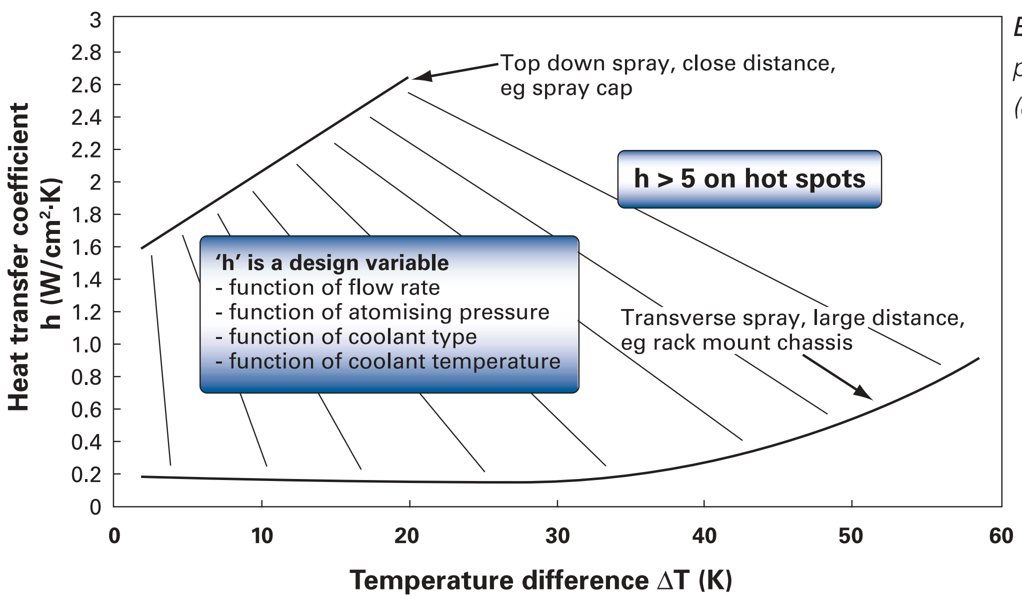


Exhibit 4.7 SprayCool performance envelope (courtesy ISR Inc)

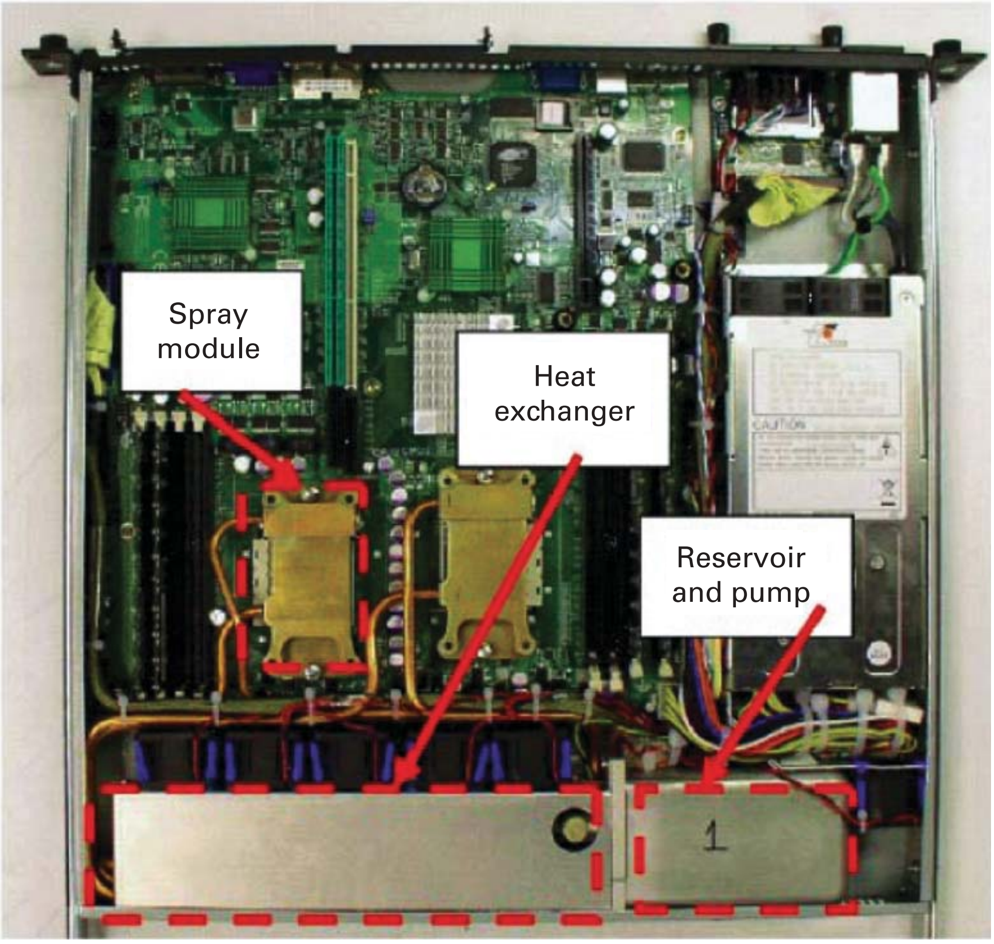


Exhibit 4.8 *Dual Opteron server fitted with SprayCool technology (courtesy ISR Inc)*

low side is pressurised between 0.5 and 1 atm.

The result is an effective cooling system that can yield an even temperature distribution and may be applied at the die or board level (Exhibit 4.8). A die-level approach is recommended as this reduces the number of thermal interfaces. At the board level the SprayCool technology can be retrofitted as a heat sink.

Any liquid with suitable properties may be used, and commonly used are the perfluorocarbons (PFCs) which do not damage bare die. The fluid also contains a little air or nitrogen to prevent cavitation. The system has been made to work from -70ºC to +120ºC with heat flux densities of 250 W/cm^2. The SprayCool system has been used in aerospace systems where alignment of system with gravity varies. The spray heads can dispense the droplets over a 60 degree cone angle with 15 to 25 µm droplet size and a range of 1/8 to 8 in. The pump stage is contained within the fluid to reduce sealing problems and lubricate the pump.

4.3 Microrefrigeration

UCB has been investigating the use of MEMS for thermal management, having developed a micro heat exchanger and microrefrigeration. COP > 2 has been achieved based on a MEMS technology with a Wankel engine capable of removing 50 W. A microchannel heat pipe structure using a two-phase system and a wicking structure to pull fluid back to the evaporator has been developed. MEMS has also been used for sensing inside the combustion zone. Purdue University is actively researching microrefrigeration units, which may involve alternative refrigeration cycles. Some of these microrefrigerators are achieving COP = 5. Purdue University has investigated the insertion of CNTs into cooling fluids to improve heat transfer but found it to be ineffective.

4.4 Advanced thermoelectric and thermionic devices

4.4.1 Peltier devices

While convective cooling technologies have seen some impressive progress recently, standard Peltier-type elements are still state-of-the-art in thermoelectric devices with well-known shortcomings such as low thermal efficiency and poor mechanical stability. However, Nextreme Thermal Solutions Inc has developed a new generation of devices with significantly enhanced performance.

Thermoelectric coolers (TECs) in active cooling technologies have traditionally suffered from a low COP. Nextreme's technology, based on thin-film technology, has improved COP which may offer a step change in the capacity of these devices but they are not yet available in volume supply, although this appears to be in the planning frame. Nextreme is also evaluating emerging thin-film device technology developed by NASA Jet Propulsion Laboratory (JPL) at California Institute of Technology (Caltech).

Nextreme's current technology is based on bismuth telluride thin-film superlattices.

Typical devices are 3 x 3 mm with thickness of ~100 μm. As heat pumps, the devices are characterised by load lines bounded by maximum cooling of 40ºC and a maximum heat flux of 175 W/cm^2. The maximum device efficiency is 4.5%. Conventional commercial TECs have much lower power density limits (~12 W/cm^2) but higher maximum cooling (65-70ºC). Nextreme devices indicate a clear advantage for cooling at higher local power densities. It should be noted that Laird Technologies has recently added Melcor TECs

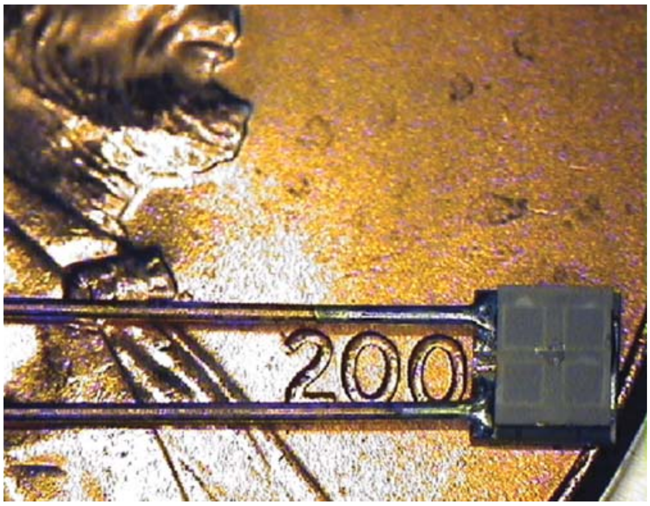


Exhibit 4.9 Embedded TEC (courtesy Nextreme Thermal Solutions Inc)

into its product portfolio and is developing new generations of TECs based on technology from Argonne National Laboratory (ANL), so further developments may be expected.

Nextreme's embedded TEC is illustrated in Exhibit 4.9.

Larger areas can be cooled by forming arrays of devices. The small size means a fast response to thermal transients. The devices have a range of current (few amps), heat flux (50-150 W/cm^2) and temperature differential (10-20 K) that yields the highest COP. COP is dependent upon the temperature differential.

The main application is seen as cooling hot spots on integrated circuit (IC) dies. Up to 14ºC local cooling of a hot spot was demonstrated (see Exhibit 1.3).

This technology is currently in low-rate prototype production and is suboptimal, with development work ongoing to optimise the devices.

The application of these devices for energy scavenging from waste heat is attracting much funding. Applications include energy recovery from automotive exhaust to reduce or possibly eliminate alternator loads, electrical power sources for wireless sensors and in implantable medical devices.

4.4.2 Thermionic devices

A number of new concepts based on thermionic emission are currently under investigation. These devices consist of two metallic plates which are separated by a gap of several micrometres. The surface on one side of the gap is processed in order to facilitate thermionic emission of electrons. While electrons are able to cross the gap between the plates there will be no exchange of phonons resulting in a much better separation between the hot and the cold electrode. With this technique theoretical Carnot efficiencies of up to 80% can be achieved compared to 6% for Peltier devices.

This approach is investigated by Cool Chips plc, a member of the Borealis Group. In its technology one of the surfaces in the gap is patterned with nanogrooves that correspond to the electron wavelength. This principle, called Avto metals, lowers the work function of the metal and improves electron emission at lower temperatures.

Another promising technology based on solid-state thermionic devices in which the vacuum gap is replaced by a semiconductor stucture is being developed by Eneco based in Salt Lake City. This is being evaluated for cooling of solid-state headlamps for the automotive industry and cooling of infrared imaging sensors.

There are a number of different approaches to improve thermionic emission of surfaces. Several groups including Professor Majumdar at UCB grow columns of CNTs on the inner surface of one of the electrodes. CNTs significantly enhance electron emission; however, Professor Majumdar pointed out that currently it is difficult to grow a sufficient density of CNTs that can provide enough current density to achieve satisfactory performance. He currently investigates a different approach where a very thin layer of benzene-like molecules, which has good electron but very low phonon conductivity, separates the electrodes.

Although the concepts of these technologies have been demonstrated none of them has yet produced a working device. However, considering the rapid advances in CNT and nanotechnology it is conceivable that the first working units will be reported in the near future. Also based on CNT, Professor Majumdar's group has only recently demonstrated the world's first thermal rectifier. Even though its efficiency is still within single figures this is an impressive achievement and will almost certainly trigger a strong research effort across the world.

4.5 Outlook

The view of the future was that there are unlikely to be quantum leaps in fluid cooling technology but there is scope for improvement in cooling capability through the clever merging of existing materials and cooling technology. One concern for all fluid cooling systems is the environmental impact of the coolants. Nextreme appears to lead the way in the implementation of new generation TECs but there is a strong possibility that some step changes in high-efficiency solid-state cooling will emerge if current technology developments can be scaled up.

5 THERMAL AND RELIABILITY MODELLING

Modelling and simulation tools are a key technology recognised by all companies visited during this mission. US organisations are using these technologies early in the design process to help understand the thermal performance of both passive and active cooling technologies and materials and the final reliability of the product.

The drivers for using modelling and simulation early in product design are cost, decreasing time to market, and the physical complexities of thermal trends in electronic systems. The advantage of adopting modelling early in the design process is to allow potential thermal problems to be identified before building physical prototypes, which will improve product quality and reliability, and speed time to market.

5.1 Modelling techniques

The last fifteen years has seen a significant growth in the use of computational fluid dynamics (CFD) and finite element analysis (FEA) tools within the electronics packaging community. During the mission a number of organisations detailed how they are using these tools to predict thermal and thermomechanical behaviour of materials and electronics-based products.

CFD technology has seen dramatic growth in the electronics thermal management sector. Particular products such as FLOTHERM from Flomerics (a UK company) and Fluent, now owned by ANSYS Inc, are being used by a number of organisations to model the flow of air and liquids in electronic cooling systems and the resultant device temperatures.

FEA tools that predict mechanical behaviour of electronic systems and in particular stresses due to temperature changes in the materials have also seen a dramatic rise in use in the electronics sector. Codes such as ANSYS and ABAQUS are particularly popular. These tools are used to predict the stress, strain and resulting damage in the materials that make up an electronic system and these values are then used to assess the reliability of the overall product.

Although modelling tools are very powerful and provide extremely useful insights into thermal management technologies they need to be used with care. In particular the materials data, boundary conditions and failure models provided by a design engineer as input to these codes need to be fully understood in terms of applicability. Exhibit 5.1 illustrates the requirements for the above modelling tools and what they predict in the context of thermal management and reliability.

In the USA groups such as the Center for Advanced Life Cycle Engineering (CALCE) at the University of Maryland and the Center for Power Electronics Systems (CPES) at Virginia Tech are particularly strong in the development and use of modelling as part of the physics-of-failure approach to electronic product reliability. Other organisations and academic institutions visited during the

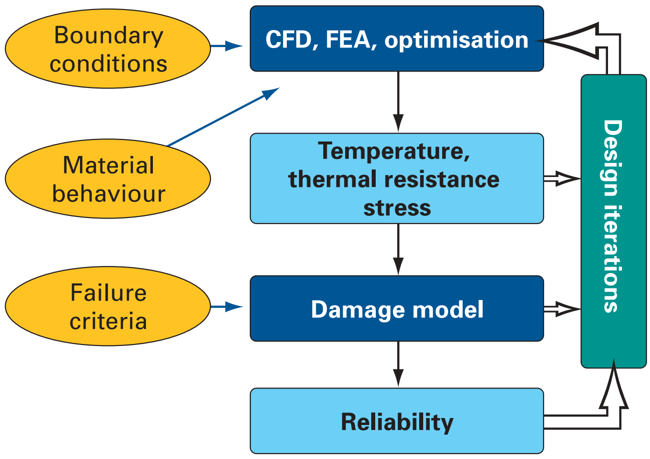


Exhibit 5.1 Thermal and reliability modelling in the design environment (courtesy Chris Bailey)

mission also demonstrated a strong awareness of modelling and many of these organisations use these tools.

Generally the UK is seen as a centre of excellence in developing and providing modelling and simulation tools with many of the novel developments originating in this country through companies such as Flomerics and academic institutions.

5.2 Thermal modelling

Both CFD and FEA are used extensively within the engineering sector to predict physical phenomena such as fluid flow, heat transfer, electromagnetic and mechanical stress.

For thermal analysis of electronic systems CFD tools will predict the governing heat transfer modes such as conduction, radiation and convection. Exhibit 5.2 illustrates these modes of heat transfer. For each mode of heat transfer the governing partial differential equations are solved using numerical techniques programmed into software tools such as FLOTHERM and Fluent.

For the thermal design engineer particular interest is in predicting the surface temperature of the die, which is known as the junction temperature ($T_{Junction}$) and also

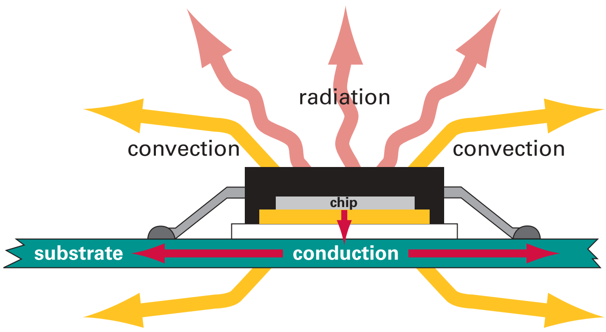


Exhibit 5.2 Modes of heat transfer (courtesy Chris Bailey)

calculating the heat removal paths and the thermal resistance for heat flow from the chip location to the ambient. The overall thermal resistance ($R_{Overall}$) in a package with a device at q watts is given by:

$$R_{Overall} = \frac{T_{Junction} - T_{Ambient}}{q}$$

This overall thermal resistance is made up of a combination of thermal resistances across each material in the whole package. Identifying how heat flows through the system and the locations of high thermal resistance throughout the electronic package enables thermal engineers to make design changes that will maximise heat removal and minimise junction temperature.

5.3 Reliability modelling

Reliability is defined as the probability that a device will perform its required function under stated conditions for a specific period of time. A reliability prediction estimates the reliability of an electronics module as used in the field. This depends on the design of the module and the in-service environmental conditions it is subjected to during its lifetime.

Many electronics module companies still adopt the MIL-217-F handbook reliability prediction methodology to calculate mean time between failure (MTBF). This calculation is based on individual failure rates for each component making up the device which are statistically obtained from field data. It is well documented that this technique can result in very poor predictions and in fact the technique is now not used by the US military due to its poor performance.

One relationship between junction temperature and semiconductor device reliability is the Arrhenius equation which can be used to estimate the failure rate, ß(T), as a function of processor temperature, T, where:

$$ß(T) = A\exp(-E/kT)$$

where A is a constant, k is the Boltzmann constant (8.16173 x 10^{-5}) and E is the activation energy.

If we consider the failure mode to be in the copper interconnect metallisation on the chip and the activation energy of the failure mechanism to be E = 1.0, then a rise in junction temperature from say T_1 = 80°C (353 K) to T_2 = 100°C (373 K) will result in an acceleration in failure rate of:

$$\frac{ß(T_2)}{ß(T_1)} = \exp[-(E/k)(\frac{1}{T_2} - \frac{1}{T_1})]$$

Clearly for the above failure mechanism the acceleration in failure rate by increasing the junction temperature by 20°C is an increase by a factor of six in this example. Of course not all failures can be modelled using the above expression as they are much more complex, and stress-related failure models are required.

The physics-of-failure approach to reliability combines mathematical modelling with accelerated life testing to predict the reliability of a product. This technique investigates the physics leading to a failure and identifies the root cause for that failure. Standards for reliability prediction can be summarised as shown in Exhibit 5.3.

Standard	Notes
MIL-217	Originates from US military standards Not used by US military since early 1990s
TELCORDIA	Originates from Bell Labs Similar approach to MIL-217-F
IEEE-1413	Guide in undertaken reliability prediction Includes physics-of-failure approach
JEDEC-148	Reliability qualification of semiconductor devices based on physics-of-failure and risk and opportunity assessment

Exhibit 5.3 *Standards for reliability prediction*

Exhibit 5.4 illustrates the physics-of-failure approach as adopted by many organisations in assessing reliability.

5.4 Modelling of passive cooling

Passive cooling technologies remove heat from the system primarily due to the high thermal conductivity of a particular material. The majority of companies the mission visited who are producing high thermal conductivity materials are using modelling to help

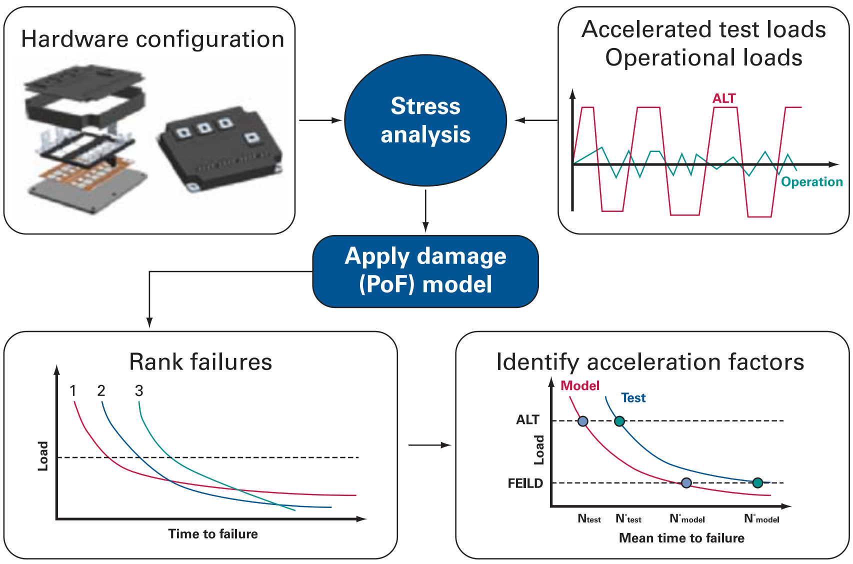


Exhibit 5.4 *Physics-of-failure (PoF) reliability methodology (courtesy Chris Bailey)*

Exhibit 5.5 Thermal modelling of heat spreader material (courtesy GrafTech International Ltd)

characterise the performance of the material both thermally and mechanically.

Exhibit 5.5 shows details from simulations undertaken at GrafTech International Ltd showing the performance of its heat spreader material eGraf (made with natural graphite materials) in consumer electronics products. In this example the use of the spreader material (with in-plane conductivity 400 W/m·K) helps reduce the localised temperature and this is clearly shown using thermal simulations. Clearly these results also support any marketing efforts for the material.

The challenge with modelling these high thermal conductivity materials is the lack of accurate temperature-dependent thermal and thermomechanical data to allow meaningful modelling of anisotropic or othotropic behaviours.

MER Corp also has an active modelling programme supporting its research efforts on producing composite structures of diamond and aluminium for applications in power electronic devices. Prediction of ideal composite thermal conductivity (K_c) as a function of particle volume fraction (f) and particle thermal conductivity (K_p) and matrix conductivity (K_m) is given by:

$$(1 - f)^3 = \frac{K_m}{K_c}\left[\frac{K_c - K_p}{K_m - K_p}\right]^3$$

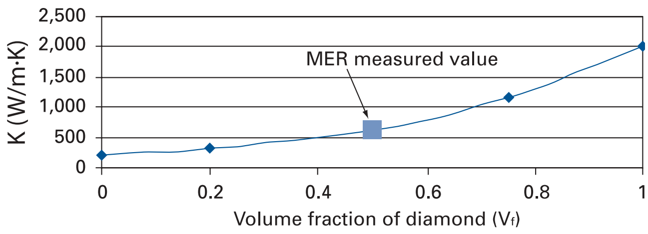


Exhibit 5.6 Predicted and measured thermal conductivity for diamond-aluminium composite (courtesy MER Corp)

Exhibit 5.6 compares predictions of thermal conductivity with experimental readings for a diamond-aluminium composite material. Clearly we can see good comparisons between model prediction and experimental readings.

Close collaboration is taking place between MER Corp and local universities such as Arizona State, Ohio and New Mexico that are providing support in the use of modelling. Working with Ohio University MER Corp has been able to characterise the performance of diamond-aluminium base plates for IGBT modules and to show that for their effective use there is a need for active liquid cooling or extended surfaces to increase the effective heat transfer coefficient to ensure a suitable and reliable junction temperature. Exhibit 5.7 illustrates the results from thermal modelling.

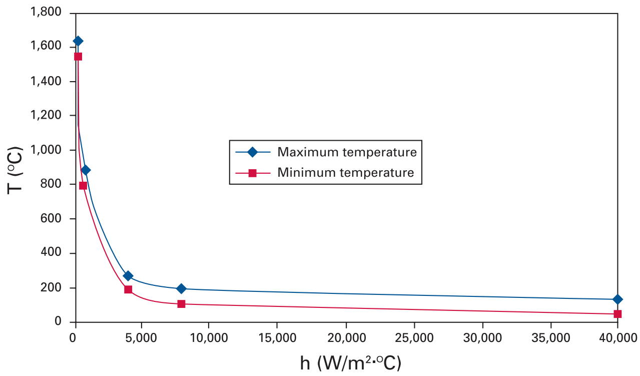


Exhibit 5.7 Junction temperature vs heat transfer coefficient for a flat plate (courtesy MER Corp)

As well as materials with high thermal conductivity other passive technologies such as thermosyphon loops, miniature heat pipes and high-performance heat sinks are being investigated for thermal management.

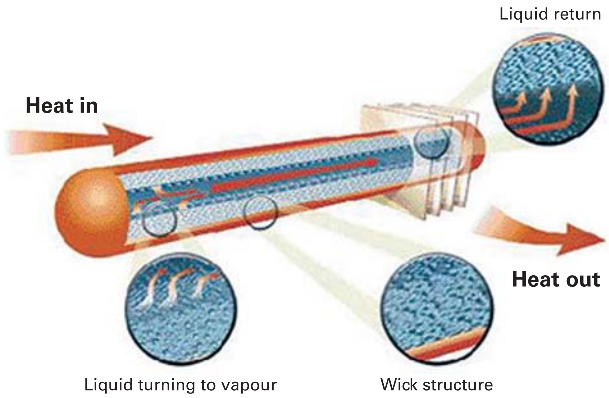


Exhibit 5.8 *Thermosyphon principle (courtesy Thermacore Europe Ltd)*

For thermosyphon loops and heat pipes CFD technology can again be used although the challenge is to capture the physics relating to phase-change mechanics and the important effect of this on heat transfer rates. Exhibit 5.8 illustrates the physics taking place in such a process.

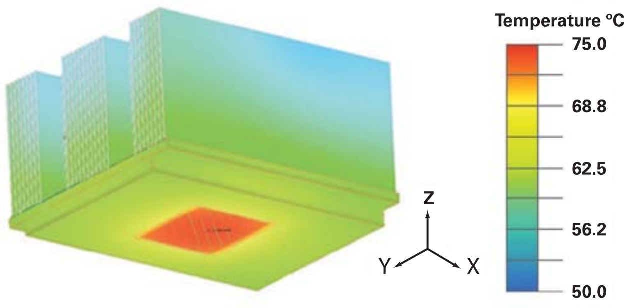


Exhibit 5.9 *Thermal modelling for heat sink design (courtesy GrafTech International Ltd)*

Using CFD to characterise heat sink performance is well established where it helps optimise fin thickness, spacing and base plate shape and size. Exhibit 5.9 illustrates typical CFD results for a heat sink design developed at GrafTech.

5.5 Modelling of active technologies

The most common form of active cooling is through forced air convection using fans. From a modelling perspective this process is well established and codes such as FLOTHERM and Fluent have a number of libraries for different fan types. One challenge for CFD modelling in this area is the use of models for low Reynolds number flows which are typically found in electronics cooling, although researchers in the UK and the USA are developing new models to better predict this type of flow.

Professor Garimella at Purdue University is working on novel research that could extend the use of air cooling by using technology that is known as ion wind. Modelling again has been used here to help understand this process.

As well as this the group at Purdue has been investigating many active cooling technologies including micropumps (Exhibit 5.10) where CFD is helping to understand micropump design in terms of the effect of

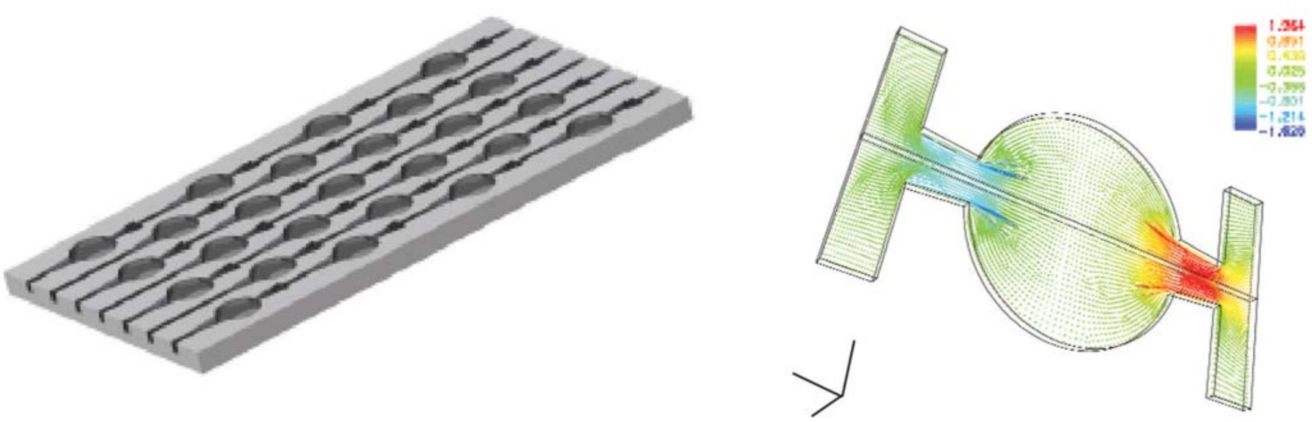


Exhibit 5.10 *CFD calculations for a micropump (courtesy Purdue University)*

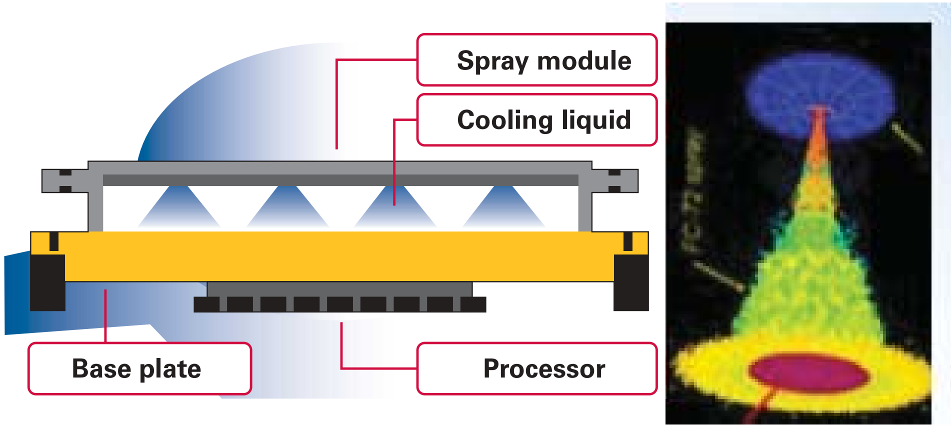


Exhibit 5.11 Modelling the spray cooling process (courtesy SprayCool)

flow rates on back pressures and heat transfer coefficients.

Microchannel flow is popular as it can disperse a lot of heat by using a small amount of fluid. Research at MER Corp is investigating nanochannels although the challenge is with pressure drops seen in these small channels.

Jet impingement and spray cooling are two other technologies that are being extensively researched in the USA. Jet impingement supplies a liquid coolant perpendicular to the cooling surface. It can accommodate critical heat fluxes up to 300 W/cm^2 and beyond depending on the fluid used. Spray cooling is seen as a competitor to jet impingement cooling and there is lots of interest in this technology in the US Air Force (USAF). Spray cooling atomises the fluid, forming a 'coolant mist' which contacts the high temperature items. SprayCool Systems from ISR Inc is a leader in this technology and uses CFD modelling extensively to help understand this complex process.

Modelling the spray cooling process (Exhibit 5.11) is particularly challenging as it involves modelling the atomisation process, collision and coalescence of liquid particles, and vaporisation on the cooling surface. This is a hot topic for future modelling research as models are required to help optimise this process.

Thermoelectric coolers (TECs) or Peltier devices act as heat pumps by force-conducting heat from a hot to a cold plate. TECs are solid-state devices which generate electrical power from a temperature gradient (known as the Seebeck effect) and converting electrical power into a temperature gradient (known as the Peltier effect). Many CFD codes such as FLOTHERM have routines for modelling the effect of these devices.

5.6 Integrated modelling

Integrated modelling and co-design are strong emphasised requirements in many of the industry roadmaps. In particular, organisations are interested in co-simulation tools that enable thermal, mechanical, electrical and acoustic analysis to be undertaken at the same time. Within the commercial modelling community particular trends are taking place:

- Co-simulation or multiphysics analysis tools
- Integrated with numerical optimisation
- Closely integrated with electronic computer-aided design (ECAD) and mechanical computer-aided design (MCAD)

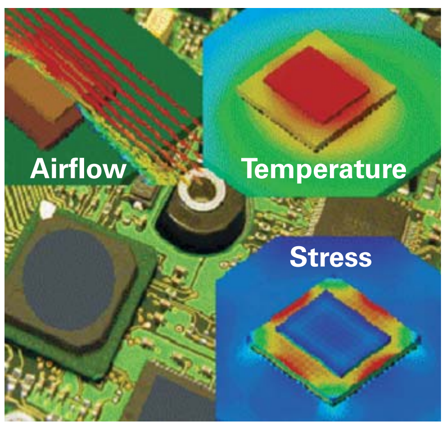


Exhibit 5.12 Co-simulation or multiphysics modelling (courtesy Chris Bailey)

Another particular area of integrated modelling is the use of models with sensor data for prognostics and diagnostics. This is a central theme of work under way at the University of Maryland (CALCE) and is also now taking place in the UK (eg Greenwich, Nottingham and Loughborough Universities).

In general for reliability there are concerns about current accelerated life tests based on particular standards and the relationship between failures observed in these tests for current thermal management technologies and what would be seen in the field. The physics-of-failure approach with other techniques such as failure mode and effect analysis (FMEA) is seen as the correct way to predict and characterise reliability.

5.7 Metrology to support modelling

There is an urgent requirement for good metrology to support the needs of modelling. Much of the IP developed by companies that use modelling is the data they have developed for use in the models. This data can be in the form of thermophysical input data or most importantly failure models for reliability estimation.

Further research in test procedures and standards for measuring the high thermal conductivities for passive cooling technologies is required as there seems to be much debate as to the accuracy of the current methods.

Techniques to measure the critical heat fluxes and heat transfer coefficients for active cooling technologies is required. Also the relationship between stress and failures in electronic materials and associated acceleration factors need to be better characterised – especially for new materials that have been adopted to satisfy environmental legislation such as the Restriction of Hazardous Substances (RoHS) directive.

5.8 Outlook

Thermal and reliability modelling is used by many organisations both large and small. This was in evidence during the mission with companies using modelling to characterise both materials and processes at the very early design stage. Current modelling tools have advanced tremendously over the last fifteen years. Future challenges for these codes will be to capture more accurately the complex physics taking place, especially for active cooling technologies (ie spray cooling), and to represent the effect of these cooling technologies at system level.

At present many of the modelling codes are developing and providing multiphysics or co-simulation analysis capabilities. Another trend being addressed by code vendors is the integration of analysis within computer-aided design (CAD) which provides greater productivity in the design process. In future, code vendors will provide users with co-simulation tools closely integrated within CAD environments.

The accuracy of these simulation codes will only be as good as the input data used. There is a requirement for metrology research to produce measurement techniques and standards that will gather the input data required for thermal and reliability analysis.

6 US RESEARCH SUPPORT MECHANISMS

Many of the organisations visited by the mission have obtained support through the National Science Foundation (NSF) and/or the Small Business Innovation Research (SBIR) or Small Business Technology Transfer (SSTR) programmes. These funds are worth $1 billion (~£510 million) a year and many innovations are supported to market in this way. In fact a number of small research-focused companies survive on these grants.

A number of organisations feel there is a skills gap between the ability of students to use modelling tools, understand the problem in hand, and effective application of modelling tools. This is a similar situation as in the UK that needs to be addressed within engineering courses both at graduate and postgraduate level.

All of the companies visited during the mission have close collaboration with universities both locally and nationally in the USA. This collaboration is supporting the companies' research efforts with the universities and companies supported through NSF and government organisations such as DOE and DoD.

At present there is no particular knowledge transfer network in the USA for thermal management research and advances. Most researchers will meet at relevant conferences such as:

- ITherm[20] – held every two years and co-located with the Electronic Components and Technology Conference (ECTC)
- SEMI-THERM[21] – held yearly in San Jose, California
- InterPACK[22] – held every two years
- THERMES[23]

Although the UK does not have any particular network focused on thermal management it does have a number of networks that include thermal management research for electronic systems. For example the Innovative Electronics Manufacturing Research Centre (IeMRC)[24] managed from Loughborough University and Knowledge Transfer Networks (KTNs) such as Materials,[25] Electronics-Enabled Products[26] and Electronics.[27]

In addition to the standard academic journals the top magazine for thermal management information in the USA is ElectronicsCooling.[28]

20 www.itherm.org
21 www.semi-therm.org
22 www.interpackconference.org
23 www.engconfintl.org/7ac.html
24 www.lboro.ac.uk/research/iemrc
25 http://amf.globalwatchonline.com
26 www.electronicproductsktn.org.uk
27 www.ktnetworks.co.uk/epicentric_portal/site/KTN/menuitem.c79fcc3b7c99ea823a8a9443ebd001a0
28 www.electronics-cooling.com

7 KEY FINDINGS AND RECOMMENDATIONS

7.1 Key findings

- The main failure mechanisms for electronics are still thermally induced and future performance will continue to be limited by thermal management.

- The significance of the field is matched by the level of activity in developing thermal management solutions in a range of materials and technologies by large companies and SMEs.

- Developments of sophisticated cooling technologies are being driven by high heat flux applications, particularly in military applications, but these are spreading out into commercial applications.

- The development of active solders by S-Bond for direct bonding of dissimilar materials without metallisation or flux assistance is significant and should be considered by UK companies.

- Carbon materials are taking their place in thermal management systems. Performance-cost is clustered around high performance, high cost and lower performance, lower cost systems. Strength and toughness may constrain market penetration in some areas.

- The USA is actively pursuing composite technologies based on combining both diamond and highly conductive carbon fibres with metal matrix. Techniques for engineering interfaces are advanced and the reducing costs of diamond and carbon fibres are making these materials more affordable. However, implementation of diamond composites remains difficult.

- There has been a greater uptake of active cooling in the USA compared with the UK as some application requirements outstrip the capability of passive cooling.

- It is apparent that modelling is being used in increasingly sophisticated ways. Thermal modelling at the device level is being complemented by system-level simulations. Co-simulation that integrates thermal, electromagnetic and mechanical analysis is also a strong requirement of users and being addressed by code vendors. The power of modelling has been recognised in a marketing context.

- Levels of investment remain high and support mechanisms for small business provide continuity and allow effective early-stage growth.

7.2 Recommendations

- The UK thermal management industry will be strengthened if a focus or network is established to bring together and coordinate its competences in materials, modelling, metrology, design and prototype build.

- Increased industry awareness of advanced materials and active cooling technologies is needed to cultivate best practice and encourage technology developments in the field.

- The USA leads in a range of materials but UK capabilities remain strong in some areas. There are still opportunities in the UK for materials development which can build on this based around sophisticated and optimised combinations of materials and interfaces.

- The thermal management industry in the UK should build on its modelling and design capability to create integrated solutions for system-level optimisation. This may extend the range of passive solutions which are preferred where possible.

- Modelling for active cooling technologies needs further research, in particular spray cooling and jet impingement. How these package level models are then used at system level needs to be characterised. Using modelling and sensors within a prognostics and diagnostics context to monitor in-service behaviour of thermal management technologies should also be an important area of future research.

- Cost implications of thermal management choices should be be evaluated at system level in order to assess overal impact of thermal management design choices. Signposting is needed in order to ensure that industry can access these services.

- Standards and metrology issues impact everything in the industry. Manufacturers' data are frequently incomplete and this degrades the value and benefits available from simulation and modelling. There is an opportunity for the UK to build on its competences in thermal and mechanical metrology in order to consolidate and develop its capability in design and simulation.

Appendix A

HOST ORGANISATIONS

S-Bond Technologies LLC

Momentive Performance Materials Inc

Laird Technologies – Thermal

GrafTech International Ltd

Applied Sciences Inc

Purdue University – CTRC

Purdue University – BTPFL/PUIECA

MER Corp

JW Composites LLC

University of California, Berkeley (UCB) – BNNI

University of California, Berkeley (UCB) – BSAC

SprayCool

Stablcor Inc

Nextreme Thermal Solutions Inc

Profiles of the host organisations are given on the following pages

S-Bond Technologies LLC

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S-Bond products are used to join metals, ceramics, glasses, and carbon materials like diamond and graphite. Its expertise in active solder technology has led to the development of a range of solutions allowing the cost-effective assembly of unique combinations of materials without plating and fluxes. Examples include copper to aluminium and graphite to aluminium for thermal management systems, sapphire to metal for lightweight sensor assemblies, and silicon carbide to titanium and other metals for lightweight armour and wear-resistant surfaces. The company also offers design-for-manufacturing review, prototyping and ‘make complete’ services based on its experience and that of its Service Provider Network.

Active solder technology was first developed in the late 1990s as a technique to join metals without using flux. The technology continued to be developed and refined by Materials Resources International (MRi) until 2002, when S-Bond was spun off as a separate company. Since then the company has focused on creating specific joining and assembly solutions for the electronics, defence, aerospace and general industrial markets. S-Bond products are used today in thermal management systems, sensor assemblies, and other applications where good bond strength, high thermal and electrical conductivity and a reduced environmental impact are important.

Momentive Performance Materials Inc

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www.momentive.com

Momentive Performance Materials was formed by joining units previously part of GE Advanced Materials, Bayer and Toshiba.

Its main products include HOPG, TC1050 and boron nitride powders for its PolarTherm product to create a group of strong thermal management interests aimed at more effective passive heat dissipation technologies. TC1050 composites are metal-clad versions of material which allows integration of TPG into structures. TC1050 technology is subject to export control whereas supply of HOPG itself is not.

Laird Technologies – Thermal

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rhill@lairdtech.com
www.lairdtech.com

Laird Technologies is a subsidiary of the British owned Laird PLC group.

The company has diverse interests in thermal management products – gap fillers, thermal interface and phase change materials, thermal greases, thermally conductive circuit boards and thermally conductive interface materials.

Laird acquired Melcor (Peltier thermoelectric device) in 2005.

GrafTech International Ltd

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www.graftech.com

GrafTech is a large industrial group with approximately 4,000 employees worldwide centred on carbon and graphite materials science.

The fit between its flexible natural graphite product and the needs of the electronics thermal management industry has led to the eGRAF product portfolio (www.graftechaet.com/Home/Brands/eGRAF.aspx) which is particularly well adapted to meeting thermal management demands in commodity products.

The electronics thermal management product range is part of a larger portfolio including other technical graphite products.

Applied Sciences Inc

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Applied Sciences Inc (ASI) is an R&D company specialising in advanced materials and their applications which has been developing advanced carbon-carbon composites using both vapour-grown carbon nanofibres and pitch-fibre fabric reinforcements, achieving high performance levels. Main products include Pyrograf nanofibre and Black Ice hyperconductive diamond/carbon/carbon composite.

Nanographite Materials (NGM) is a joint venture (JV) between ASI and the Japanese GSI Creos Corp which focuses on developing both metal and carbon-matrix composites of Pyrograf fibres.

Purdue University – CTRC

Contact: Prof Suresh Garimella
Goodson Professor of Mechanical Engineering and Director, CTRC

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Purdue hosts the NSF Compact, High-Performance Cooling Technologies Research Center (CTRC). This was established to address the needs of its industry members in the area of high-performance heat removal from compact spaces. Members include Aavid Thermalloy, Apple, Delphi Electronics and Safety, Denso, GrafTech, Honeywell, Eaton, Intel, Modine Manufacturing, Nanoconduction, Nokia, Rockwell Collins, Samsung, Sandia National Labs, Sony and Sterling PCU.

CTRC is a designated NSF Industry/University Cooperative Research Center (I/UCRC) which addresses the R&D needs of a diverse industrial community through member-directed investigations with a product-oriented focus.

Purdue University – BTPFL/PUIECA

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Professor of Mechanical Engineering

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Mudawar Thermal Systems Inc
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USA

Purdue University also hosts the Boiling and Two-Phase Flow Laboratory (BTPFL) and the Purdue University International Electronic Cooling Alliance (PUIECA) directed by Professor Issam Mudawar which addresses a wide range of single and two phase cooling approaches with a focus on systems for and fundamentals of high and extreme heat flux thermal management, notably liquid jet impingement jet cooling and spray cooling.

Also of notable interest is the Thermal Design Innovation Initiative (TDII) allowing companies a fast track to thermal management solutions.

MER Corp

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Materials and Electrochemical Research Corporation (MER Corp) is devoted to high-technology materials and electrochemical R&D with an emphasis on advanced composites, coatings, nanotubes and near net-shape metals/alloys as well as energy conversion systems including batteries, fuel cells and gas storage. MER was started in 1985 with SBIR contract funding and subsequently developed and commercialised aluminium nitride ceramics.

MER has a JV with Mitsubishi focusing on fullerene/nanotube application development and production. MER R&D frequently involves collaboration with major universities and international corporations, seeking opportunities to commercialise and innovate in advanced material technologies.

JW Composites LLC

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USA

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JW Composites LLC specialises in advanced coatings and composite materials. Refractory metal and metal carbide coatings allow molten metals to wet and bond to a variety of ceramic surfaces including graphite fibre, graphite foam, diamond and cubic boron nitride.

Based upon research spanning 20 years with funding support from DOE, NASA, NSF and the US Navy, JW has used this to allow pressureless infiltration of a wide range of graphitic materials as well as bonding and infiltrating diamond which is used to support the mainstream business of Molybond diamond and cubic boron nitride products.

JW is co-located with Quality Plating in Salt Lake City to allow supply of composites with metallisation for integration.

University of California, Berkeley (UCB) – BNNI

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The Berkeley Nanosciences and Nanoengineering Institute (BNNI) directed by Professor Arun Majumdar has been researching novel interface materials based on dense nanotube arrays. The technology is available to license through Atlas Scientific which also has interests in cryocoolers (room temperature down to 50 mK) and rare-earth based regenerative heat exchangers.

University of California, Berkeley (UCB) – BSAC

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Berkeley Sensor and Actuater Center (BSAC) – the NSF I/UCRC for microsensors and microactuators – is developing various MEMS-based devices for advanced thermal management including microcapillary pumped loop (micro-CPL) for chip cooling for cooling power transistors (300 W/cm^2) and miniature refrigeration loops based on Wankel compressors returning COP of 0.5.

SprayCool

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Managing Director

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SprayCool is a system solution from ISR Inc which was founded in 1988 with an SBIR programme award from the Air Force Research Laboratory and is now operating out of six locations in the USA with over 270 employees.

SprayCool continues to benefit from many US Government agencies and now operates in commercial as well as defence systems.

Stablcor Inc

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Stablcor is a carbon-carbon composite laminate material bonded to copper foil sheets, principally intended for the PCB industry. The properties available include low CTE, high in-plane conductivity (75-250 W/m·K) and high stiffness (11-40 MSI) and low density (1.65-1.7 g/cm^3).

Stablcor sheets bonded into a PCB stack can impart controlled CTE, improve heat dissipation and suppress low-frequency resonance in the board – all of which can improve reliability. Compared with other PCB core options, such as copper-moly-copper or copper-invar-copper, density is also much lower, which is important for weight-critical applications. CTE control is also improved which is required for particular applications.

The mission was unable to visit Stablcor but participated in an internet conference in order to assess developments in this area.

Nextreme Thermal Solutions Inc

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Nextreme Thermal Solutions is developing advanced thermoelectric devices based on thin-film superlattice Peltier device technology initially demonstrated by RTI International.

Nextreme develops, manufactures and markets embedded thermoelectric components for cooling ICs, precise temperature control and power generation applications.

These devices have performance indices which are markedly improved compared to industry standard devices currently available. Applications for heat pumping are now being commercially funded whereas applications for energy harvesting are being funded by government.

Nextreme, which currently has 30 employees, was founded in December 2004 with $8 million (~£4.1 million) Series A venture financing as a spin-off from RTI International which had developed the superlattice thin-film technology over the previous 10 years.

Appendix B

MISSION PARTICIPANTS

Dr Robin Young
Mission Leader
Faraday Advance and Materials KTN

Prof Chris Bailey
University of Greenwich

Dr Thomas Starke
Rolls-Royce plc

Dr Chris Stirling
Morgan Carbon

Dr Mark Harrington
Smiths Aerospace

Dr Paul Cooper
Radstone Technology

Dr Norman Stockham
TWI Ltd

Dr Chris Beck
DTI Global Watch Service

Profiles of the participants are given on the following pages

FARADAY ADVANCE

Dr Robin Young – *Mission Leader*
Technology Translator
Faraday Advance and Materials KTN

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www.faraday-advance.net

Faraday Advance is the Knowledge Transfer Network (KTN) which supports future materials for low pollution, high efficiency, and cost-effective transport. Key outputs include increasing the impact of science on business, building teams to meet industry needs, technology road-mapping, and engaging industry in science and engineering.

Robin is interested in the following areas for collaboration:

- Reliability and stability of thermal management techniques
- Packaging issues in advanced thermal management
- Interface and bonding technologies for low thermal resistance
- Metrologies to support modelling activities

the UNIVERSITY of GREENWICH

Prof Chris Bailey
Director of the Computational Mechanics and Reliability Group
University of Greenwich

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www.gre.ac.uk

Chris is Professor of Computational Mechanics and Reliability at the University of Greenwich, London. His research group focuses on the development of virtual prototyping tools based on multiphysics modelling and numerical optimisation.

Funded through the EPSRC, DTI and the European Commission (EC), his group collaborates closely with industry developing and using software tools for thermal design and reliability predictions of electronic and photonic devices. Example applications include power electronic modules, system-in-package (SiP) devices, vertical-cavity surface-emitting laser (VCSEL) optical packages plus many others.

Chris is a committee member of the International Microelectronics and Packaging Society (IMAPS) and the Innovative Electronics Manufacturing Research Centre in the UK. He was the Programme Chair for the Institute of Electrical and Electronics Engineers (IEEE) Electronics System-Integration Technology Conference held in Dresden, Germany in 2006 and is the local organiser of the IEEE EuroSimE conference to be held in London in 2007.

Chris is interested in the following areas for collaboration:

- Multiphysics and multiscale modelling for thermal design
- Micro-/nanoengineered thermal management structures
- Reliability prediction methodologies
- Active cooling technologies
- Teaching material for thermal design and modelling

Rolls-Royce

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Materials Specialist for the Strategic Research Centre
Rolls-Royce plc

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Rolls-Royce is the world-leading provider of power systems and services for use on land, at sea and in the air and operates in four global markets – civil aerospace, defence aerospace, marine and energy. Rolls-Royce has a broad customer base comprising 600 airlines, 4,000 corporate and utility aircraft and helicopter operators, 160 armed forces and more than 2,000 marine customers, including 70 navies.

Tom is interested in the following areas for collaboration:

- High-temperature electrical components including electrical machines, wires, capacitors and thermal management systems
- New technology based on nanomaterials
- Power semiconductors and packaging

Morgan Carbon
A DIVISION OF MORGAN CRUCIBLE

Dr Chris Stirling
Technical Support Manager
Morgan Carbon

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Morgan Carbon is a division of Morgan Crucible Company plc, a UK-based global company that supplies a broad range of carbon and ceramic products used in a wide spectrum of applications from transport and telecommunications to fire protection and medical instruments. Morgan Carbon manufactures carbons, carbides and related products for diverse electrical, mechanical, tribological and thermal applications in markets ranging from industrial traction to semiconductor processing, and from armour to diamond synthesis.

Chris is interested in the following areas for collaboration:

- High thermal conductivity carbon-based composites (thermally isotropic and anisotropic materials)
- Incorporation of high-conductivity carbon materials in thermal management structures and devices
- Cost-effective engineered solutions and performance demonstration

smiths aerospace
bringing technology to life

Dr Mark Harrington
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Smiths Aerospace is a leading global provider of innovative solutions to builders and operators of military and civil aircraft and engines, from large transport to fighters and unmanned air vehicles, from helicopters to regional and business jets. The solutions are systems comprising electronics, mechanical hardware and software. Smiths Aerospace uses its unique range of specialisations essential to create affordable integrated aerospace systems, critical to aircraft performance, through itspertise in digital, electrical power and mechanical systems. All of its capabilities are backed by a global customer services organisation providing tailored integrated support solutions.

Mark is interested in the following areas for collaboration:

- Techniques and technologies for cooling complex aircraft electrical electromechanical and electronic systems
- Thermal models of avionic equipment
- Health management of aircraft systems

RADSTONE TECHNOLOGY

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Radstone Technology designs high performance, rugged embedded computer subsystems and support software for harsh environment applications. The company provides a broad product offering to customers in the radar, sonar, communications, signal intelligence, real-time image processing and video tracking markets.

Paul is interested in the following areas for collaboration:

- Thermomechanical reliability of electronic systems
- Thermal interface technologies
- Carbon-based thermal materials
- Liquid cooling technologies
- Thermal, mechanical and chemical harsh environment protection
- Thermal test methodologies

Dr Norman Stockham
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TWI is one of the world's foremost independent research and technology organisations (RTOs), specialising in materials, assembly and associated technologies. From its headquarters in Cambridge, UK and 16 bases worldwide it supports 3,500 companies in 75 countries.

TWI provides companies with a wide range of technical and support services including: product design, material and process selection, assessment of manufacturing systems, production line troubleshooting, technology transfer and staff training.

TWI has been assisting companies to develop electronic, photonic and sensor based products for over 40 years. It brings a unique multidisciplinary skill base encompassing a wide knowledge of device and board level electronics, linked to a broad understanding of materials, modelling and simulation, testing, inspection and failure analysis.

Norman is interested in the following areas for collaboration:

- Advanced thermal management technologies
- Low thermal impedance bonding materials and technologies
- Nanotechnology-based thermal management materials
- Validation techniques for thermal modelling
- High-temperature materials and interconnection systems
- Health monitoring sensors

dti

Dr Chris Beck
International Technology Promoter – Performance Engineering and Materials
DTI Global Watch Service

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As one of the DTI International Technology Promoters (ITPs) for Performance Engineering and Materials, Chris concentrates his efforts throughout North America, helping to create partnerships between UK and US organisations and identifying new technologies or collaboration opportunities.

Previously Chris worked as a Senior Project Leader in the microtechnology department at TWI. Prior to joining TWI Chris managed the process development and automation team at Marconi Caswell where he focused on the manufacture of telecommunications equipment. This involved extensive travel to the USA and Canada to work with companies on materials and assembly-related projects and helped to forge new business relationships.

Chris gained a PhD from the University of Leeds. He is a Chartered Engineer and a member of the Institute of Materials.

Appendix C

MATERIALS DATA

Material	Direction	An/isotropic	Thermal conductivity (W/m·K)	CTE (ppm/K)
Silicon		Isotropic	150	2.5
Alumina		Isotropic	20	6.7
Copper		Isotropic	400	17
Aluminium		Isotropic	230	23
'Kovar'		Isotropic	17	5.9
Pyro graphite		Isotropic	1,700	-1
Diamond		Isotropic	1,300	2
Diamond		Isotropic	2,000	2
CuW		Isotropic	167	6.5
CuMo		Isotropic	184	7
E-glass fibres epoxy		Isotropic	0.16	11
E-glass fibres epoxy		Isotropic	0.16	20
Invar silver		Isotropic	153	6.5
C-fibres epoxy		Isotropic	330	-1.1
C-fibres copper		Isotropic	400	0
Short C fibres Al		Isotropic	185	6
Short fibres polymer		Isotropic	20	4
Short fibres polymer		Isotropic	330	7
C-fibres carbon		Isotropic	400	-1
Si Al		Isotropic	126	6.5
Si Al		Isotropic	160	13.5
SiC Al		Isotropic	170	6.2
SiC Al		Isotropic	220	16.2
Graphite fibre, aluminium		Isotropic	400	4.5
Graphite fibre, aluminium		Isotropic	600	5
Diamond aluminium		Isotropic	550	7
Diamond aluminium		Isotropic	600	7.5
Beryllium		Isotropic	240	6.1
Boron nitride		Isotropic	1,300	3.8
Silicon carbide		Isotropic	270	4.3
Aluminium nitride		Isotropic	150	2.7
Betyllia		Isotropic	215	3.4
Cordierite		Isotropic	2.5	2.5
Mullite		Isotropic	6.7	4
Gallium arsenide		Isotropic	0.5	6
FR4/e-glass		Isotropic	0.35	5.5
PTFE ceramic		Isotropic	0.55	17
Stablcor xy	xy	Anisotropic	75	1
Stablcor xy	xy	Anisotropic	250	5
Stablcor	z	Anisotropic	75	1
Polymide		Isotropic	0.3	17
Graphmet 350 (Al) xy	xy	Anisotropic	229	6
Graphmet 350 (Al) z	z	Anisotropic	359	6
MetGRAF 7-200 (Al) xy	xy	Anisotropic	200	7
MetGRAF 7-200 (Al) z	z	Anisotropic	125	24
MetGRAF 4-230 (Al) xy	xy	Anisotropic	230	4
MetGRAF 4-230 (Al) z	z	Anisotropic	120	24
MetGRAF 7-300 (Cu) xy	xy	Anisotropic	287	7
MetGRAF 7-300 (Cu) z	z	Anisotropic	225	16
Copper - C fibre xy	xy	Anisotropic	400	2
Copper - C fibre z	z	Anisotropic	200	10
C-foam - copper		Isotropic	342	7.4
AlSiC-9		Isotropic	200	8

For additional data see *Thermal Materials Solve Power Electronics Challenges,* Carl Zweben, Power Electronics Technology, February 2006

Appendix D

LIST OF EXHIBITS

Appendix E

GLOSSARY

~	approximately
≈	approximately equal to
<	less than
>	greater than
%	per cent
£	pound sterling (£1 ≈ $1.97, Jan 07)
$	US dollar ($1 ≈ £0.51, Jan 07)
ß	failure rate
ΔT	temperature difference
Ω	ohm – unit of electric resistance = 1 V/A
μin	micro-inch = 10^{-6} in = 25.4 x 10^{-9} m
μm	micrometre = 10^{-6} m
μΩ	micro-ohm = 10^{-6} Ω
1D	one-dimensional
2D	two-dimensional
3D	three-dimensional
A	(1) ampere – unit of electric current (2) a constant in the Arrhenius equation
Ag	silver
Al	aluminium
Al_2O_3	aluminium oxide (alumina)
AlN	aluminium nitride
AMD	Advanced Micro Devices Inc (HQ: Sunnyvale, CA, USA)
ANL	Argonne National Laboratory (DOE, Argonne, IL, USA)
ASI	Applied Sciences Inc (Cedarville, OH, USA)
atm	atmosphere – unit of pressure = 1.013 x 10^5 Pa
Au	gold
ave	average
AZ	Arizona (state, USA)
bar	unit of pressure = 10^5 Pa
Be	beryllium
BeO	beryllium oxide
BNNI	Berkeley Nanosciences and Nanoengineering Institute (UCB, Berkeley, CA, USA)
BSAC	Berkeley Sensor and Actuater Center (UCB, Berkeley, CA, USA)
BTPFL	Boiling and Two-Phase Flow Laboratory (Purdue University, West Lafayette, IN, USA)
°C	degrees Celsius: 0°C = 32°F = 273.15 K
C	carbon
CA	California (state, USA)
CAD	Computer-aided design
CALCE	Center for Advanced Life Cycle Engineering (University of Maryland, College Park, MD, USA)
Caltech	California Institute of Technology (Pasadena, CA, USA)

CEO	Chief Executive Officer
CFD	computational fluid dynamics
CH_4	methane
CHF	critical heat flux
cm	centimetre = 0.01 m
cm^2	square centimetre = 10^{-4} m^2
cm^3	cubic centimetre = 10^{-6} m^3
CNT	carbon nanotube
COP	coefficient of performance
Corp	Corporation
CPES	Center for Power Electronics Systems (Virginia Tech, VA, USA)
CPL	capillary pumped loop
CPS	Ceramics Process Systems (Chartley, MA, USA)
CTE	coefficient of thermal expansion
CTRC	Compact, High-Performance Cooling Technologies Research Center (NSF/Purdue University, West Lafayette, IN, USA)
Cu	copper
CVD	chemical vapour deposition
DBC	direct bond copper
DoD	Department of Defense (USA)
DOE	Department of Energy (USA)
DSP	digital signal processing
DTI	Department of Trade and Industry (UK)
E	activation energy
EC	European Commission
ECAD	electronic computer-aided design
ECTC	Electronic Components and Technology Conference
EDM	electro-discharge machining
E-glass	electrical (borosilicate) glass
EMI	electromagnetic interference
EPSRC	Engineering and Physical Sciences Research Council (UK)
ext	extension
f	particle volume fraction
F	fax
°F	degrees Fahrenheit: 32°F = 0°C = 273.15 K
FBDIMM	fully buffered dual in-line memory module
FEA	finite element analysis
FE-SEM	field-emission scanning electron microscope
FMEA	failure mode and effect analysis
FR4	Flame Resistant 4 (epoxy material)
g	gram = 0.001 kg
h	heat transfer coefficient
HOMG	highly oriented mesophase-based graphite
HOPG	highly oriented pyrolytic graphite
HPHT	high pressure, high temperature
HQ	headquarters
Hz	hertz – unit of frequency = 1 cycle/s
IC	integrated circuit

IEEE	Institute of Electrical and Electronics Engineers (USA)
IeMRC	Innovative Electronics Manufacturing Research Centre (EPSRC/Loughborough University, UK)
IGBT	insulated gate bipolar transistor
IL	Illinois (state, USA)
IMAPS	International Microelectronics and Packaging Society
in	inch = 0.0254 m
in^2	square inch = 6.45 x 10^{-4} m^2
IN	Indiana (state, USA)
Inc	Incorporated (company)
iNEMI	International Electronics Manufacturing Initiative
IP	intellectual property
ITP	International Technology Promoter (network, DTI, UK)
ITRS	International Technology Roadmap for Semiconductors
I/UCRC	Industry/University Cooperative Research Center (programme, NSF, USA)
J	joule – unit of work or energy = 1 N·m = 1 W·s
JPL	Jet Propulsion Laboratory (NASA/Caltech, Pasadena, CA, USA)
JV	joint venture
k	Boltzmann constant
K	(1) kelvin (2) thermal conductivity
K_c	composite thermal conductivity
K_m	matrix thermal conductivity
K_p	particle thermal conductivity
kg	kilogram
KTN	Knowledge Transfer Network (UK)
kW	kilowatt = 1,000 W
lb	pound – unit of mass = 0.4536 kg
LCD	liquid-crystal display
LDMOS	lateral double-diffused MOSFET
LED	light-emitting diode
LLC	limited liability company
LTCC-M	low-temperature co-fired ceramic on metal
Ltd	Limited (company)
m	metre
m^2	square metre
m^3	cubic metre
MA	Massachusetts (state, USA)
max	maximum
MCAD	mechanical computer-aided design
MCPCB	metal-core printed circuit board
MD	Maryland (state, USA)
MEMS	micro-electro-mechanical system(s)
MER	Materials and Electrochemical Research Corp (Tucson, AZ, USA)
mil	milli-inch = 0.001 in = 25.4 x 10^{-6} m
mJ	millijoule = 0.001 J
mK	millikelvin = 0.001 K
mm	millimetre = 0.001 m

mm^2	square millimetre = 10^{-6} m^2
MMC	metal-matrix composite
MMCC	Metal Matrix Cast Composites LLC (Waltham, MA, USA)
Mo	molybdenum
MOSFET	metal-oxide semiconductor field-effect transistor
MPa	megapascal = 10^6 Pa
MRi	Materials Resources International (Lansdale, PA, USA)
MSI	million pounds per square inch (10^6 lb/in^2) – unit of stiffness
MTBF	mean time between failure
MWCNT	multiwall carbon nanotube
N	newton – unit of force = 1 kg·m/s^2
NASA	National Aeronautics and Space Administration (USA)
NASDA	National Space Development Agency of Japan *(On 1 October 2003 NASDA was merged into Japan Aerospace Exploration Agency – JAXA)*
NC	North Carolina (state, USA)
NGM	Nanographite Materials (JV between ASI (USA) and GSI Creos Corp (Japan))
Ni	nickel
nm	nanometre = 10^{-9} m
NSF	National Science Foundation (USA)
O	oxygen
OH	Ohio (state, USA)
ORNL	Oak Ridge National Laboratory (DOE, Oak Ridge, TN, USA)
Pa	pascal – unit of pressure = 1 N/m^2
PA	Pennsylvania (state, USA)
PAN	polyacrylonitrile
PCB	printed circuit board
PCF	phase-change film
PDMS	polydimethyl siloxane
PFC	perfluorocarbon
PhD	Doctor of Philosophy
PMMA	polymethylmethacrylate
PO	Post Office
PoF	physics-of-failure
ppm	parts per million
psi	pounds per square inch – unit of pressure: 1 psi = 6,895 Pa
PTFE	polytetrafluoroethylene
PUIECA	Purdue University International Electronic Cooling Alliance (Purdue University, West Lafayette, IN, USA)
q	power
R	thermal resistance
$R_{Overall}$	overall thermal resistance
R&D	research and development
Ra	arithmetical mean surface roughness (usually measured in µm or µin)
RF	radio frequency
RoHS	Restriction of Hazardous Substances (EU directive 2002/95/EC)
RTO	research and technology organisation
s	second
SBIR	Small Business Innovation Research (programme, USA)

sd	standard deviation
SEM	scanning electron micrograph
Si	silicon
SiC	silicon carbide
SiP	system-in-package
SME	small or medium-sized enterprise
Sn	tin
STTR	Small Business Technology Transfer (programme, USA)
T	(1) temperature
	(2) telephone
T_i	interface temperature
T_s	saturation temperature
$T_{Ambient}$	ambient temperature
$T_{Junction}$	junction temperature
TDII	Thermal Design Innovation Initiative (Purdue University, West Lafayette, IN, USA)
TEC	thermoelectric cooler
THz	terahertz = 10^{12} Hz
Ti	titanium
TIM	thermal interface material
TN	Tennessee (state, USA)
TPG	thermal pyrolytic graphite
TRM	transmit-receive module
TV	television
UCB	University of California, Berkeley (USA)
UK	United Kingdom
US(A)	United States (of America)
USAF	United States Air Force
UT	Utah (state, USA)
V	(1) volt – unit of electric potential
	(2) volume
V_f	volume fraction
VA	Virginia (state, USA)
VCSEL	vertical-cavity surface-emitting laser
VDMOS	vertical double-diffused MOSFET
vdW	van der Waals
VIP	vacuum insulation panel
VME	VersaModule Eurocard
vs	versus
W	(1) watt – unit of power = 1 J/s
	(2) tungsten (wolfram)

Appendix F

ACKNOWLEDGMENTS

The mission team would like to extend its deepest thanks to the host organisations for their hospitality, openness and support without which the mission and this report would not have been possible.

The mission would not have been possible without the support of the DTI Global Watch Service in both the organisation and funding of the mission and its dissemination through the seminar event.

The team would like to thank numerous individuals at the DTI and at Pera for their work behind the scenes. Particular thanks is owed to Chris Beck, Robert Dugon and Charlotte Leiper of the DTI Global Watch Service for their support and invaluable advice in the planning and execution of this mission and to Graham Dyer for his help in producing this document at short notice.

We would also like to thank Carlos Gorrichategui from NextTechs for his assistance in arranging meetings with NGM and Atlas Scientific.

Other DTI products that help UK businesses acquire and exploit new technologies

Grant for Research and Development – is available through the nine English Regional Development Agencies. The Grant for Research and Development provides funds for individuals and SMEs to research and develop technologically innovative products and processes. The grant is only available in England (the Devolved Administrations have their own initiatives).
www.dti.gov.uk/r-d/

The Small Firms Loan Guarantee – is a UK-wide, Government-backed scheme that provides guarantees on loans for start-ups and young businesses with viable business propositions.
www.dti.gov.uk/sflg/pdfs/sflg_booklet.pdf

Knowledge Transfer Partnerships – enable private and public sector research organisations to apply their research knowledge to important business problems. Specific technology transfer projects are managed, over a period of one to three years, in partnership with a university, college or research organisation that has expertise relevant to your business.
www.ktponline.org.uk/

Knowledge Transfer Networks – aim to improve the UK's innovation performance through a single national over-arching network in a specific field of technology or business application. A KTN aims to encourage active participation of all networks currently operating in the field and to establish connections with networks in other fields that have common interest.
www.dti.gov.uk/ktn/

Collaborative Research and Development – helps industry and research communities work together on R&D projects in strategically important areas of science, engineering and technology, from which successful new products, processes and services can emerge.
www.dti.gov.uk/crd/

Access to Best Business Practice – is available through the Business Link network. This initiative aims to ensure UK business has access to best business practice information for improved performance.
www.dti.gov.uk/bestpractice/

Support to Implement Best Business Practice – offers practical, tailored support for small and medium-sized businesses to implement best practice business improvements.
www.dti.gov.uk/implementbestpractice/

Finance to Encourage Investment in Selected Areas of England – is designed to support businesses looking at the possibility of investing in a designated Assisted Area but needing financial help to realise their plans, normally in the form of a grant or occasionally a loan.
www.dti.gov.uk/regionalinvestment/

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