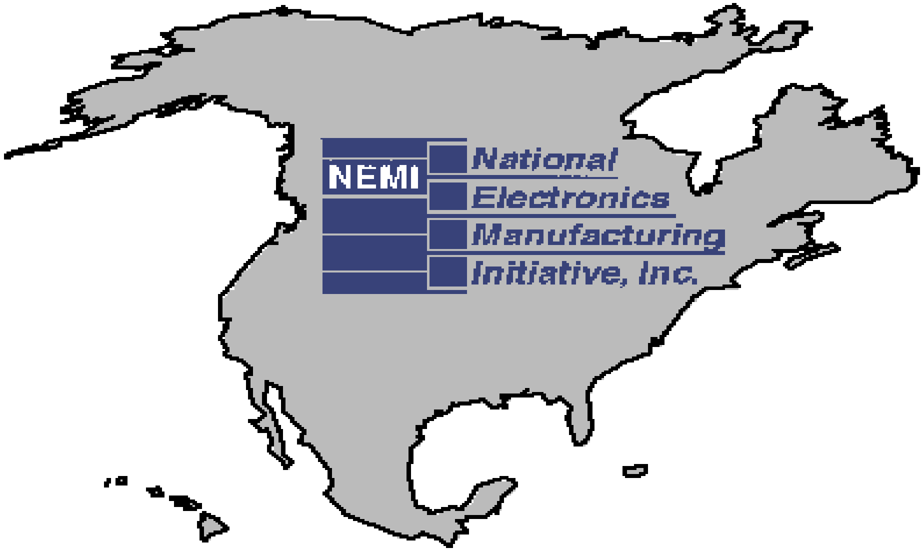

Thermal Management Roadmap
Cooling Electronic Products from Hand-Held Devices to Supercomputers

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EXECUTIVE SUMMARY

The 2002 Thermal Management Roadmap is an update of much of the material covered in the 2000 Roadmap plus some additional new sections. Specifically, new sections are being added to address and discuss: 1) the increasingly important cooling challenge at the facility level in computer data centers and telecommunication centers; 2) portable systems including notebook computers and handheld devices; and 3) recent DARPA (Defense Advanced Research Projects Agency) sponsored advanced cooling technology development activities.

As noted in the preceding roadmap, in almost all product sectors, increases in chip or component power dissipation are demanding significant enhancements in cooling in order to maintain temperatures at acceptable levels. The size of heat sinks cannot increase much beyond their current size because of the desire to shrink chassis size. The cooling airflow rate that may be supplied is limited by the space that is available for fans or blowers and by increasingly stringent acoustic emission and electromagnetic compatibility (EMC) standards. The combination of these factors is driving the need for significant innovation and major alternative cooling solutions. It is still expected that considerable effort must be directed at the development and application of fans with high-pressure and/or low acoustic emission characteristics. The development of cost effective, compact, reliable water-cooling techniques, along with the application of heat pipes, vapor chambers, spray cooling, vapor-compression refrigeration, and thermoelectric devices, offers the potential to provide these cooling solutions. In addition, performance and reliability requirements may drive the use of cooling technologies that provide lower temperatures, in order to keep up with the increasing complexities introduced with each new technology generation. The overall thermal budget will require improvements not only external to the chip package, but also internal to the package to reduce interface resistances and improve spreading using enhanced materials and manufacturing methods. At the system level, increased system powers and shrinking volume will require more efficient means of getting the dissipated heat out of the box.

More specifically, the cooling challenge facing each product sector may be summarized as follows:

- Large Business Systems - The Large Business Systems (high performance) product sector continues to face unprecedented increases in heat flux at the chip and module level, as well as increases in heat density on the system floor and at the installation level. The continued use of air-cooling will necessitate advanced fan/blower technology for low acoustic noise and/or high-pressure-head operation and further advances in the optimization and manufacture of heat sinks. Even with such advances, it is anticipated that inherently more effective cooling technologies such as water cooling and possibly direct immersion cooling will have to be utilized to meet the growing power dissipation requirements. The overall thermal budget will require improvements, not only external to the chip package, but also to reduce interface

resistances and improve thermal spreading internal to the package using improved materials both for thermal and electrical performance. At the system level, increased system powers will require efficient means of getting the heat to the outside environment in a way such that the temperature of the surrounding room environment is not adversely affected.

- Office Systems – Office Systems (cost/performance) products also face significant power increases, which will require both improvements in air-cooling technology as well as the introduction of liquid cooling technologies. Because of the increased sensitivity to costs, a major element of the cooling challenge will be greater reliance on design for manufacturability and manufacturing processes, which will make it possible to improve cooling capability without incurring proportional increases in cost. Design for low power consumption and minimum environmental impact will become increasingly important.
- Consumer – This sector includes low cost, high volume products that have relatively short life cycles and are so cost sensitive as to be unlikely candidates for advanced cooling methods.
- Portable - Because battery life imposes such a major constriction on power dissipation, portable (hand held) electronic products are not likely to face any significant cooling challenge. Most applications today do not require any active thermal management. Only minimal thermal management depending upon natural convection and the use of solutions such as thermal grease or heat spreaders is employed. The power dissipation levels currently predicted may be achieved with little or no research effort. Most of the thermal issues in hand held products are related to heat spreading from a few components (such as the up to 2 W dissipation of the power amplifier die in a cell phone). Therefore, the solutions needed involve spreading the heat using thermal vias, heat slugs or heat spreaders, and in some cases micro-heat pipes. New battery technologies, leading to storage of far higher power densities, could radically alter this scenario. The new technologies, however, are more likely to be used primarily to reduce weight rather than to increase power consumption.
- Automotive - Electronic products for use in automotive applications must operate in a harsh environment, which poses a special packaging and cooling challenge. In automotive environments, ambient temperatures reach 90 to 125°C, and possibly as high as 165°C for under-the -hood applications. In addition, there is the potential for exposure to a number of hostile fluids. With operating junction temperatures of some automotive electronic devices (such as power drivers) rising as high as 175°C, there is a need for components and packaging that can survive these higher operating temperatures, as well as a need for effective, robust, and inexpensive cooling solutions. Most of the cooling solutions today rely on a combination of conduction and air-cooling. In the future, the use of heat pipes, phase change materials (PCMs), liquid-cooling techniques, and more aggressive use of refrigeration will depend largely on the development of low-cost technologies that can be proven reliable in the automotive environment.
- Military/Avionics - Electronic products for military applications face equally harsh thermal environments within which they must operate and may also include exposure to more severe shock and vibration environments. These applications include land-based, shipboard, airborne, missile-based, and space-based environments. In many of these applications the weight and volume occupied by cooling devices and hardware become even greater constraints than in conventional applications. With the current emphasis on the use of

commercial-off-the-shelf (COTS) components in military systems, it is expected that there will be an increased emphasis on utilizing commercially available cooling technology to meet these demands and reduce costs.

Common to all product sectors, cost and time-to-market factors are playing an increasingly important role in maintaining competitiveness. To keep pace with the shrinking design cycle time and help reduce development costs, computer-aided design tools are increasingly important. Advanced tools are needed that integrate electrical, thermal, and mechanical analysis and simulation into a user-friendly package, enhancing the speed with which future designs can be created and evaluated.

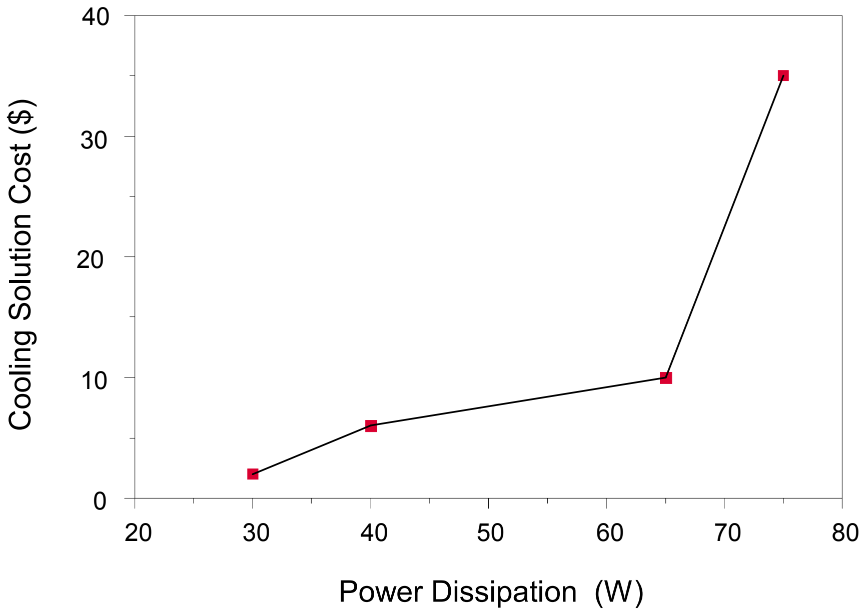
INTRODUCTION

Thermal management is a key enabling technology in the development of advanced micro-electronic packages and systems. It has facilitated many of the so-called *Moore's Law* advances in computers and electronic products, which took place in the latter part of the 20th century. Increased chip power driven by increased circuit density and increased clock rates are resulting in increased heat fluxes at the chip level. In many instances module level heat fluxes are rising as well. In order to satisfy junction temperature requirements in terms of performance and reliability, improvements in cooling technologies will be required.

One consequence of increased power dissipation and heat flux is increased cooling costs. An example of the relationship between power dissipation and cooling cost from an article ("Managing the Impact of Increasing Microprocessor Power Consumption," by Gunther, Binns, Carmean, and Hall) published in the Intel Technology Journal (1Q2001) is shown in Figure 1. The figure illustrates the relative implementation cost of various cooling solutions ranging from a simple aluminum heat sink to a more elaborate heat pipe technology. As the authors noted, there is a non-linear relationship between the cooling capabilities and the cost of the solution. In other words the cost of cooling in dollars/watt increases as the watts dissipated increase. Cooling costs have traditionally been a very small percentage of total system cost, ranging from less than 1% for some PCs to 3-5% for some large servers. Nonetheless, the cost of cooling as with other components of the product cost equation, is receiving increased attention. The cost of thermal management technologies must keep pace with the reductions in overall package and system cost per function, which are being realized in virtually all product sectors.

This Thermal Management Roadmap addresses the need to develop improved cooling technology in terms of heat transfer processes, materials, and innovative designs. If successfully implemented, it will contribute to the increased competitiveness of packaged electronic products consistent with the goals of the NEMI Roadmap initiative.

Figure 1 Cost of removing heat from a microprocessor



The Thermal Management Roadmap identifies needs for further advances and development in these following thermal technologies:

- thermal spreaders
- heat pipes
- water cooling
- refrigeration cooling
- thermal interfaces
- air cooling
- direct immersion cooling
- thermoelectric cooling

SITUATION ANALYSIS

While thermal management is driven by the need to satisfy the heat flux and temperature requirements, the choice of an appropriate cooling technology is constrained by market application requirements. The following product sectors and typical applications categorize the information in this roadmap:

- Large Business Systems - Greater than $3000 high-end workstations, servers, supercomputers, telecommunications (switches, routers, optical cross-connects, long haul transport, and network core equipment) representing the most demanding requirements.
- Office Systems - Less than $3000 notebooks, desktop personal computers, telecommunications
- Consumer – Low cost, high volume products including low end games, smart toys etc.
- Portable - Less than $700 battery-powered products, mobile products, hand-held cellular telecommunication, and other hand-held products.
- Harsh Environment - Hostile and special environments, principally automotive, military, and avionic applications.

ROADMAP OF QUANTIFIED KEY ATTRIBUTE NEEDS

The task of dissipating heat from integrated circuit chips, while maintaining acceptable junction temperatures, poses a significant challenge for manufacturers of semiconductors and electronic systems. Some of the key drivers in the thermal design of the system are chip size, power dissipation, junction temperature, and cooling air temperature. The following sections provide an overview of the forecasted requirements for each product sector. These requirements will be key factors in determining the needs of electronics packages and products in the future.

LARGE BUSINESS SYSTEMS

Chip power dissipation and heat flux are expected to increase further over the next decade as shown in Figure 2 and Figure 3. Two trend lines are shown in each of the figures to cover the possible range of values. In most cases for high-performance, Large Business Systems the requirement will be to maintain die temperatures at or below 105°C. In some cases it may even be desirable to reduce die temperatures well below 105°C to increase performance. It is expected that the trend towards increasing heat flux will be accompanied by continued pressure to reduce the cost of cooling consistent with overall product cost reductions. Although air-cooling is viewed as the preferred cooling option from a cost perspective, it is expected that increased heat flux will necessitate the use of other cooling technology options as well. In addition, for many high performance applications, the demand for system availability is increasing as well, often approaching 100 percent. Consequently, whichever cooling technology option is chosen, provisions for graceful degradation will have to be incorporated in future designs to ensure that failures of cooling devices (e.g. fans or liquid pumps) will not interrupt the operation of the system.

Figure 2 High performance chip power trend.

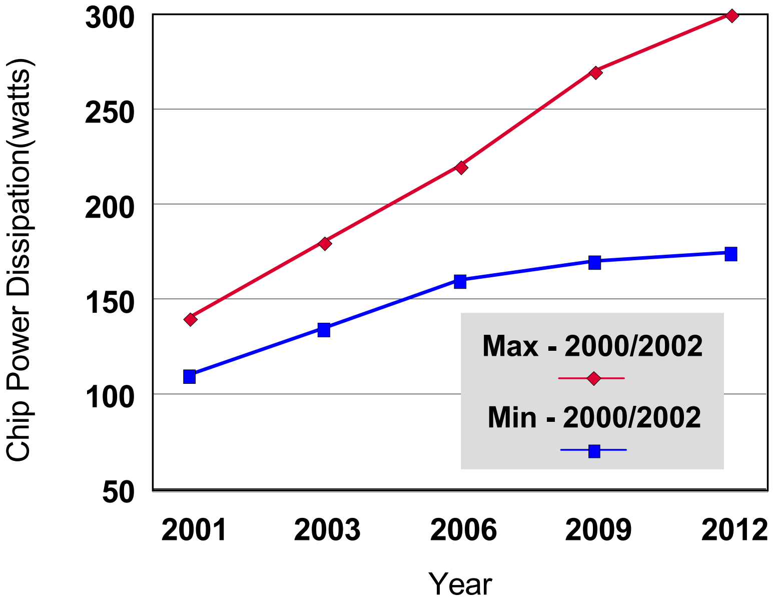
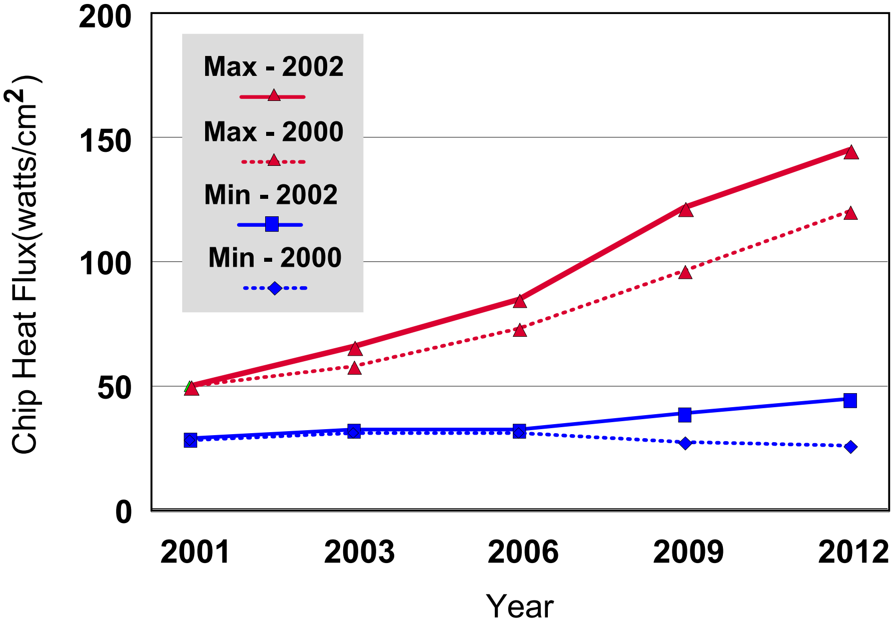


Figure 3 High performance chip heat flux trends.



OFFICE SYSTEMS

As shown in Figure 4, the cost/performance, Office Systems product sector is also projected to face a continued trend of increasing power dissipation at the die level, however generally on par with the prediction from the 2000 roadmap. Die size, on the other hand, is expected to increase throughout the projected time period, from 1.9-2.5 cm^2 in 2002 to 3.1-4.4 cm^2 in 2016. As shown in Figure 5 this will result in chip heat flux ranging from 34 to 64 W/ cm^2. In some respects this may be expected to pose an even greater cooling challenge than in the high performance product sector, because of the even more demanding product cost constraints that preclude many cooling options. In spite of its limitations, air-cooling is still viewed as the only option to keep cost within bounds. It is expected that for most cost/performance systems the requirement will be to maintain die temperatures at or below 100°C.

Figure 4 Cost-performance chip heat dissipation trends.

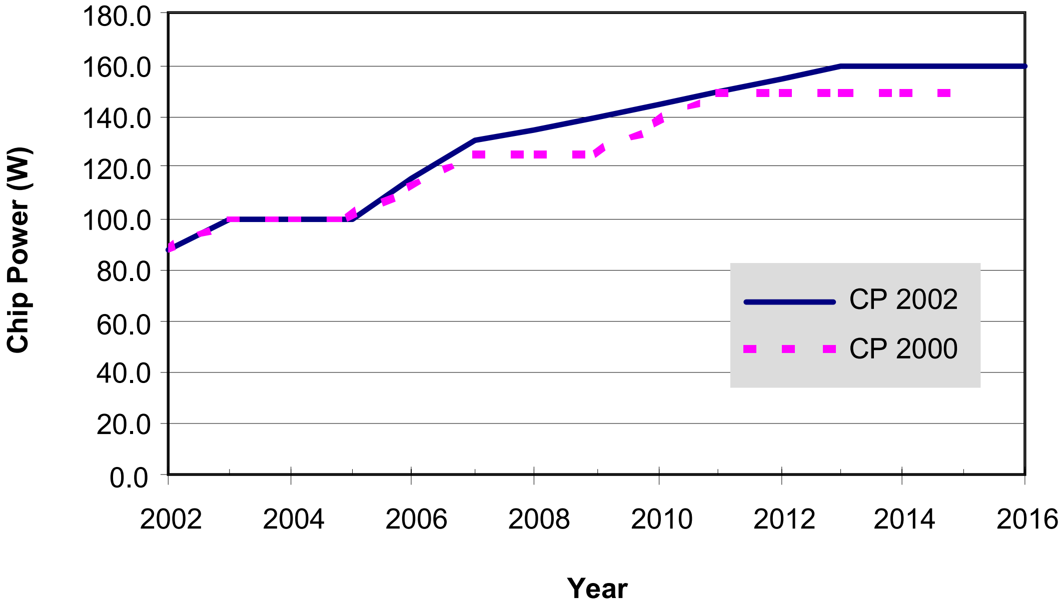
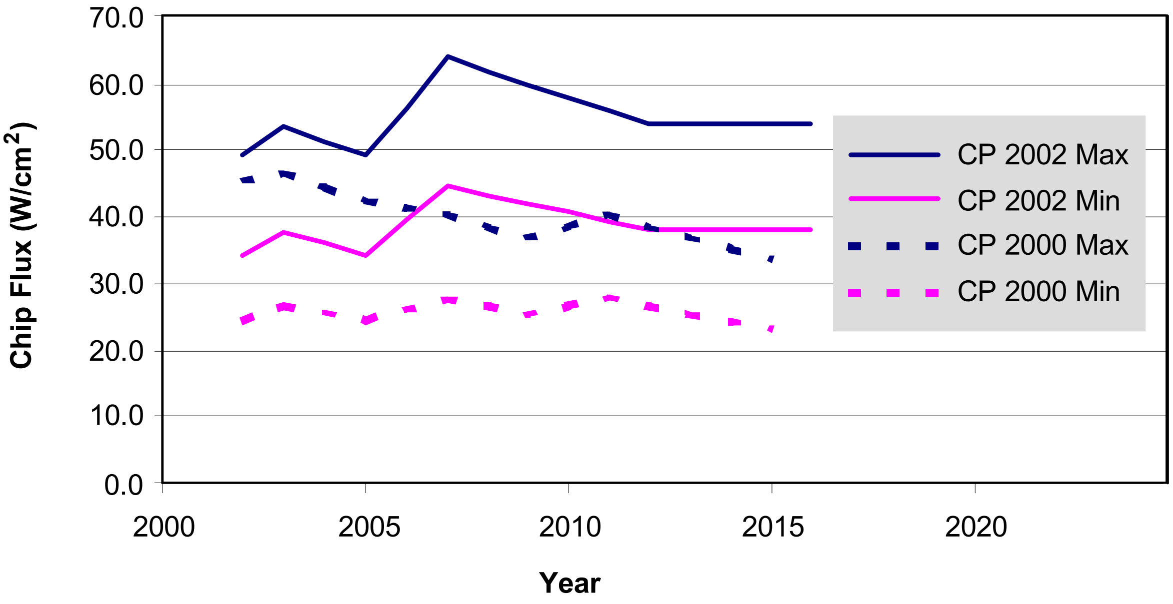


Figure 5 Cost performance chip heat flux trends.



Cost/performance, Office Systems products will also pose a significant thermal management challenge. Although chip heat fluxes are projected to be within the range of air cooling, the maximum levels are well above what is commonly achieved at present. The higher levels will require improvements in air cooling technology similar to those needed for the High Performance sector. However, the problem of providing the required cooling improvements will be made even more severe due to the even greater cost constraints placed on this product sector. An alternative to high performance heat sinks on modules coupled with high pressure-head blowers might be a hybrid water-to-air cooling system. This approach would also require the development of new thermal components in terms of low cost, compact cold plates, pumps, and water-to-air heat exchangers. As in the case of high performance products, improvements will also be required in the paths internal to the chip/module package.

TELECOMMUNICATION

Telecommunication applications run the gamut from Office Products (cost/performance) to, Large Business Systems (high performance) products. As might be expected, both the chip power trend (Figure 6) and chip heat flux trend (Figure 7) in telecommunication applications reflects the increasing power trend for both the cost/performance and high performance product sectors. Architects of the next-generation Internet Protocol (IP) network core are demanding exponentially higher system throughputs to keep up with network traffic growth. With projected node sizes from 100's of Gb/s to 100's of Tb/s, extrapolating current equipment would incur up to 100's of kilowatts of power consumed and dissipated per node. This trend is reflected in the projected growth in heat flux based upon footprint area at the equipment level as shown in Figure 8. As a result, power reduction strategies and high-density thermal management become two of the critical elements for feasible design of future telecom equipment.

Figure 6 Maximum chip power trend in telecommunication applications

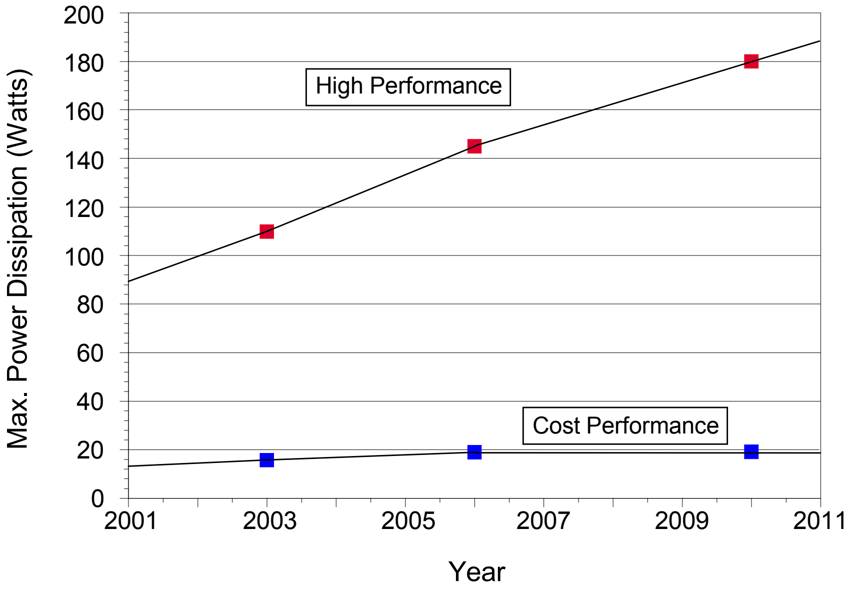


Figure 7 Maximum chip heat flux trend in telecommunication applications

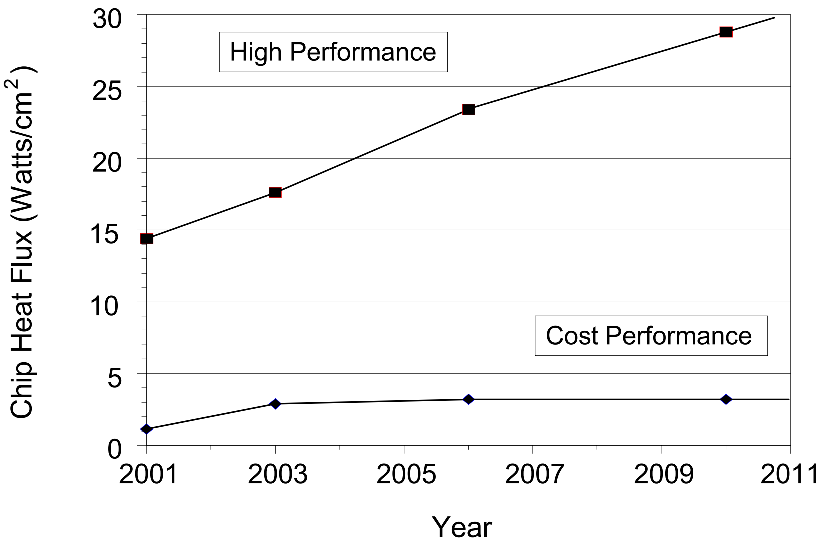
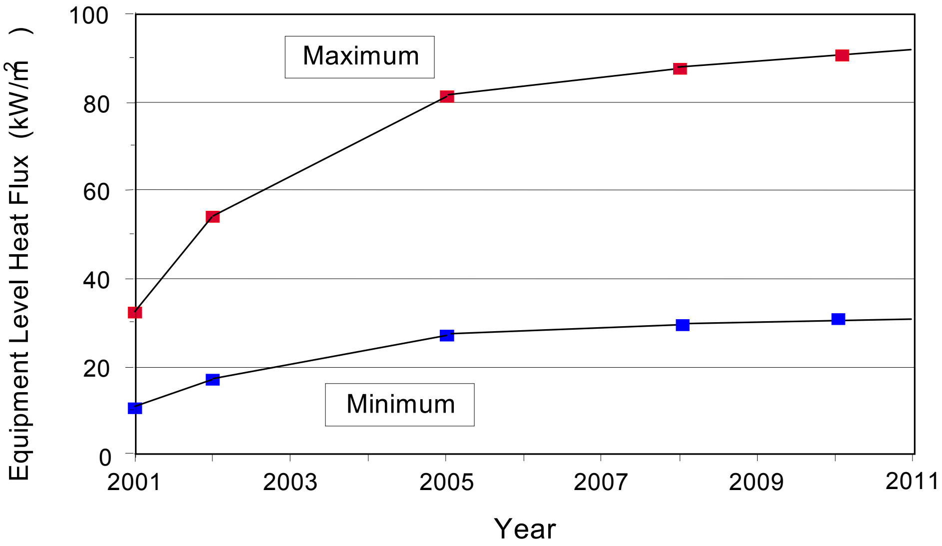


Figure 8 Telecom equipment level heat flux trend



Due to the growth of wireless communication, as well as predictions of the near future in this field, it is expected that base stations will also face significant challenges. This is basically due to the outside environmental deployment of base stations. Base stations (as well as outdoor enclosures housing transmission equipment) are subjected to extreme weather conditions, high humidity and temperature, as well as being impacted by solar loading. At the same time, they are expected to operate with high reliability.

However, a projection of future base station development clearly shows the trend from today's macro cell application to more deployment of micro cells in the future. This is predominantly due to anticipated future requirements for high data rate transfer, where the micro cell is the preferable choice. This will allow approximately 10X reduction in thermal dissipation, diminishing the complexity of the overall thermal management task. So, natural and forced air convection in conjunction with heat pipes will be the cooling technologies, which will dominate in this field.

Another important issue in the thermal management of telecommunication equipment is in the area of spacecraft telecommunication arrays designed to communicate with ground-based systems. These include GEO satellites (22,300 miles above the earth), LEO/MEO satellites (400 to 10,000 miles), and high-altitude aircraft systems (10 miles). Airborne systems experience higher longer-term vibration environments and much higher shock environments than ground-based equipment and must be both lighter-weight and lower-cost. Both air-cooling and liquid-cooling technologies may be employed. Space-based equipment is also exposed to high magnitude, although short duration, vibration environments with high magnitude shock environments. These systems must be extremely light-weight and very low cost. The mode of cooling is limited to conduction- and/or radiation cooling, with solid-to-liquid phase change materials (PCMs) being employed to control non-uniform power distributions, fluctuating power cycles, and cyclical environments.

A number of thermal design challenges are associated with telecommunication arrays. Temperature gradients across the arrays result in array pointing errors. The variable conditions under which these arrays must operate also cause thermal design challenges. A non-uniform power distribution is inherent across the array with a dissipation of high power bring concentrated in the center of the array. There is also the problem of a fluctuating power cycle, as well as asymmetric interface conditions. In these instances, component junction temperatures must be maintained at less than 120°C with temperature gradient across the array of less than 10°C.

Development opportunities posed include the development of two-phase cooling systems in the form of capillary-pumped loops with thin, low profile, evaporators dictated by the narrow spacing required between the microwave modules comprising the array. The development of multiple, parallel, evaporator paths is also essential to this application. Improved surface finishes, associated with the space-radiator heat sink, that will reduce cost and improve the ratio of absorptivity (solar)-to-emissivity will provide long-life surfaces that will be immune to radiation effects. In addition, thermal spreaders with high thermal conductivity, low weight, and low coefficient of thermal expansion (CTE) will become invaluable.

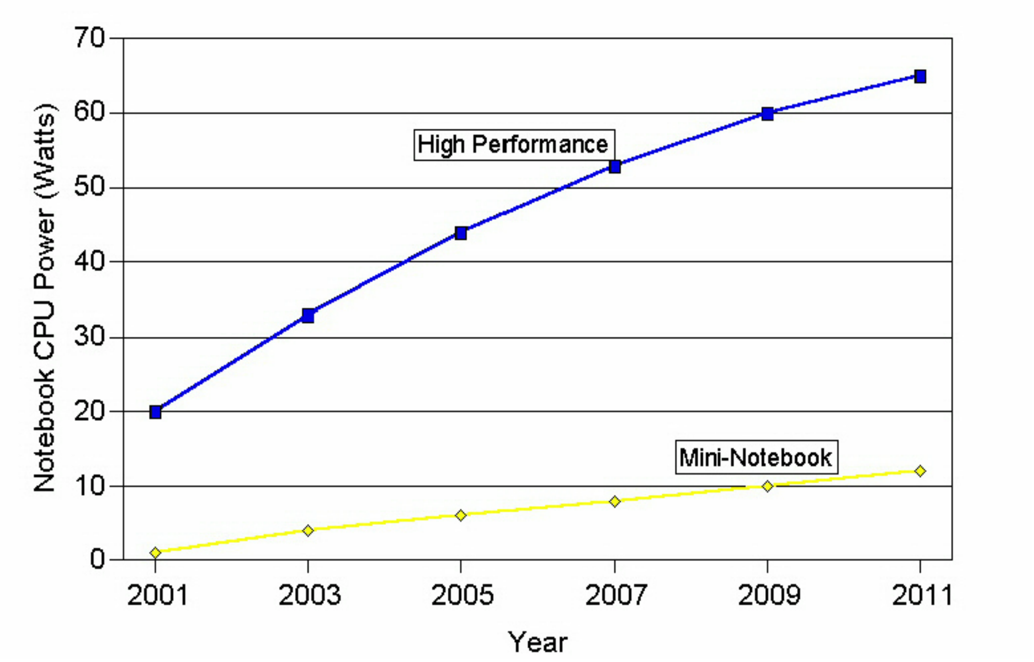
PORTABLE SYSTEMS

Notebook computers and hand held devices like PDAs (personal digital assistants) and cell phones are rapidly becoming a pervasive part of many aspects of everyday life. They share similar in characteristics in terms of the wide range of environments they are expected to operate in, the premium placed on lightweight and compact size, and their reliance on battery power at least some of the time. However as discussed below, the thermal challenge posed by notebook computers and hand held devices is significantly different due to the difference in their power trends.

NOTEBOOK COMPUTERS

Portable computers, especially those in the form factor of a notebook are becoming more and more popular in the personal computer product sector. In response to the market demands, the performance and functionality of the notebook computers are increasing with time. These changes in turn are driving up the power consumption of the Central Processor Unit (CPU) inside notebook computers. Over the past ten years, the power of the CPU has increased almost ten fold and reached nearly 20 W in 2001. Notebook CPU power is projected to continue to increase in the future as shown in Figure 9. The rate of the power increase in the future, however, is likely to be smaller than in the past due to the constraints on the battery capacity, physical size of the computer box, and cooling technology constraints. There are two curves in the figure; the upper curve is for the CPU power trend for high-performance notebook computers with a platform size about the same as A4 paper (210 mm x 297 mm) and with a thickness in the neighborhood of 40 mm, the lower curve is for the CPU power trend for mini-notebook computers with a platform about the same as A5 paper and with thickness of 20 mm or less.

Figure 9 Notebook computer CPU power trend.



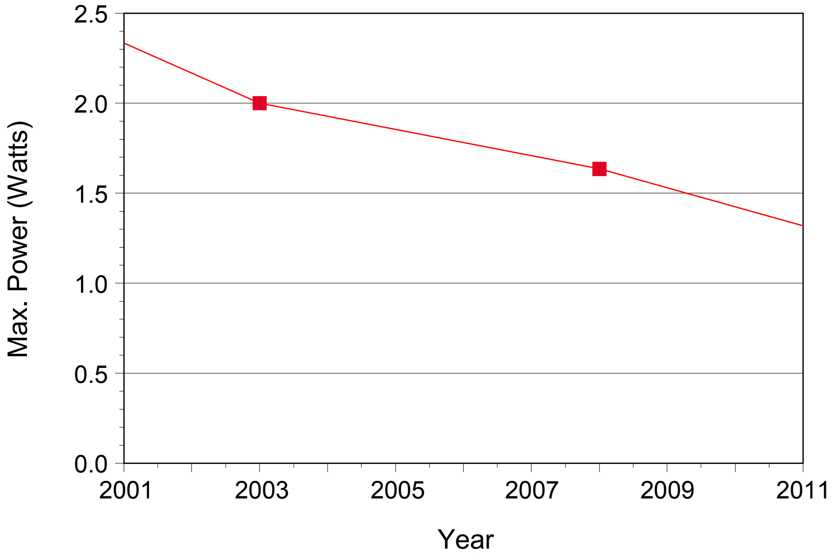
The ever-increasing power of the CPU in notebook computers will pose a significant challenge to product design and manufacturing. For the high-performance notebook computers, forced-air cooling is likely to be the main cooling technology to be used. This cooling method is viewed as the most cost-effective approach in the foreseeable future. For the mini-notebook computers, natural convection and heat conduction will continue to be the dominant cooling methods.

As mentioned earlier, a major challenge for forced-air cooling technology is the development of fans or blowers that can generate an adequate static pressure to drive a useful amount of air flow passing through high-efficiency heat sinks while keeping the acoustic noise low. This challenge is a major one for the manufacturers of high-performance notebook computers. In addition, the power consumption, cost, size, and weight of the fans as well as the heat sinks must also be addressed in the notebook computer environment. Because of these constraints, forced-air cooling may run into its limit and other types of cooling technology may emerge in the future. On the other hand, better heat transfer materials and technology for heat spreading and heat transfer between solids, in particular between the CPU package and the heat sinking device are also required to cope with high CPU power dissipation. Currently, heat pipes are frequently used in notebook computers for the purpose of transferring heat from the CPU to the heat-sinking device. The most commonly used heat pipes are cylindrical in shape with diameters around 3 mm. However, with the ever-increasing power of the CPU, the diameter of the heat pipes will likely be greater in the future unless better heat pipe technology is developed. A variant of the heat pipe, called a vapor chamber, has been developed and is gradually being introduced into products for the purpose of spreading heat or reducing the heat flux from the CPU to the heat-sinking device. The vapor chamber can be used to mitigate the demand for a better thermal interface between the CPU package and the heat-sinking device. Nonetheless, a better thermal interface is always desirable when facing the increasing power of future CPU chips. Thin and light materials that have high thermal conductivity are also very desirable in the notebook computer arena. Graphite fiber composites are one example. Unfortunately, their current high cost cannot be justified for wide adoption in the notebook computers - especially the cost-sensitive mini-notebook computers.

Portable Systems

In addition to their small size and portability, portable systems are unique in that their power dissipation is projected to decrease over the next ten years. As shown in Figure 10, maximum power dissipation in portable systems is projected to decrease by 2.5X over the next ten years. Battery life poses a major constraint on power dissipation. Most of the power dissipation is at the power amplifier, which may be as small as 1 mm^2 and dissipate about 0.6 W. Most of the thermal issues in portable products are related to spreading the heat from these components. The solutions used involve spreading the heat using thermal vias to heat slugs or heat spreaders in the system, and in some cases micro-heat pipes. It is currently possible to achieve predicted power dissipation levels with these solutions. No significant thermal issues are expected as long as battery life remains a constraint. Possible breakthroughs in plastic batteries could double or triple the available power. This higher power could be needed if “wireless browsing” becomes the norm, and more aggressive thermal management techniques would be required.

Figure 10 Maximum power dissipation trend in portable systems



HARSH ENVIRONMENT

Product sectors falling within the domain of harsh environment principally include automotive and military/airborne applications. Both are characterized by unusually harsh environmental factors of ambient temperature (from extremely cold to extremely hot), high relative humidity, exposure to demanding shock and vibration conditions, and substantial airborne contaminants (e.g. sand, dust, and gaseous pollutants).

Automotive Electronics

High volume automotive electronic modules/systems can be expected to dissipate power levels from a few mWs to a kW or more in the future, depending on the function and application. The worst-case thermal condition is typically encountered during vehicle start and run following a hot soak condition (hot soak refers to the environment created after extended driving followed by parking in a restricted air flow environment). Maximum ambient temperatures for this condition are 85°C for the passenger compartment, 85 - 100°C for body mounted assemblies, and 95 - 125°C, but possibly as high as 165°C for under-the-hood applications. Operating junction temperatures for digital and analog ICs are now allowed to reach 150°C for some applications and power devices can have operating junction temperatures as high as 175°C, with short transients up to 200°C. The under-hood and body- mounted automotive environment requires that the electronic modules be capable of operating reliably in the presence of materials such as transmission fluid, brake fluid, power steering fluid, nitrogen oxides, salt spray, engine coolant, oil, grease, humidity levels up to 100 percent, and in some cases immersion in water for short periods of time

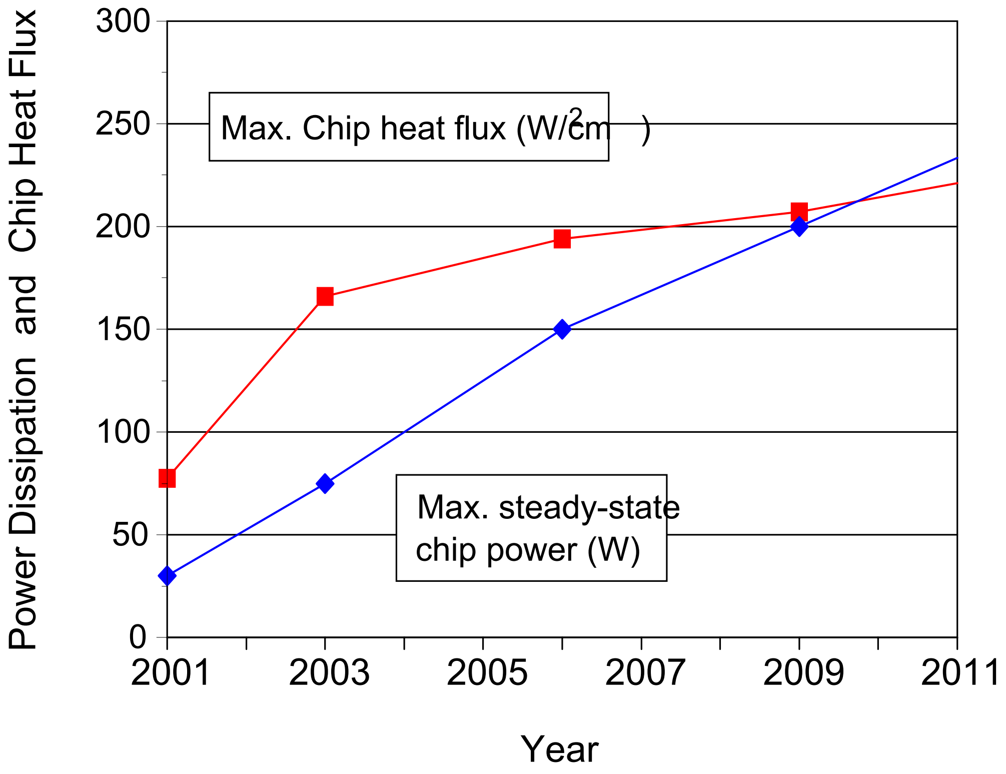
Power dissipation for digital and analog ICs in automotive applications will typically follow the trend in the computer and communications applications with a delay of two to five years. These chips will be subject to the more severe automotive thermal and cost environment and consequently may not be able to utilize the same thermal management techniques.

On the other hand, power dissipation for power devices (e.g. transistors, smart power) can vary from zero in some applications to values as high as shown in Table 1 and Figure 11.

Table 1 Projected chip size, power dissipation and heat flux for automotive power devices

Year	2001	2003	2005	2009	2011
Chip Area (cm^2)	0.39	0.45	0.77	0.97	1.1
Max. Steady-State Chip Power (W)	30	75	150	200	250
Max. Chip Heat Flux (W/cm^2)	77.5	166	194	207	228

Figure 11 Maximum steady-state chip power and heat flux trend for automotive power devices



The development of low cost semiconductor devices and device packaging that can reliably operate at junction temperatures of 175°C for digital and analog devices and 200 °C for power drivers has the potential to significantly reduce that thermal design cost for many automotive applications. Packaging solutions with low junction-to-case and junction-to-board thermal resistances are needed. Cost allowable per chip is currently in the $1.00 to $0.50 range (total factory cost including interconnect) for high performance thermal stacks (1°C/W). New thermal management concepts will need to be about the same price for higher performance or will need to be lower cost for equivalent performance.

If available, high temperature devices could be used today in some under-hood applications. This is particularly true for high value capacitors used for electrical noise and switched current ripple suppression. Most of these devices are only specified to 125°C, while automotive applications require ambient operation at 150°C.

In the future, the automotive industry is in need of very low cost, robust, and long-life (20+ years) electronic thermal management systems capable of dissipating up to 1.0 kW or more in +100°C ambient environments. Passive thermal cooling systems (such as adhesives, thermal spreaders, dielectric isolation materials, potting materials, and thermal spreaders with high thermal conductivity and capable of operation in an automotive environment) will be preferred wherever possible. Electronic components and system level packaging materials are also needed to reduce the need for higher cost and more complex active thermal cooling systems.

Military Electronics

Military electronics includes ground-based and airborne electro-optical sensor systems; ground-based, shipboard and satellite phased-array-radar systems, missile electronics and electrical power generation units for aircraft. In each of these areas there are new or increased demands to be met. One overriding issue for all military electronic systems, regardless of platform, is the current emphasis on the use of commercial-off-the-shelf (COTS) components. This is both a supply and a cost issue. These are plastic components that have lower values for the maximum allowable junction temperature. Unfortunately, the military has not relaxed the extreme nature of the ambient environments in which they need to operate their systems. In fact, the environment has become more severe within the last ten years. Airborne electronics that are air-cooled must still meet the requirements of Mil-E-5400T, which dictates the maximum allowable cooling air temperatures as a function of altitude. For Class 1A electronics, these temperatures range from 55°C at sea level to 26°C at 45,000 feet. These systems are fan-cooled and with the decrease in air density at the higher altitudes, the inadequate air mass flow rate is a serious design issue. Better fan design is needed if COTS components are to be successfully used in military systems. Cooling techniques for air-cooled systems must be improved, because techniques that have proved adequate for military components will no longer serve for COTS components.

In the thermal management of electro-optical systems, there is a need for more efficient thermoelectric cooler (TEC) devices. More efficient devices might make it feasible to use TECs as a means of refrigeration for large heat loads and as replacements for cryogenic refrigerators to provide cooling for IR detector focal plane arrays for military electro-optical systems. Current electro-optics systems are under pressure to use less expensive PWB technology and COTS surface mount (SMT) components. PWBs that utilize fewer, more-efficient, conductive (copper) layers within the PWBs will be required in the future. The military desires that, for ground-based systems such as tanks, liquid-cooling techniques be abandoned in favor of air-cooled systems, preferably systems cooled by natural convection. The drivers for this shift in technology are lower weight, lower cost, and higher reliability.

For power amplifiers, such as those used in phased-array-radar systems, the next generation devices will likely use substrate materials such as gallium nitride (GaN), instead of the current gallium arsenide (GaAs). Heat flux densities for these devices will be approximately 10 to 20 times greater than the GaAs devices. This increase in heat flux density will require improved die attach methods and high thermal conductivity heat spreaders, such as graphite or diamond. These high heat fluxes will also require particular attention to other material properties such as the coefficient of thermal expansion (CTE), since the temperature excursions will be greater. An additional requirement for RF microwave systems is adhesives that exhibit a lower thermal resistance. These adhesives would be used to bond Monolithic Microwave Integrated Circuit (MMIC) devices to substrates to reduce the thermal resistance between the chip and the coolant. It may also be possible to use liquid immersion cooling with fluorocarbon (dielectric) liquids in direct contact with the RF microwave chip. There are a number of chemical issues and some electrical considerations, but the excellent possibilities warrant some study of this technology. It is also possible that sub-cooled, flow boiling of these dielectric liquids may be very advantageous for military applications. The use of sub-cooled, flow-boiling would bring the benefits of higher local boiling heat transfer coefficients directly at the heat source (MMIC chip) without the penalty of a two-phase refrigeration loop requiring an evaporator, compressor, condenser, and vapor loop (with all of the problems associated with pressure drop, reliability, and initial cost).

For recent military radar systems, the use of fluorocarbon liquids is inadequate because of the low latent heat of vaporization of the fluorocarbons. In a few of these cases, where an expendable liquid heat exchanger was used, the liquids utilized were ammonia and methanol. Recently, water and ethylene-glycol water have been used, but the system pressure was lowered below ambient pressure to decrease the temperature at which the water boiled. Much knowledge is needed for these applications to be fully developed.

Electronics used in missiles include PWBs, power supplies, control systems, and both electro-optic and RF microwave sensors. The missions normally are transient in nature requiring transient thermal models to predict performance throughout the flight. Aerodynamic heating environments must be considered because of the external loads added to the electronics and because they eliminate the natural heat sink offered by the usually cold temperatures of the environment at high altitudes. Electronic modules and PWBs require materials of high thermal conductance and the transient nature of the typical missile mission requires extensive use of phase-change-materials (PCMs) at the component-level, module-level, and PWB-level. Thermoelectric devices (TECs), cryogenic refrigerators, and Joule-Thomson (J-T) coolers are utilized to provide cooling for specific components as well as IR detector focal-plane-arrays (FPAs). Systems are trending toward higher component dissipation and higher storage temperatures. The higher dissipations require the use of PCMs. Higher storage temperatures require the development of new PCM materials with an increased latent heat of fusion and melting point temperatures between 90°C and 110°C. These improved characteristics will insure that component junction temperatures can be maintained at 125°C (or less) for the duration of the mission, which is on the order of 45 seconds to five minutes. The weight of the PCM is also an issue for all missile applications.

END-USER PERSPECTIVE OF THERMAL MANAGEMENT

Thermal management of larger electronic equipment systems does not end at the chip or system level but rather at the facility level. As is shown in Figure 12, equipment heat dissipation is soaring and every solution that might allow higher heat densities in the equipment room must be scrutinized. A relatively little studied link of this thermal-management chain is the thermal interface between air-cooled electronic equipment and the equipment room. Inadequate matching has the potential to jeopardize significant investments in sophisticated electronic equipment and to interrupt a vast amount of revenue-generating services.

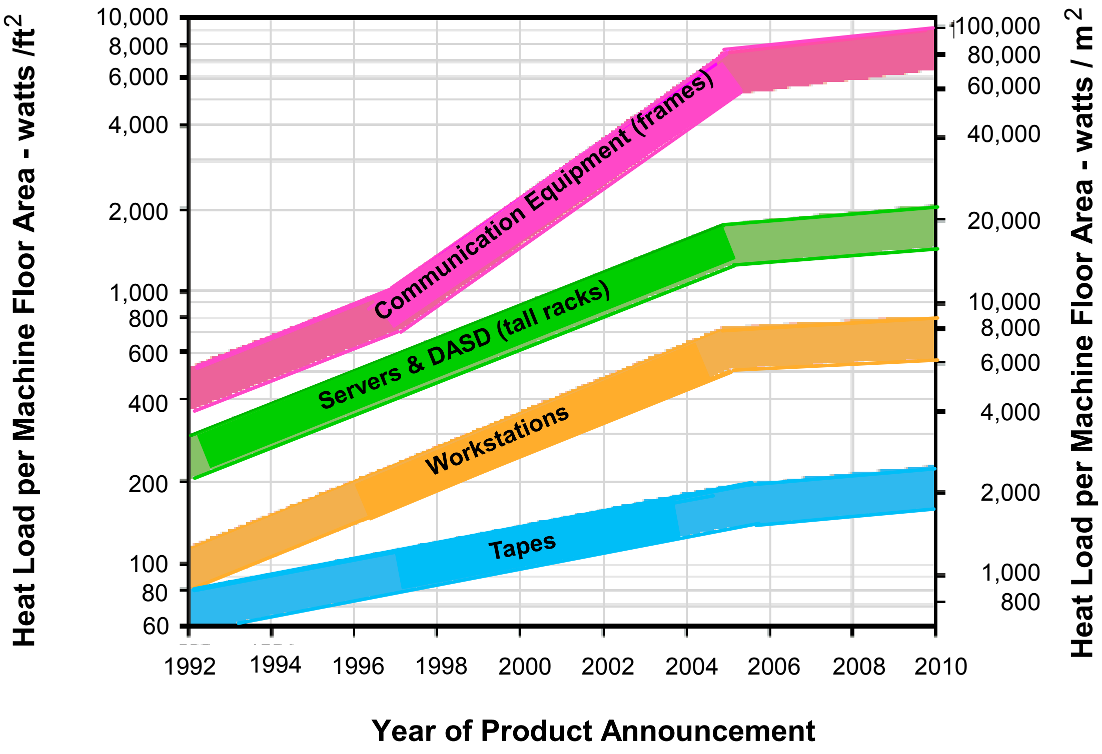
To meet the demand for new and improved voice, data, and video services, data and telecommunications centers are installing a vast amount of equipment with high heat output. Since the equipment often is not designed for a particular type of equipment room, the environmental systems in the facility may not be suitable. The equipment also comes from suppliers that may be less familiar with the environmental constraints of the particular type of equipment room. Telecommunications service providers, for example, are challenged by all of the above.

Higher equipment heat dissipation requires higher airflows for effective equipment cooling. Small noisy high-speed fans dominate today's forced convection designs of telecommunications gear. The resultant fan noise is a major concern for service providers both in telecommunications central offices and in outside plants. In the central office environment, the noise levels have reached the point where an eight-hour-a-day exposure may lead to hearing loss. This poses a challenge to thermal designers to determine how to provide adequate cooling and at the same time reduce noise produced by cooling equipment.

The energy efficiency of electronic equipment has generally increased over the years so that each "function" requires less energy. However, the increase in the number of functions (per volume of electronics) has far outpaced the efficiency gain. The result is electronic equipment with heat-dissipation numbers at the system level that would have been unimaginable just a few years ago. Still, much development and resources goes into making the electronics more compact.

This development makes perfect sense for an array of mobile equipment. One may, however, question the rationale and drive behind this evolution for larger air-cooled systems since many data and telecommunications rooms cannot accommodate the heat density from such systems. Empty space must often be incorporated into the equipment lineups to reduce the overall heat density on the equipment floor. Should the equipment space still be fully populated due to pressure from space planners, the reliability and longevity of the equipment may be jeopardized. End user's operating large equipment systems often voice the opinion that equipment manufacturers make their equipment unnecessarily compact and—as a result—unnecessarily expensive. From an end-user's perspective, equipment suppliers need to better recognize facility limitations in removing heat dissipated from air-cooled electronic equipment.

Figure 12 Thermal loading (at the facility level) for various product families



The Uptime Institute, 2000.

Several industry groups have developed, or are in the process of developing, thermal guidelines and requirements for ensuring network integrity and longevity while leaving room for innovative equipment designs and environmental solutions. For example, Telcordia Generic Requirements document *GR-3028 Thermal Management in Telecommunications Central Offices* classifies and reports relevant attributes of both the electronic equipment and the equipment room so that manufacturers understand the various environments in which the equipment will be deployed, and so that the end users understand the equipment attributes for successful deployment of new equipment systems. Such a well-developed "holistic" approach is required to understand today and tomorrow's thermal management challenges.

Each type of equipment room has an inherent practical upper limit of heat density for adequate equipment cooling. Although normal uninterrupted air-conditioning operation may handle elevated heat loads quite well, catastrophic air-conditioning failures often result in harmful equipment temperature conditions within a fraction of an hour. Indeed, steep temperature gradients and high temperatures following the onset of a cooling outage often limit the acceptable heat density in the equipment room. Understanding these heat-density limits help ensure equipment reliability as well as aid in establishing equipment and space planning and infrastructure capacity planning.

A major obstacle for effective thermal management is cooling airflow schemes (the location of air-intake and air-exhaust) that are non-compatible with the preferred alternating hot-cold aisles configuration in equipment rooms. This configuration helps avoid air mixing in the equipment space, which increases the overall thermal efficiency and the allowable heat density. Another obstacle for effective thermal management is the way heat-release data currently is reported for electronic equipment. Suppliers generally specify the maximum (nameplate) heat release from the equipment. In reality, equipment configuration and traffic diversity result in significantly lower heat dissipation. To help the end user with equipment selection for greatest heat density, the equipment data sheet should include the equipment airflow scheme and the actual heat dissipation at the system level.

Almost without exception, electronic equipment in telecommunications central offices is air-cooled. Since a transition to liquid-cooled equipment is expected to be long and painful, both equipment suppliers and service providers maintain status quo with regard to cooling medium. And, end users operating central offices will continue to have problems with accommodating high-heat dissipating equipment. In this environment, supplemental and spot-cooling techniques as well as turnkey cooling solutions developed by the equipment manufacturers are imperative in accommodating “hot” equipment. Measures to house such equipment will play a central role in managing tomorrow’s data and telecommunications centers.

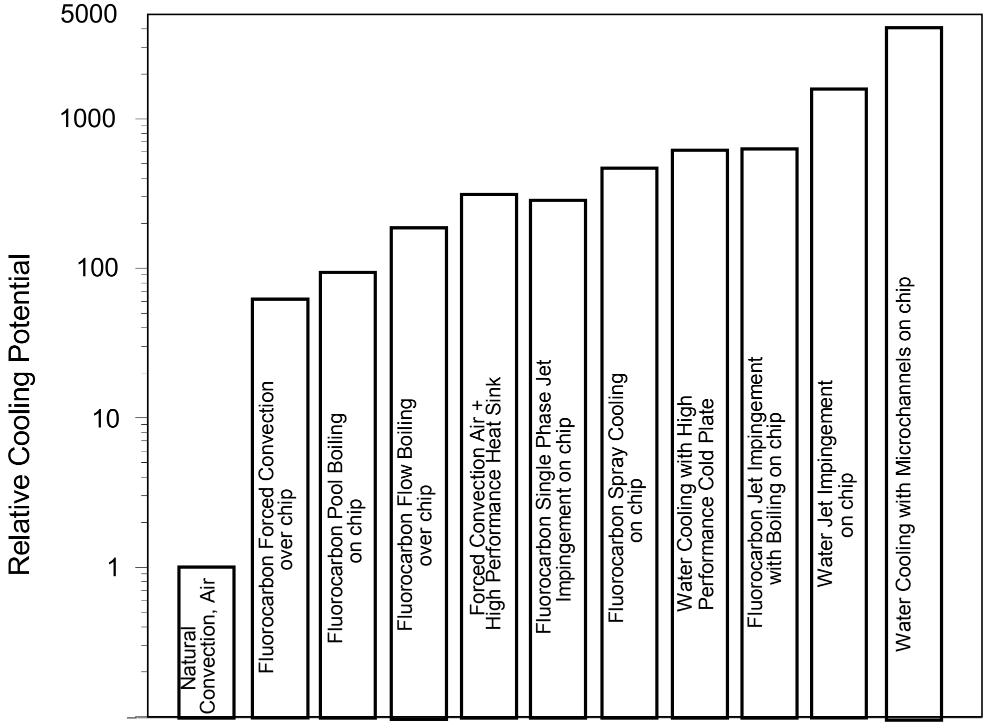
As was noted in an earlier section discussing telecommunications products, some of these products are installed in outside enclosures. An outside plant structure with no active means of controlling the temperature inside its envelope within a preset temperature range is referred to as a thermally uncontrolled environment. The thermal, heat dissipation, and the environmental issues are truly intertwined for such environments, and there is a need for better appreciation of how dramatically this environment differs from the controlled central office environment.

The bulk of sophisticated telecommunications equipment that goes into the thermally uncontrolled outdoor environment goes into outdoor cabinets. It is necessary to address requirements for these outdoor structures and associated telecommunications equipment. Successful implementation requires the specification of testing procedures for determining the cabinet temperature under outdoor design conditions. Key variables include equipment heat dissipation (internal load), equipment design (ventilation scheme), outdoor conditions (external load), and cabinet design (envelope, heat exchangers). It is also necessary to define basic environmental requirements for outside plant equipment that all equipment must satisfy. After specified aging and temperature cycling, the equipment must meet certain test criteria. The industry is currently developing new generic requirements applicable to uncontrolled outside plants. This document will not replace issued documents but rather—in one single volume—update, complement, and eliminate discrepancies among the documents as well as provide alternative ways of addressing thermal issues. For example, computer modeling has the potential to be faster, more cost-effective, and provide higher repeatability than conventional testing. Lastly, it may be possible to adopt an “Internal Thermal Loading” requirement, where an outdoor cabinet manufacturer would state the maximum equipment heat dissipation the cabinet can support such that the internal cabinet temperature is limited to the maximum equipment temperature. This approach would allow separation of equipment testing on one hand and housing testing on the other.

CRITICAL ISSUES

The continued use of air-cooling to maintain die temperatures below 100°C with higher die power will necessitate advanced fan/blower technology engineered for low acoustic noise and/or high-head operation, and further advances in the optimization and manufacture of heat sinks. Even with such advances, it is anticipated that more effective cooling technologies such as water cooling and possibly direct immersion will have to be utilized to meet the growing power dissipation requirements. Figure 13 illustrates the cooling potential of various modes of cooling relative to natural convection as a base. For example natural convection with a heat sink confined to the chip footprint might typically be in the range of 0.1 to 0.15 W/cm^2. The chart dramatically illustrates the wide range of cooling leverage (up to 4000X) offered by higher performance air cooling schemes, water cooling, and direct immersion cooling, albeit at increased levels of complexity and cost. In addition to the need to accommodate higher heat flux, lower junction temperatures may be desirable to improve performance and maintain high reliability as each new technology generation increases in complexity. Assembly and packaging technologies are being driven to simultaneously meet very demanding requirements in the areas of performance, power, junction temperature, package geometry, and cost. These demands, plus increased reliability expectations, will push the cooling and packaging limits of electronic products. Technology generations beyond 100 nm will either require materials beyond conventional metals and dielectrics or conceptually new approaches to interconnect. All of these areas will require increased focus in terms of thermal and packaging evaluation. Increases in the number of processors packaged within a system frame coupled with higher chip power will drive the total frame level power dissipation to higher and higher levels. This will necessitate the development of more efficient means of rejecting the heat load from the system such that heating of the room does not become excessive.

Figure 13 Relative cooling potential of various modes of cooling



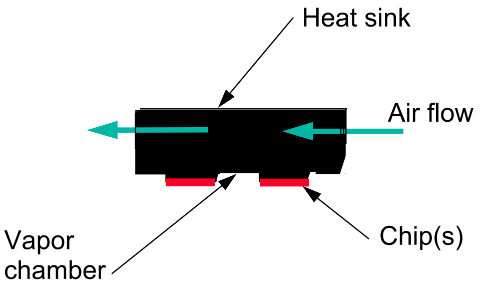
TECHNOLOGY NEEDS

Continued improvements in the thermal performance of electronic packages and systems to accommodate increased heat flux and maintain or even reduce junction temperature, will require the improvement of existing cooling technology, as well as the development and implementation of some new cooling techniques. Better ways will have to be developed, internal to the package, to spread and transport heat from concentrated chip heat sources to the external package/printed circuit board surfaces. Better ways will also have to be developed to spread and transport heat external to the package from the package/printed circuit board surfaces to the cooling medium. At the box/system level, improvements will have to be made in devices and techniques used to circulate and move the cooling fluid over the electronic packages to be cooled. Cooling techniques, which are currently in use (and are candidates for improvement) or which are projected for the future, are briefly identified in the following sections

THERMAL SPREADERS

Thermal spreaders have been used to spread heat from concentrated chip heat sources to the larger surface area provided by the module cap or heat sink for removal by the external cooling medium. Improved thermal spreaders, using higher conductivity materials (e.g. diamond or graphite composites), are needed to accommodate higher heat fluxes. Vapor chambers (Figure 14) are already being used as thermal spreaders and have potential for further applications in the future. Similarly, growing use of two-phase thermosyphons, micro-heat pipes, and MEMS (micro-electromechanical systems)-driven pumps for liquid loops can be anticipated.

Figure 14. Vapor chamber heat spreader



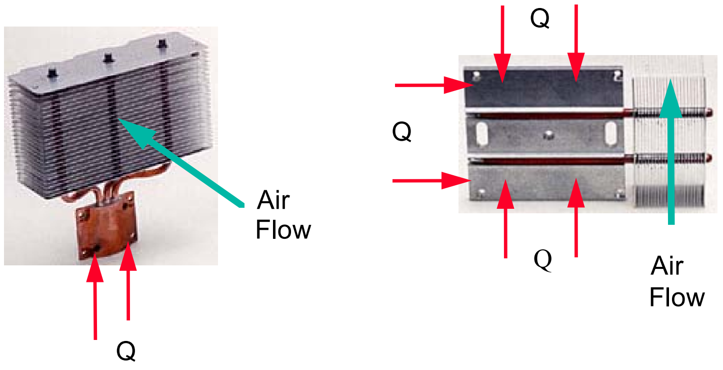
THERMAL INTERFACES

Thermal interface materials are used to provide a thermal conduction path between adjacent surfaces (e.g. chip and cap or chip and thermal spreader). Four types of materials are in use today: 1) epoxy type pastes loaded with high thermal conductivity powders, 2) elastomeric materials loaded with high thermal conductivity filler materials, 3) thermal greases loaded with high conductivity filler materials, and 4) solders. Many materials needs may be enumerated. The first need is a reliable and standardized method to measure the thermal performance of the thermal interface materials, which includes and distinguishes between the bulk conductivity of the material and the interfacial resistance that may exist due to different conditions in the material along a surface. Secondly, normal process variations need to be characterized to gain an understanding of the parameters that impact the thermal performance of the interface material during use conditions. Thirdly, time variant thermal properties need to be understood. Does the grease dry-out with time and heat, changing the thermal performance? Is the paste material sensitive to cracking under thermo-mechanical stress? Materials offering higher effective thermal conductivity in the range of 20-100 W/m-C, coupled with reduced bond line capability (~10-25µm) and low elastic moduli for stress decoupling in the laminate structure, are needed to meet future requirements.

Heat Pipes

Heat pipes (shown in Figure 15) are used in applications to provide a low thermal resistance path to remove heat from high-powered chips. In almost all cases the heat pipe is used to transfer the heat from a device to a region where space is available to accommodate the required size heat sink, or where air is not preheated by other components within the chassis. As power dissipation increases there will probably be more applications benefiting from the use of heat pipes.

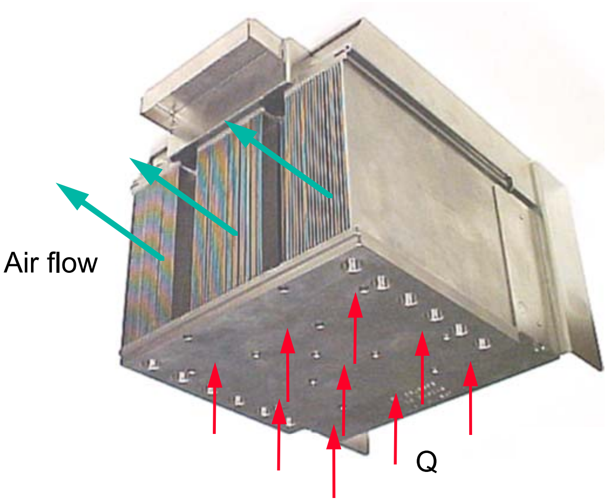
Figure 15 Examples of heat pipes used for electronics cooling



Air Cooling

Air-cooling has been, and continues to be, the most pervasive cooling option. Air-cooling is the preferred solution when it is necessary to keep cost within bounds. Significant engineering development will be needed to extend air-cooling limits to accommodate the power increases projected for the near future. It is expected that at a chip heat flux level of about 50 W/cm^2, conventional heat sink designs will become too large and major alternate solutions and innovations will be needed. High performance heat sink designs with high fin density and high aspect fins are continuing to evolve (Figure 16) and may provide some relief. Greater attention needs to be devoted to manufacturability considerations in design and to reducing manufacturing costs for high performance designs. System fans and active heat sink fans with enhanced, airflow and pressure drop characteristics are needed to support high performance heat sink designs. In addition, fans will have to be developed which exhibit reduced acoustic emissions.

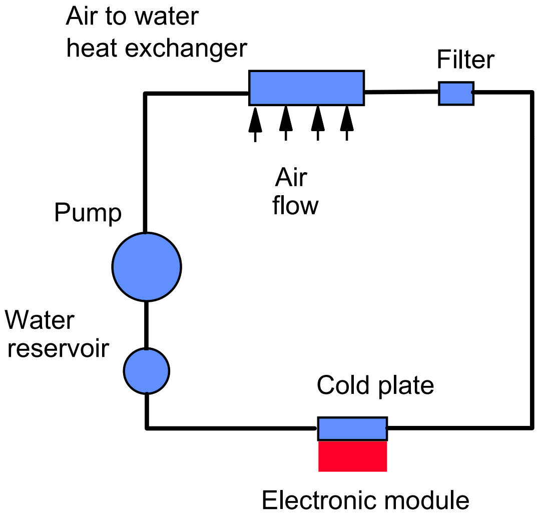
Figure 16 Example of a large air-cooled heat sink for a high performance, processor module



Water Cooling

Water has been effectively used in the past to cool high performance electronic modules. It is clear from the projected power increases in both the Large Business Systems and Office Systems product sectors that it will be necessary to resort to water cooling again, possibly within the next few years or sooner. The major requirement will be to develop an innovative, water-cooling technology that is both low-cost and reliable and occupies minimum volume in a system. Such a closed-loop water-cooling system could reject the total heat load to air via an air-to-water heat exchanger (as shown in Figure 17).

Figure 17 Closed loop water-cooling system with heat rejection to air



As already shown in Figure 13, direct water-cooling of chips offers the highest cooling potential. Although, the cooling potential of water-cooling with micro-channels is well established and has been demonstrated in the laboratory, considerable development will be required before this technique can be considered practical for implementation in a product.

Direct Immersion Cooling

It is possible that in some cases, even with improved thermal interface materials, the internal temperature rise from the case-to-chip may be too large because of the projected increase in power. In such instances it may be necessary to resort to direct immersion cooling with a dielectric liquid contacting the chip. Such cooling schemes could take the form of single-phase liquid-impingement jet cooling (Figure 18), pool boiling (with or without enhancements), or two-phase liquid spray cooling (Figure 19). Spray cooling of electronics within an enclosure has been implemented in military systems and in supercomputer modules. Whatever form the application of direct liquid immersion cooling may take, the major requirement will be that it is done at a reasonable cost, is reliable and occupies the minimum possible packaging volume.

Figure 18. Liquid jet impingement cooling

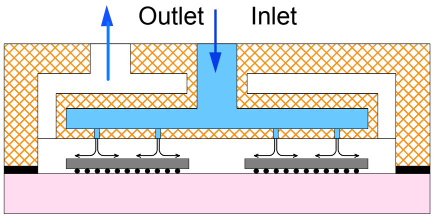
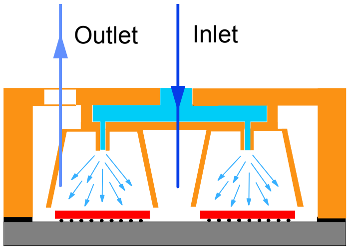


Figure 19 Liquid spray cooling



Refrigeration Cooling

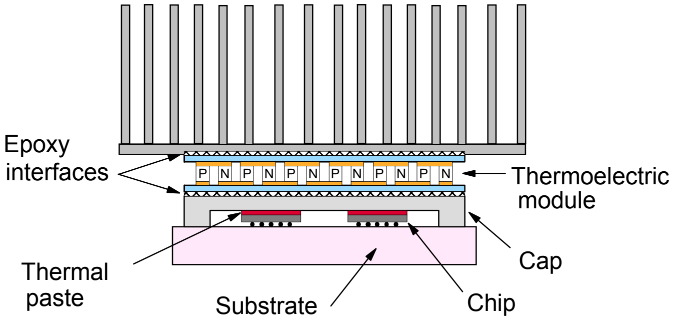
Both large servers and workstations have employed vapor compression cycle refrigeration (Figure 20) to lower temperatures of the CMOS (complementary metal oxide semiconductor) processor in order to achieve increased system performance. Current technologies exhibit improvements of approximately two percent for every 10°C reduction in chip temperature. With this technology, the evaporator is mounted directly on the processor module. The remaining hardware (i.e. compressor, condenser, valves, etc.) is typically packaged in a separate enclosure attached to the bottom of the system (workstation) or mounted inside the rack (servers). Using this technology chip temperatures in the range of -20 to 40°C have been achieved. As with water cooling the major requirement is to develop a refrigeration cooling technology, which is low cost, reliable, and occupies a minimum volume within the system.

Figure 20 Refrigeration loop and components for cooling a high performance processor

Thermoelectric Cooling

Thermoelectric coolers (Figure 21) offer the potential to enhance the cooling of electronic module packages to reduce chip junction temperatures or accommodate higher power. They also offer the advantages of being compact, quiet, with no moving parts, and they can provide an active control of temperature. Compared to vapor-compression refrigeration TECs are limited in the magnitude of the heat flux, which can be accommodated. TECs also exhibit a lower coefficient of performance (COP) than conventional refrigeration systems. The COP of a TEC will vary depending upon the usage conditions, but will typically be less than 1. This means that the electrical power consumed by the TEC will be as great as (and often more) than the power dissipated by the component being cooled. These limitations are due to the currently available materials and methods of fabrication. As a result, thermoelectric devices have been restricted to applications characterized by relatively low heat flux. A number of efforts are underway to improve the performance of thermoelectric coolers by the development of new thermoelectric materials and thin film coolers. If successful, these efforts promise increased heat pumping capability and higher COPs, which could open the door to a much broader application of thermoelectric devices to augment electronic cooling.

Figure 21 Cooling enhancement of an electronic module with a thermoelectric cooler



Thermal Design Tools

Sophisticated thermal design tools are now an essential element in the day-to-day design of electronic components, packages, and systems. These tools take a variety of forms. Thermal conduction codes are used to model heat flow and temperatures within a package. Computational fluid dynamics (CFD) codes are used to model fluid flow around and through package assemblies along with the associated pressure drop and heat transfer from exposed package surfaces to the fluid stream. In additon, some CFD codes have conjugate capability making it possible to model thermal conduction within the package structure simultaneously with modeling fluid flow and heat transfer in the cooling fluid.

Over the past decade much has been done to improve the graphical user interface for problem definition and data input, especially with CFD codes tailored for use to model electronic equipment. Nonetheless, further improvements are needed to reduce the time consumed in defining the package geometry and structure and to enter related data preparatory to running a model. Seamless integration of computer-aided design solid modeling tools, electronic design automation (EDA) tools, and CFD tools is needed providing thermal designers the ability to take

CAD solid modeling generated data and EDA generated data and move them effortlessly into finite element thermal conduction modeling tools or CFD modeling tools.

Further effort is required to optimize thermal analysis codes for parallel processing to reduce solution time and provide the capability to model more complex thermal problems. In addition, further work is required to enable CFD codes to better model turbulence and convective heat transfer in the transition flow regime. More extensive benchmarking is required to validate the accuracy of the CFD codes.

Further discussion of research and development needs in thermal and thermo-fluid simulations may be found in the **Modeling & Simulation Design Tools** section of this report.

GAPS AND SHOWSTOPPERS

The potential gaps and showstoppers related to thermal management are summarized for each product sector as follows:

LARGE BUSINESS SYSTEMS (HIGH PERFORMANCE)

As might be expected high performance products will continue to present a major thermal management challenge. Although some high performance computers already use refrigeration cooling, most still rely upon air-cooling. In order to extend air-cooling as much as possible it will be necessary to design and develop heat sinks with higher fin density. Methods of manufacturing high performance heat sinks (at low cost) need to be developed. In addition, it will be necessary to develop low cost, compact, high-pressure head air moving devices with reduced acoustic emissions to provide air flow across high performance heat sinks. Beyond 2001 maximum chip heat flux projections may exceed 50 W/cm^2 and may require the use of water-cooled cold plates or some form of immersion cooling. The key to whether or not water-cooled cold plates will be attractive to the system developer will hinge upon the development of low cost, reliable, compact water-cooling systems. In addition, it will be desirable - if not mandatory - to develop water-cooling systems, which reject their heat load to customer room air as opposed to customer, supplied water. The same requirements apply to immersion or vapor-compression cooled systems if they are to be considered. For both air and water-cooled scenarios, the heat transfer path from chip to package will need improvement, with respect to thermal interface enhancement.

OFFICE SYSTEMS (COST PERFORMANCE)

Office Systems products will also pose a significant thermal management challenge. Although chip heat fluxes are projected to be within the range of air-cooling, the maximum levels are well above what is commonly achieved at present. The higher levels will require improvements in air-cooling technology similar to those needed for the high performance sector. However, the problem of providing the required cooling improvements will be made even more severe due to the even greater cost constraints placed on this product sector. An alternative to high performance heat sinks on modules coupled with high-pressure head blowers might be a hybrid water-to-air cooling system (Figure 17). This approach would also require the development of new thermal components in terms of low cost, compact cold plates, pumps, and water-to-air heat exchangers. As in the case of high performance products, improvements will also be required in the paths internal to the chip/module package. Telecommunication products all fall within the range of air-cooling, but here also improvements may be needed at the high performance end.

At the box level, system heat rejection to customer-supplied water may need to be considered to reduce the heat load to customer air. As with the office systems product sector, this would necessitate the development of new thermal components in terms of low cost, compact cold plates, pumps, and heat exchangers. In addition base station cooling will also require improvements. The improvements required may include additional use of heat pipes and improved phase change materials for management of transient thermal loads.

PORTABLE

At present, it is possible to meet the projected thermal requirements for portable products by means of natural convection cooling coupled with radiation. This situation could change if breakthroughs are made in battery technology significantly increasing available power. If this happens more efficient means of spreading and rejecting the heat will be required. This could create a need for micro heat pipes and micro fans, which are not available today.

HARSH ENVIRONMENT

Automotive Electronics

For automotive applications, electronic components and system level packaging materials that can reliably operate at junction temperatures of 175°C for digital and analog devices and 200°C for power drivers are needed to reduce the need for higher cost and more complex thermal cooling systems. Passive thermal cooling systems will be preferred wherever possible. In addition to the current issues, it is anticipated that after 2003 high power 42-volt electrical systems and a much larger volume of hybrid and electric vehicles will substantially increase the need for high power thermal management systems. These applications will need packaging solutions capable of even higher power densities in order to make these systems technically feasible.

Military Electronics

For space-based phased-array-radar systems, low weight requirements will dictate new materials of low weight and high thermal conductivity. New phase change materials (PCM) will also be required. Radar arrays will also require the utilization of two-phase thermal management systems that employ capillary-pumped-loops with thin, flat evaporators and multiple parallel evaporators, such as those described in the section on telecommunication arrays. The power dissipation levels for these radar systems, however, will far exceed that of the telecommunication arrays.

Future electrical generation for the More Electric Aircraft (MEA) will require higher levels of power generation and increased thermal management. Power conditioning circuits will switch from silicon substrates to silicon carbide (SiC) substrates with a 5x increase in heat flux for air-cooled applications and a more than 3x increase in heat flux for liquid cooled applications. The corresponding operating temperatures will increase from 150 to 250°C for both applications.

The thermal technology improvements needed for each product sector to fill gaps and avoid showstoppers are summarized in Table 2.

Table 2 Thermal Improvements Needed by Product Sector

Product Sector	Requirements
Portable	No significant improvements needed as long as battery power remains constrained. Breakthroughs in plastic batteries could necessitate more aggressive thermal solutions (e.g. improved thermal interfaces, thermal spreaders, package integrated heat sinks, etc.)
Office Systems	Improved thermal interfaces Thermal spreaders Thermal integration with EMC shielding Low cost, compact and reliable water cooling Low cost, compact, reliable and efficient refrigeration High heat flux, efficient thermoelectric cooler High performance air cooling solutions Advanced modeling tools
Large Business Systems	Improved thermal interfaces Thermal spreaders Mechanically robust packages that minimize the thermal resistance path to air Thermal integration with EMC shielding Low cost, compact and reliable water cooling Low cost, compact, reliable and efficient refrigeration Low cost, compact, and reliable dielectric liquid cooling High heat flux, efficient thermoelectric cooler Abatement of heat load impact on installation Advanced modeling tools
Automotive, Military	Low cost, reliable heat pipe technology for automotive environment Passive electrical components/system level packaging materials capable of operating at 150 ^oC Low-cost liquid or refrigerant cooling systems utilizing automotive cooling components Low- cost, self-contained, phase change materials Analog and digital ICs capable of operating w/ T_J = 170 ^oC Power transistor capable of operating w/ T_J = 200 ^oC Capillary-pumped loops with very flat, multiple-parallel-path evaporators PWBs with high-efficiency, copper, power and signal plane layers Light-weight, high latent heat of fusion, PCMs with capability to vary the melting point Direct immersion cooling of RF MMIC chips using sub-cooled flow boiling Improved fan performance making the air-cooling of military electronics more feasible

RESEARCH NEEDS

The continued development of new and improved thermal management technology will require the combined efforts of industry based development and university based research with a focus on practical application. Extensive heat transfer, thermo-fluid, and thermomechanical research is needed to define new opportunities (i.e. path breaking) and to improve predictability and reliability (i.e. gap-filling). Research outcomes required to satisfy the thermal technology needs identified in the previous section are outlined below:

THERMAL SPREADERS -

- Inexpensive, high thermal conductivity, materials (possibly composites) offering a closer expansion match to the TCE of silicon
- Algorithms for optimizing thermal/thermomechanical design of thermal spreaders
- Techniques for achieving improved thermal spreading within a chip to alleviate hot spots due to localized high heat flux concentrations
- Correlations and analytical models of dry-out and rewetting of micro-channels and micro-porous structures to facilitate design of micro-heat pipes

THERMAL INTERFACES -

- Thermal pastes, epoxies, and elastomers loaded with high thermal conductivity nanoparticles
- New interface materials based on carbon nanotubes and other materials
- Novel techniques/materials to minimize interfacial stresses
- Correlations and analytic relations to predict fatigue life of bonded interfaces
- Standardized method to characterize thermal performance of interface materials
- Self-contained solid-to-solid phase change materials or micro-encapsulated materials as suitable interface materials for a range of applications including harsh environment

HEAT PIPES -

- Flexible heat pipes
- Heat pipes that handle high heat fluxes
- Low cost heat pipes that can transport heat effectively over large distances (>0.5 m)
- Designs to reduce the gravitational orientation impact on heat pipe efficiency, especially for avionics applications
- Heat pipe technology capable of withstanding harsh environments
- Sound numerical models and optimization tools for predicting the performance and operational limits, including dry-out, in heat pipes
- Correlations and algorithm for design of thermosyphons (i.e. wickless heat pipe)

AIR COOLING -

- Models and correlations to predict heat transfer in transition and low Reynolds number flow over packages and in heat sink passages
- Low Reynolds number turbulence models for use in CFD codes
- Heat sink design and optimization procedures for the minimization of heat sink thermal resistance, subject to mass and volume constraints
- Advanced manufacturing techniques for metal and composite material heat sinks
- Concepts for higher head-moderate flow, low noise, compact fans
- Novel, low power consumption, low acoustic emission micro-fans for forced convection cooling in notebook computers and handheld electronics, including low-frequency and ultrasonic piezoelectric fans
- Novel miniature fan concepts including low-frequency and ultrasonic piezoelectric fans for minimal noise emission and power consumption
- High pressure/high flow blowers with low acoustical power

WATER COOLING -

- Miniaturized components that have high reliability and provide enhanced
- performance (e.g. pumps and heat exchangers)
- MEMS and meso-scale components to create low-cost, low-noise, water-to-air heat exchangers
- MEMS and meso-scale components to create low cost, package-size cold plates
- Microchannel heat sinks with novel integrated micropumps to minimize package volume for high heat flux applications
- Methods to enable direct water cooling of chips or chip packages

Direct Liquid Immersion -

- Single-phase and two-phase heat transfer correlations for new families of dielectric coolants
- Nanoparticles for addition to dielectric coolants to create a nanofluid with enhanced heat transfer characteristics
- Convective and phase change cooling correlations to account for highly non-uniform heat flux boundary conditions
- CHF (critical heat flux) models to account for highly non-uniform surface heat fluxes
- Characterization of boiling and two-phase flow in narrow passages and 3-D structures
- MEMS and mesoscale components to enhance convective, as well as pool and flow boiling, heat transfer
- Correlations and models for evaporative spray cooling heat transfer

SUB-AMBIENT AND REFRIGERATION COOLING -

- Highly reliable miniaturized components such as compressors, condensers and evaporators
- MEMS and mesoscale components to create low-cost, low noise refrigerators using solid-state, vapor compression, or absorption cycles
- MEMS and mesoscale components to create low-cost, package- size cold plates using solid-state, vapor compression, or absorption cycles
- New thermoelectric materials and fabrication methods that can improve the performance of thermoelectric coolers

LOW TEMPERATURE REFRIGERATION -

- Application of Auto-refrigerating Cascade (ARC) systems to provide low temperature cooling for electronic packages
- Application of mechanically cascaded (2-stage) refrigeration systems to provide low temperature cooling for electronic packages

ADVANCED COOLING TECHNOLOGY DEVELOPMENT ACTIVITIES

The need for the development of compact, high heat flux cooling devices has recently received attention by federal government research agencies. The largest focused program of this type over the past two decades is the three year (1999-2002) *HERETIC* program funded through the Defense Advanced Research Projects Agency (DARPA). Under this program, several multi-investigator teams of researchers from university, industry, and government laboratories have focused on the development of micro-fluidic and solid-state heat removal methodologies and devices that are integrable with dense, high performance electronics and photonics. Such devices are envisioned to be capable of dramatically reducing the thermal resistance between heat sources and the thermal sinks. They should also lead to a reduction in overall system volume and weight.

Brief summaries of the individual projects constituting the fluidic and solid-state efforts are given below. The focus of the fluidic effort has focused on spray cooling, heat pipes, thermosyphons, and compact flow loops. Further project details and an overview of the *HERETIC* program, may be found at the DARPA HERETIC web site (www.darpa.mil/mto/heretic/index.html).

- ***EDIFICE: Embedded Droplet Impingement for Integrated Cooling of Electronics*** *(lead institution – Carnegie Mellon University)*

  This project is directed at developing an integrated droplet, impingement cooling device called EDIFICE for embedded droplet impingement for cooling of electronics. The device is aimed at accommodating heat fluxes in the range of 50–100 W/cm^2 in portable electronics. It will combine efficient phase-change heat transfer utilizing latent heat of vaporization of dielectric coolants and on-chip control to provide localized, adaptive, on-demand cooling.

- ***Integrated Thermal Management Using Laminate and Ceramic – MEMS Technologies*** *(lead institution – Florida International University)*

  This effort is aimed at the development of thermal management approaches integrated into a multi-layer co-fired ceramic substrate. The two approaches being pursued are: 1) passive cooling using embedded micro heat pipe structures as both heat pipes and heat spreaders; and 2) active cooling using integrated piezo pumped, no-moving parts micro-pumps and micro-machined fluid channels. The integration of passive, heat spreading, micro-heat exchangers, and pumped liquid cooling should accommodate heat fluxes in the 200 W/cm^2 range.

- ***Microfluidic Technologies for Integrated Thermal Management: Micro-machined Synthetic Jets (λJets) and VIDA Heat Transfer Cells*** *(lead institution – Georgia Institute of Technology)*

  The goal of this project is to provide new thermal management technologies for integrated circuits over a broad range of power dissipation requirements. The researchers will develop and demonstrate two novel micro-fluidic technologies that produce micro-scale fluid flows designed to increase the local heat transfer from integrated circuits at the device and package levels, and the global heat transfer from external surfaces to ambient air.

- ***Chip Level Thermal Management Using MEM Thermoacoustic Refrigerators*** *(lead institution – Rockwell Science Center)*

  Thermoacoustic refrigeration is a novel refrigeration process utilizing acoustic energy to produce heat pumping. It has the potential for high efficiency operation, without the need for cooling liquids or moving parts, making it amenable to miniaturization to chip-scale dimensions for thermal management of electronic components. The goal of the project is the development and demonstration of a miniaturized refrigeration device based on the thermoacoustic principle.

- ***Electro-kinetic Micro Coolers*** *(lead institution – Stanford University)*

  Two-phase convection heat transfer devices yield the highest cooling rates per unit volume in electronic systems. Far greater rates of cooling can be achieved using high –pressure pumping (>5 atm) of the liquid phase. Until now, the IC industry has lacked compact, inexpensive pumps that can reliably deliver the required pressure drop. This project will develop two-phase cooling devices using electro-kinetic (EK) pumping of the liquid phase.

- ***Microfabrication Alliance for Innovative Cooling of Microelectronics (MAICOM)*** *(lead institutions – Georgia Institute of Technology/University of Maryland))*

  This project will develop two promising microfabricated thermal management technologies that allow direct integration with chips and can provide on demand, variable capacity cooling using liquids. Two-phase thermosyphons with compact heat evaporators employing microfabricated enhancement structures and compact, single-phase and two-phase forced fluid loops incorporating fabricated heat exchangers will be developed. In addition, thin, flat, high performance heat spreader substrates using microfabricated wick structures will also be developed.

- ***Integrated Micro-Module for High Thermal Flux Removal*** *(lead institution – University of California, Berkeley)*

  The goal of this effort is to integrate high-speed electronics with an active, controlled thermal management system. A micro-cooler system will be developed that will reside directly on the heat-producing chips. A thermal management approach that will include micro-machined channels in both silicon and a ceramic substrate will be used for module level integration.

- ***Modular Micromachined Si Heat Removal*** *(lead institution – University of California, Los Angeles)*

  This project is aimed at reducing the thermal resistance of the semiconductor chip itself, and the thermal resistance between the "convector" and the air that is the ultimate heat sink. Using patterned reactive ion etching followed by anodic (porous) silicon vapor channels (large porosity) and liquid channels (low porosity) will be created "monolithically" from the silicon chip and coupled to a bi-porous micro-heat-pipe with theoretical capability of handling up to 1kW/cm^2. For moderate-power-density devices with high absolute power, an active module based on phase change micro-jets, like an inkjet printer, with a condenser will be developed. Two fully packaged and operational electronic devices will be built from the new thermal management technology and tested.

- ***Monolithically Integrated Thermoelectric Coolers for Mid-IR Laser*** *(lead institution – Jet Propulsion Laboratory)*

  This effort seeks to address innovative solid-state thermal management device development, integration and packaging, modeling and simulation and a system demonstration focused on mid-infrared lasers. The team is investigating the integration of advanced thermoelectric microdevices operating under pulsed conditions with IR lasers as a means of achieving deep spot cooling of the laser active region. The successful development of such monolithically integrated thermoelectric microcoolers with mid-IR lasers into a near room temperature thermal management package will free such lasers from the requirement of liquid cryogens and provide compact, low cost IR, and coherent IR sources for dual use applications.

- ***Integrated Microelectronics and Photonics Active Cooling Technology*** *(lead institution – University of California, Santa Cruz)*

  This project is aimed at a new approach for active cooling based on heterostructure integrated thermionic (HIT) coolers utilizing conventional semiconductor materials so that coolers and optical devices can be integrated. The core of the solution is the use of heterojunctions to filter the hot from the cold electrons and achieve cooling. With modern

MBE (molecular beam epitaxy) and MOCVD (metal organic chemical vapor deposition) growth techniques, the barrier height can be adjusted and optimized for cooling at a given temperature. Furthermore, it is relatively simple to individually tune barrier heights in multistage coolers to improve the performance. The overall research effort involves a wide spectrum of activities ranging from nanostructured materials design and growth, device design and fabrication, novel measurements of thermoelectric behavior, and finally, systems integration and packaging.

- ***Heat Removal by Inverse Nottingham Effect*** *(lead institution – University of North Carolina)*

  This project is exploring the selection of materials, structures and design to realize efficient cooling in semiconductors by means of the inverse Nottingham effect. Basically, emitted electrons are at higher energy under the application of a large electric field on the surface of a semiconductor. If these electrons can be collected in vacuum to avoid heating, and the electrons for the replenishment to re-establish thermal equilibrium come from lower energy such as the valence band, cooling can result. The research program is organized into 3 phases focusing on: 1) the demonstration of cooling with several schemes such as the incorporation of resonant tunneling, and lowering of the emission barrier by coating as well as bandgap engineering; 2) selection of the most viable system; and 3) optimization of a basic system for actual cooling applications.

RECOMMENDATIONS

The following constitutes the major cooling technology areas for development and innovation:

- Low cost, higher thermal conductivity, packaging materials, such as adhesives, thermal pastes, and thermal spreaders need to be developed for use in products ranging from high performance computers to automotive applications.
- Advanced cooling technology in the form of high performance heat pipe/vapor chamber cooling technology, thermoelectric cooling technology, direct liquid cooling technology, as well as high performance air-cooling and air-moving technologies, need to be investigated.
- Closed loop, liquid-cooling solutions, which are compact, cost-effective, and reliable should be developed.
- High-performance cooling systems, which will minimize the impact to the environment within the customer's room and beyond, need to be developed.
- Advanced modeling tools which integrate the electrical, thermal, and mechanical aspects of package/product function, while providing enhanced usability and minimizing interface incompatibilities, need to be developed.
- Advanced experimental tools for flow, temperature and thermomechanical measurements for obtaining local and *in-situ* measurements in microcooling systems

It is further recommended that action should be taken to pool resources to fund cooling technology development, promote the involvement of university/research labs and establish a closer working relationship with vendors.

GLOSSARY

ARC	Auto-refrigerating cascade
CAD	Computer-aided design
CFD	Computational Fluid Dynamics
CHF	Critical heat flux
CMOS	Complementary metal oxide semiconductor
COP	Coefficient of Performance
COTS	Commercial-off-the-shelf
CTE	Coefficient of thermal expansion
EMC	Electromagnetic compatibility
FPA	Focal plane array
GaN	Gallium nitride
Gb	Gigabyte
GEO	Geosynchronous Earth Orbit
IC	Integrated circuit
IP	Internet Protocol
IR	Infrared
J-T	Joule-Thomson
LEO	Low Earth Orbit
MEA	More Electric Aircraft
MEMS	Microelectronic mechanical systems
MEO	Middle Earth Orbit
MMIC	Monolithic Microwave Integrated Circuit
NEMI	National Electronics Manufacturing Initiative
PDA	Personal digital assistant
PC	Personal computer
PCM	Phase change material
PWB	Printed wire board
RF	Radio frequency
SMT	Surface mount technology
Tb	Terabyte
TEC	Thermoelectric cooler

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