The Changing Automotive Environment: High-Temperature Electronics

R. Wayne Johnson, *Fellow, IEEE*, John L. Evans, Peter Jacobsen, James R. (Rick) Thompson, and Mark Christopher

***Abstract*—The underhood automotive environment is harsh and current trends in the automotive electronics industry will be pushing the temperature envelope for electronic components. The desire to place engine control units on the engine and transmission control units either on or in the transmission will push the ambient temperature above 125 °C. However, extreme cost pressures, increasing reliability demands (10 year/241 350 km) and the cost of field failures (recalls, liability, customer loyalty) will make the shift to higher temperatures occur incrementally. The coolest spots on engine and in the transmission will be used. These large bodies do provide considerable heat sinking to reduce temperature rise due to power dissipation in the control unit. The majority of near term applications will be at 150 °C or less and these will be worst case temperatures, not nominal. The transition to X-by-wire technology, replacing mechanical and hydraulic systems with electromechanical systems will require more power electronics. Integration of power transistors and smart power devices into the electromechanical actuator will require power devices to operate at 175 °C to 200 °C. Hybrid electric vehicles and fuel cell vehicles will also drive the demand for higher temperature power electronics. In the case of hybrid electric and fuel cell vehicles, the high temperature will be due to power dissipation. The alternates to high-temperature devices are thermal management systems which add weight and cost. Finally, the number of sensors in vehicles is increasing as more electrically controlled systems are added. Many of these sensors must work in high-temperature environments. The harshest applications are exhaust gas sensors and cylinder pressure or combustion sensors. High-temperature electronics use in automotive systems will continue to grow, but it will be gradual as cost and reliability issues are addressed. This paper examines the motivation for higher temperature operation, the packaging limitations even at 125 °C with newer package styles and concludes with a review of challenges at both the semiconductor device and packaging level as temperatures push beyond 125 °C.**

***Index Terms*—Automotive, extreme-environment electronics.**

TABLE I
MAJOR AUTOMOTIVE ELECTRONIC SYSTEMS

Category	Example Systems
Engine & Power Train	EFI (electronic fuel injection), ECU (engine control unit), TCU (transmission control unit), KCS (knock control system), cruise control, cooling fans
Chassis & Safety	Active 4-wheel steering, active control suspension, ABS (anti-lock brake system), TRC (traction control system), VSC (vehicle stability control), air bag system
Comfort & Convenience	Preset steering wheel position, climate control, power seat, power windows, door lock control, mirror controls
Displays & Audio	Radio (AM, FM, satellite), CD player, TV and DVD player, cellular phone, navigation system, instrument cluster
Signal Communications & Wiring Harness	Communications bus, starter, alternator, battery, diagnostics

TABLE II
AUTOMOTIVE TEMPERATURE EXTREMES (DELPHI DELCO ELECTRONIC SYSTEMS) [3]

Location	Typical Continuous Max Temperature	Vibration Level	Fluid Exposure
On engine On transmission	140°C	Up to 10Grms	Harsh
At the engine (intake manifold)	125°C	Up to 10Grms	Harsh
Underhood (near engine)	120°C	3 – 5Grms	Harsh
Underhood (remote location)	105°C	3 – 5Grms	Harsh
Exterior	70°C	3 – 5Grms	Harsh
Passenger compartment	70-80°C	3 – 5Grms	Benign

I. INTRODUCTION

IN 1977, the average automobile contained $110 worth of electronics [1]. By 2003 the electronics content was $1510 per vehicle and is expected to reach $2285 in 2013 [2]. The turning point in automotive electronics was government regulation in the 1970s mandating emissions control and fuel economy. The complex fuel control required could not be accomplished using traditional mechanical systems. These government regulations coupled with increasing semiconductor computing power at decreasing cost have led to an ever increasing array of automotive electronics. Automotive electronics can be divided into five major categories as shown in Table I.

The operating temperature of the electronics is a function of location, power dissipation by the electronics, and the thermal design. The automotive electronics industry defines high-temperature electronics as electronics operating above 125 °C. However, the actual temperature for various electronics mounting locations varies considerably. Delphi Delco Electronic Systems recently published the typical continuous maximum temperatures as reproduced in Table II [3]. The corresponding underhood temperatures are shown in Fig. 1. The authors note that typical junction temperatures for integrated circuits are 10 °C to 15 °C higher than ambient or baseplate temperature, while power devices can reach 25 °C higher. At-engine temperatures of 125 °C peak can be maintained by placing the electronics on the intake manifold.

Manuscript received August 18, 2003.

R. W. Johnson is with the Electrical and Computer Engineering Department, Auburn University, Auburn, AL 36849 USA (e-mail: johnson@eng.auburn.edu).

J. L. Evans is with the Industrial and Systems Engineering Department, Auburn University, Auburn, AL 36849 USA (e-mail: jevans@eng.auburn.edu).

P. Jacobsen is with the Automotive Advanced Product Development, Eaton Corporation, Southfield, MI 48076 USA (e-mail: PeterJacobsen@Eaton.com).

J. R. Thompson and M. Christopher are with Siemens VDO Automotive–Hunstville, Huntsville, AL 35824 USA (e-mail: thompson-james@siemens.com; mark.christopher@siemens.com).

Digital Object Identifier 10.1109/TEPM.2004.843109

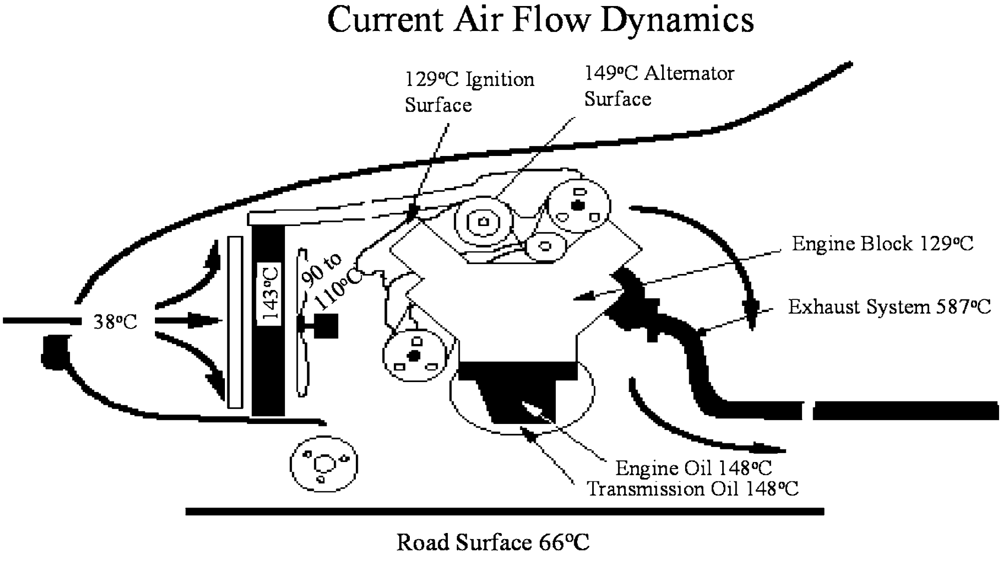

Fig. 1. Engine compartment thermal profile (Delphi Delco Electronic Systems) [3].

TABLE III
THE AUTOMOTIVE ENVIRONMENT (GENERAL MOTORS AND DELPHI DELCO ELECTRONIC SYSTEMS) [4]

Temperature	Driver interior	-40°C to +85°C
	Underhood	-40°C to +125°C
	On-engine	-40°C to +150°C
	In the exhaust and combustion areas	-40°C to +200-600°C
Mechanical Shock	During assembly (drop test)	3000g
	On the vehicle	50-500g
Mechanical Vibration		15g, 100Hz to 2kHz
Electromagnetic Impulses		100 to 200V/m
Exposure to	Common	Humidity, salt spray
	In some applications	Fuel, oil, brake fluid, transmission fluid, ethylene glycol, exhaust gases

TABLE IV
REQUIRED OPERATION TEMPERATURE FOR AUTOMOTIVE ELECTRONIC SYSTEMS (TOYOTA MOTOR CORP. [5]

ECU Location	Detail Position	Required Operation Temperature
Passenger Room	Under dash board	-30 to +85°C
Engine Room	ECU Box	-30 to +105°C
	Underhood	-30 to +125(150)°C
	Connected to Engine	-30 to >+175°C

TABLE V
MECHATRONIC MAXIMUM TEMPERATURE RANGES (DAIMLERCHRYSLER, EATON CORPORATION, AND AUBURN UNIVERSITY) [6]

On-Engine	150 –200° C
In-Transmission	150 – 200°C
On Wheel - ABS sensors	150 – 250°C
Cylinder pressure	200 – 300°C
Exhaust sensing	Up to 850°C, ambient 300°C

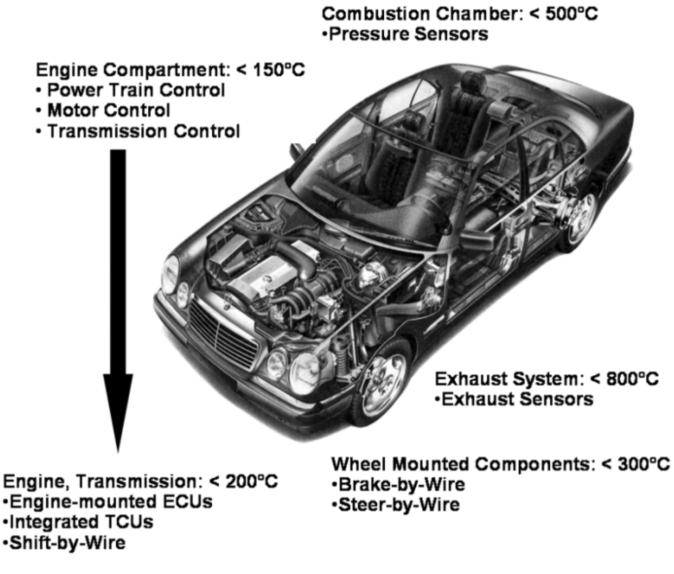

Fig. 2. Automotive temperatures and related systems (DaimlerChrysler) [8].

In a 1998 paper, authors from General Motors Global Research and Development Operations and Delphi Delco Electronic Systems described the automotive environment for sensors and actuators as shown in Table III [4]. In 1999, Toyota Motor Corporation, IC Design and Evaluation Department published the required operation temperatures for automotive electronics systems shown in Table IV [5]. In this case, the engine control unit (ECU) box is a specially designed area with air or water cooling. It was also noted that in the engine cylinder block, over 200 °C is reached.

DaimlerChrysler, Eaton Corporation, and Auburn University jointly published a summary of automotive high-temperature electronics requirements that is shown in Table V [6]. The current DaimlerChrysler on-engine temperature specification is −40 °C to +165 °C and the in-transmission specification is −40 °C to +150 °C [7]. Fig. 2 shows temperatures and related automotive electronic systems [8]. Fig. 3 shows an actual measured transmission temperature profile during normal and excessive driving conditions [8]. Power braking is a commonly used test condition where the brakes are applied and the engine is revved with the transmission in gear. A similar real-world situation would be applying throttle with the emergency brake applied. Note that when the temperature reached 135 °C, the over temperature light came on and at the peak temperature of 145 °C, the transmission was beginning to smell of burnt transmission fluid.

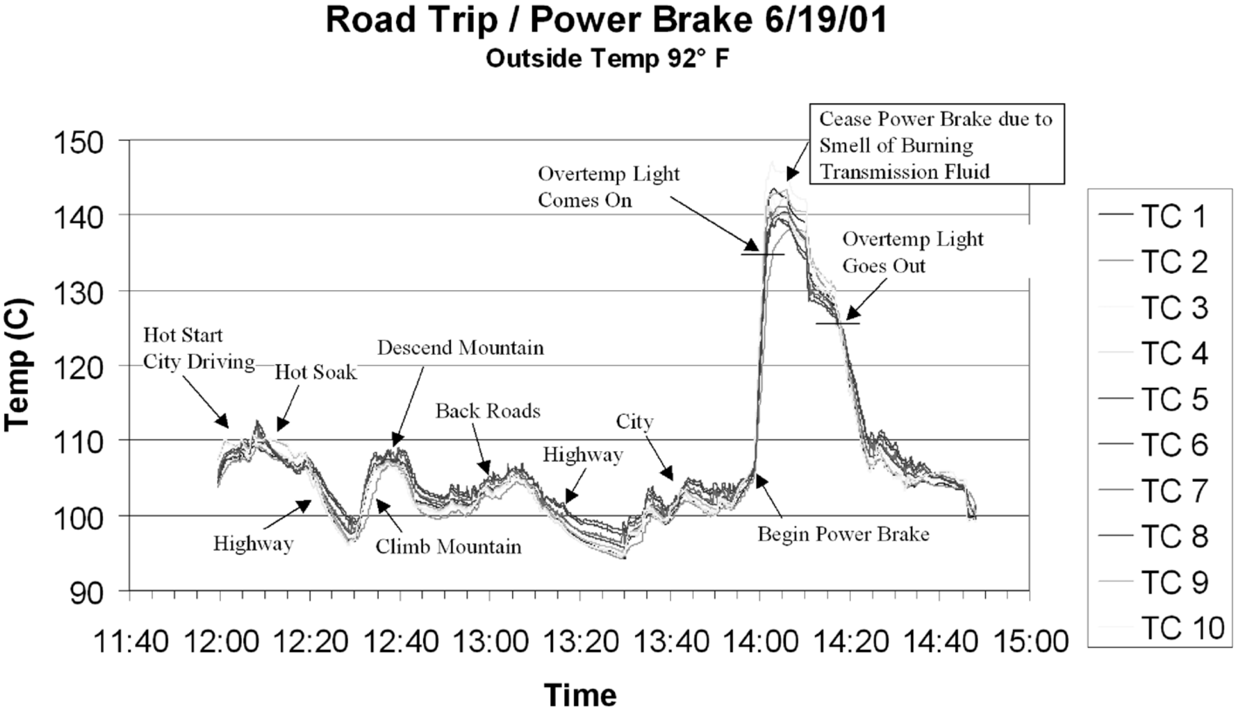

Fig. 3. Measured transmission temperatures during normal and excessive driving conditions. (DaimlerChrysler) [8].

TABLE VI
2002 INTERNATIONAL TECHNOLOGY ROADMAP FOR SEMICONDUCTORS AMBIENT OPERATING TEMPERATURES FOR HARSH ENVIRONMENTS (AUTOMOTIVE) [9]

	2001	2002	2003	2004	2005	2006	2007
Complex ICs	-40°C to +125°C	-40°C to +125°C	-40°C to +125°C	-40°C to +125°C	-40°C to +125°C	-40°C to +125°C	-40°C to +125°C
Power/Linear	-40°C to +150°C	-40°C to +150°C	-40°C to +180°C	-40°C to +180°C	-40°C to +200°C	-40°C to +200°C	-40°C to +200°C

The 2002 update to the International Technology Roadmap for Semiconductors (ITRS) did not reflect the need for higher operating temperatures for complex integrated circuits, but did recognize increasing temperature requirements for power and linear devices as shown in Table VI [9]. Higher temperature power devices (diodes and transistors) will be used for the power section of power converters and motor drives for electromechanical actuators. Higher temperature linear devices will be used for analog control of power converters and for amplification and some signal processing of sensor outputs prior to transmission to the control units. It should be noted that at the maximum rated temperature for a power device, the power handling capability is derated to zero. Thus, a 200 °C rated power transistor in a 200 °C environment would have zero current carrying capability. Thus, the actual operating environments must be lower than the maximum rating.

In the 2003 edition of the ITRS, the maximum junction temperatures identified for harsh-environment complex integrated circuits was raised to 150 °C through 2018 [9]. The ambient operating temperature extreme for harsh-environment complex integrated circuits was defined as −40 °C to +125 °C through 2009, increasing to −40 °C to +150 °C for 2010 and beyond. Power/linear devices were not separately listed in 2003.

The ITRS is consistent with the current automotive high-temperature limitations. Delphi Delco Electronic Systems offers two production engine controllers (one on ceramic and one on thin laminate) for direct mounting on the engine. These controllers are rated for operation over the temperature range of −40 °C to +125 °C. The ECU must be mounted on the coolest spot on the engine. The packaging technology is consistent with 140 °C operation, but the ECU is limited by semiconductor and capacitor technologies to 125 °C.

The future projections in the ITRS are not consistent with the desire to place controllers on-engine or in-transmission. It will not always be possible to use the coolest location for mounting control units. Delphi Delco Electronics Systems has developed an in-transmission controller for use in an ambient temperature of 140 °C [10] using ceramic substrate technology. DaimlerChrysler is also designing an in-transmission controller for use with a maximum ambient temperature of 150 °C (Figs. 4 and 5) [11].

II. MECHATRONICS

Mechatronics, or the integration of electrical and mechanical systems offers a number of advantages in automotive assembly. Integration of the engine controller with the engine allows pretest of the engine as a complete system prior to vehicle assembly. Likewise with the integration of the transmission controller and the transmission, pretesting and tuning to account for machining variations can be performed at the transmission factory prior to shipment to the automobile assembly site. In addition, most of the wires connecting to a transmission controller run to the solenoid pack inside the transmission. Integration of

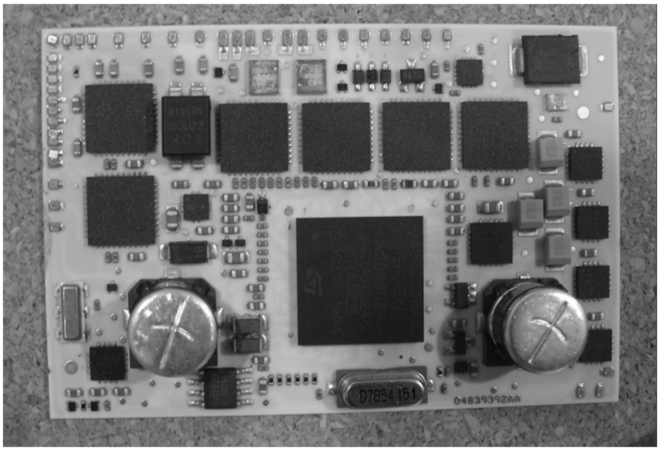

Fig. 4. Prototype DaimlerChrysler ceramic transmission controller [11].

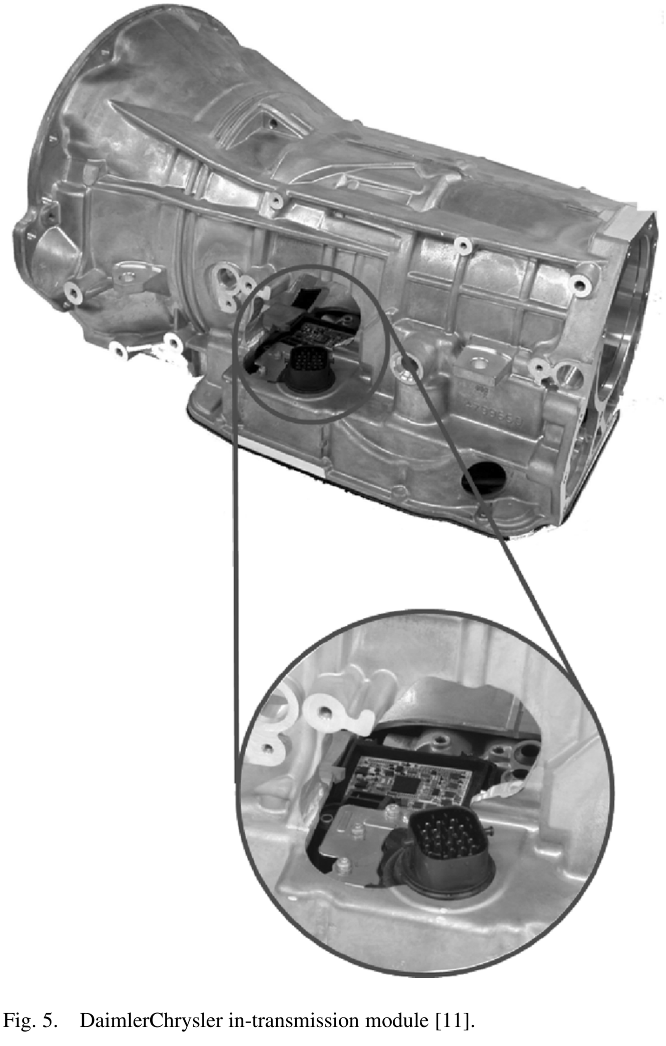

Fig. 5. DaimlerChrysler in-transmission module [11].

the controller into the transmission reduces the wiring harness requirements at the automobile assembly level.

The trend in automotive design is to distribute control with network communications. As the industry moves to more X-by-wire systems, this trend will continue. Automotive final assembly plants assemble subsystems and components supplied by numerous vendors to build the vehicle. Complete mechatronic subsystems simplify the design, integration, management, inventory control, and assembly of vehicles. As discussed in the previous section, higher temperature electronics will be required to meet future mechatronic designs.

III. PACKAGING CHALLENGES AT 125 °C

Trends in electronics packaging, driven by computer and portable products are resulting in packages which will not meet underhood automotive requirements at 125 °C. Most notable are leadless and area array packages such as small ball grid arrays (BGAs) and quad flatpacks no-lead (QFNs). Fig. 6 shows the thermal cycle test $(-40\ ^\circ\mathrm{C}$ to $+125\ ^\circ\mathrm{C})$ results for two sizes of QFN from two suppliers [12]. A typical requirement is for the product to survive 2000–2500 thermal cycles with $< 1\%$ failure for underhood applications. Smaller I/O QFNs have been found to meet the requirements.

Fig. 7 presents the thermal cycle results for BGAs of various body sizes [13]. The die size in the BGA remained constant (8.6×8.6 mm). As the body size decreases so does the reliability. Only the 23-mm BGA meets the requirements. The 15-mm BGA with the 0.56-mm-thick BT substrate nearly meets the minimum requirements. However, the industry trend is to use thinner BT substrates (0.38 mm) for BGA packages.

One solution to increasing the thermal cycle performance of smaller BGAs is to use underfill. Capillary underfill was dispensed and cured after reflow assembly of the BGA. Fig. 8 shows a Weibull plot of the thermal cycle data for the 15-mm BGAs with four different underfills. Underfill UF1 had no failures after 5500 cycles and is, therefore, not plotted. Underfill, therefore, provides a viable approach to meeting underhood automotive requirements with smaller BGAs, but adds process steps, time, and cost to the electronics assembly process.

Since portable and computer products dominate the electronics market, the packages developed for these applications are replacing traditional packages such as QFPs for new devices. The automotive electronics industry will have to continue developing assembly approaches such as underfill just to use these new packages in current underhood applications.

IV. TECHNOLOGY CHALLENGES ABOVE 125 °C

The technical challenges for high-temperature automotive applications are interrelated, but can be divided into semiconductors, passives, substrates, interconnections, and housings/connectors. Industries such as oil well logging have successfully fielded high-temperature electronics operating at 200 °C and above. However, automotive electronics are further constrained by high-volume production, low cost, and long-term reliability requirements. The typical operating life for oil well logging electronics may only be 1000 h, production volumes are in the range of 10s or 100s and, while cost is a concern, it is not a dominant issue. In the following paragraphs, the technical challenges for high-temperature automotive electronics are discussed.

Semiconductors: The maximum rated ambient temperature for most silicon based integrated circuits is 85 °C, which is sufficient for consumer, portable, and computing product applications. Devices for military and automotive applications are typically rated to 125 °C. A few integrated circuits are rated to

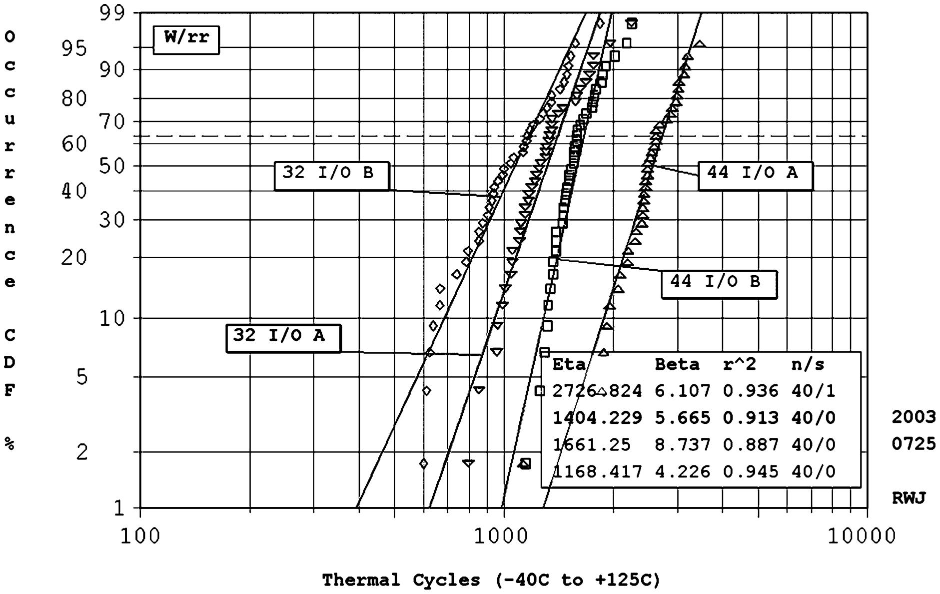

Fig. 6. Weibull plot of thermal cycle data for two QFN I/O counts from two suppliers [12].

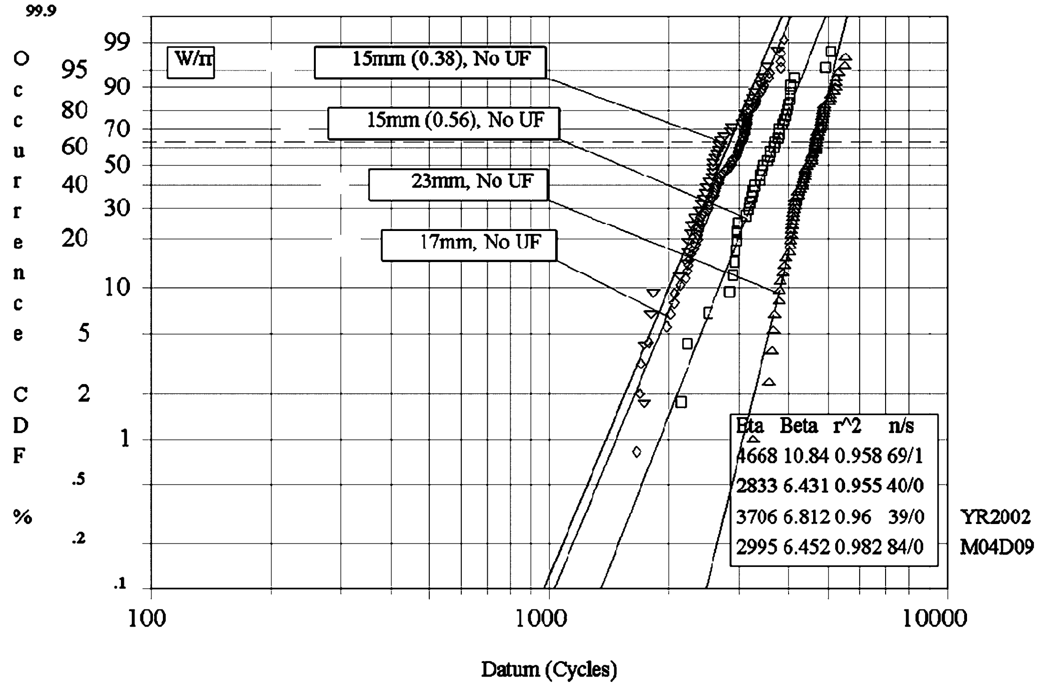

Fig. 7. Weibull plot of thermal cycle data for BGAs of various sizes [13].

150 °C, particularly for power supply controllers and a few automotive applications. Finally, many power semiconductor devices are derated to zero power handling capability at 200 °C. Nelms *et al.* and Johnson *et al.* have shown that power insulated-gate bipolar transistors (IGBTs) and metal–oxide–semiconductor field-effect transistors (MOSFETs) can be used at 200 °C [14], [15]. The primary limitations of these power transistors at the higher temperatures are the packaging (the glass transition temperature (T_g) of common molding compounds is in the 180 °C to 200 °C range) and the electrical stress on the transistor during hard switching.

A number of factors limit the use of silicon at high temperatures. First, with a bandgap of 1.12 eV, the silicon p-n junction becomes intrinsic at high temperature (225 °C to 400 °C depending on doping levels). The intrinsic carrier concentration (n_i) is given by (1)

$$n_i = \sqrt{N_c N_v} e^{(-E_g/2kT)} \tag{1}$$

where

N_c effective density of states in the conduction band;
N_v effective density of states in the valence band;
E_g bandgap energy;
k Boltzmann's constant;
T absolute temperature.

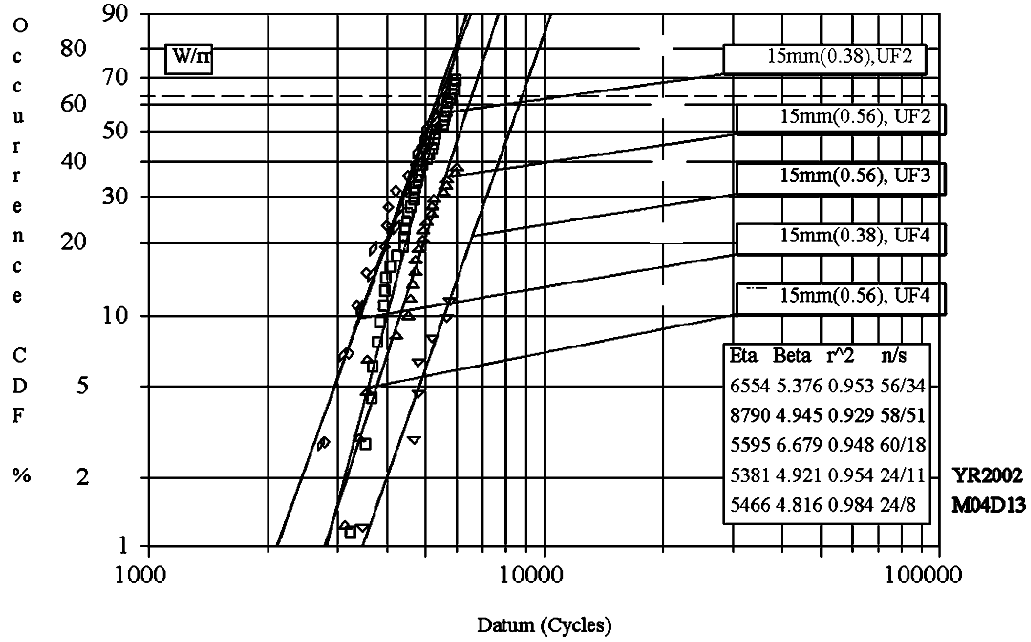

Fig. 8. Weibull plot of thermal cycle data for 15-mm BGAs with various underfills [13].

As the temperature increases, the intrinsic carrier concentration increases. When the intrinsic carrier concentration nears the doping concentration level, p-n junctions behave as resistors, not diodes, and transistors lose their switching characteristics. One approach used in high-temperature integrated circuit design is to increase the doping levels, which increases the temperature at which the device becomes intrinsic. However, increasing the doping levels decreases the depletion widths, resulting in higher electric fields within the device that can lead to breakdown.

A second problem is the increase in leakage current through a reverse-biased p-n junction with increasing temperature. Reverse-biased p-n junctions are commonly used in IC design to provide isolation between devices. The saturation current (I_o, the ideal reverse-bias current of the junction) is proportional to the square of the intrinsic carrier concentration

$$I_o \propto n_i^2 \propto T^3 e^{(E_{go}/kT)} \tag{2}$$

where $E_{go}=$ bandgap energy at $T = 0^\circ$K.The leakage current approximately doubles for each 10 °C rise in junction temperature. Increased junction leakage currents increase power dissipation within the device and can lead to latch-up of the parasitic p-n-p-n structure in complimentary metal–oxide–semiconductor (CMOS) devices. Epitaxial-CMOS (epi-CMOS) has been developed to improve latch-up resistance as the device dimensions are decreased due to scaling and provides improved high-temperature performance compared to bulk CMOS.

Silicon-on-insulator (SOI) technology replaces reverse-biased p-n junctions with insulators, typically SiO_2, reducing the leakage currents and extending the operating range of silicon above 200 °C. At present, SOI devices are more expensive than conventional p-n junction isolated devices. This is in part due to the limited use of SOI technology. With the continued scaling of device dimensions, SOI is being used in some high-performance applications and the increasing volume may help to eventually lower the cost.

Other device performance issues at higher temperatures include gate threshold voltage shifts, decreased noise margin, decreased switching speed, decreased mobility, decreased gain-bandwidth product, and increased amplifier input–offset voltage [16]. Leakage currents also increase for insulators with increasing temperature. This results in increased gate leakage currents, and increased leakage of charge stored in memory cells (data loss). For dynamic memory, the increased leakage currents require faster refresh rates. For nonvolatile memory, the leakage limits the life of the stored data, a particular issue for FLASH memory used in microcontrollers and automotive electronics modules.

Beyond the electrical performance of the device, the device reliability must also be considered. Electromigration of the aluminum metallization is a major concern. Electromigration is the movement of the metal atoms due to their bombardment by electrons (current flow). Electromigration results in the formation of hillocks and voids in the conductor traces. The mean time to failure (MTTF) for electromigration is related to the current density (J) and temperature (T) as shown in (3)

$$\mathrm{MTTF} = AJ^{-n}e^{(E_a/kT)} \tag{3}$$

where

A constant;
n constant (1–2);
E_a activation energy (0.5–1 eV).

The exact rate of electromigration and resulting time to failure is a function of the aluminum microstructure. Addition of copper to the aluminum increases electromigration resistance. The trend in the industry to replace aluminum with copper will improve the electromigration resistance by up to three orders of magnitude [17].

Time dependent dielectric breakdown (TDDB) is a second reliability concern. Time to failure due to TDDB decreases with increasing temperature. Oxide defects, including pinholes, asperities at the Si–SiO$_2$ interface and localized changes in chemical structure that reduce the barrier height or increase the charge trapping are common sources of early failure [18]. Breakdown can also occur due to hole trapping (Fowler–Nordheim tunneling). The holes can collect at weak spots in the Si–SiO$_2$ interface, increasing the electric field locally and leading to breakdown [18]. The temperature dependence of time-to-breakdown (t_{BD}) can be expressed as [18]

$$t_{\mathrm{BD}}(T) \propto \exp\left(\frac{E_{\mathrm{tbd}}}{kT}\right) \tag{4}$$

where

E_{tbd} activation energy (0.2–0.6 eV);
k Boltzmann's constant;
T absolute temperature.

Values reported for E_{tbd} vary in the literature due to its dependence on the oxide field and the oxide quality. Furthermore, the activation energy increases with breakdown time [18].

With proper high-temperature design, junction isolated silicon integrated circuits can be used to junction temperatures of 150 °C to 165 °C, epi-CMOS can extend the range to 225 °C to 250 °C and SOI can be used to 250 °C to 280 °C [16, pp. 224]. High-temperature, nonvolatile memory remains an issue.

For temperatures beyond the limits of silicon, silicon carbide-based semiconductors are being developed. The bandgap of SiC ranges from 2.75–3.1 depending on the polytype. SiC has lower leakage currents and higher electric field strength than Si. Due to its wider bandgap, SiC can be used as a semiconductor device at temperatures over 600 °C. The primary focus of SiC device research is currently for power devices. SiC power devices may eventually find application as power devices in braking systems and direct fuel injection. High-temperature sensors have also been fabricated with SiC. Berg *et al.* have demonstrated a SiC-based sensor for cylinder pressure in combustion engines [19] at up to 350 °C and Casady *et al.* [20] have shown a SiC-based temperature sensor for use to 500 °C. At present, the wafer size, cost, and device yield have made SiC devices too expensive for general automotive use. Most SiC devices are discrete, as the level of integration achieved in SiC to date is low.

Passives: Thick and thin-film chip resistors are typically rated to 125 °C. Naefe *et al.* [21] and Salmon *et al.* [22] have shown that thick-film resistors can be used at temperatures above 200 °C if the allowable absolute tolerance is 5% or greater. The resistors studied were specifically formulated with a higher softening point glass. The minimum resistance as a function of temperature was shifted from $\sim$ 25 °C to $\sim$ 150 °C to minimize the temperature coefficient of resistance (TCR) over the temperature range to 300 °C. TaN and NiCr thin-film resistors have been shown to have less than 1% drift after 1000 h at 200 °C [23]. Thus, for tighter tolerance applications, thin-film chip resistors are preferred. Wire wound resistors provide a high-temperature option for higher power dissipation levels [21].

High-temperature capacitors present more of a challenge. For low-value capacitors, negative-positive-zero (NPO) ceramic and MOS capacitors provide low-temperature coefficient of capacitance (TCC) to 200 °C. NPO ceramic capacitors have been demonstrated to 500 °C [24]. Higher dielectric constant ceramics (X7R, X8R, X9U), used to achieve the high volumetric efficiency necessary for larger capacitor values, exhibit a significant capacitance decrease above the Curie temperature, which is typically between 125 °C to 150 °C. As the temperature increases, the leakage current increases, the dissipation factor increases, and the breakdown strength decreases. Increasing the dielectric tape thickness to increase breakdown strength reduces the capacitance and is a tradeoff. X7R ceramic capacitors have been shown to be stable when stored at 200 °C [23]. X9U chip capacitors are commercially available for use to 200 °C, but there is a significant decrease in capacitance above 150 °C.

Consideration must also be given to the capacitor electrodes and terminations. Ni is now being substituted for Ag and PdAg to lower capacitor cost. The impact of this change on high-temperature reliability must be evaluated. The surface finish for ceramic capacitor terminations is typically Sn. The melting point of the Sn (232 °C) and its interaction with potential solders/brazes must also be considered. Alternate surface finishes may be required.

For higher value, low-voltage requirements, wet tantalum capacitors show reasonable behavior at 200 °C if the hermetic seal does not lose integrity [23]. Aluminum electrolytics are also available for use to 150 °C. Mica paper (260 °C) and Teflon film (200 °C) capacitors can provide higher voltage capability, but are large and bulky [25]. High-temperature capacitors are relatively expensive. Volumetrically efficient, high-voltage, high-capacitance, high-temperature and low-cost capacitors are still needed.

Standard transformers and inductor cores with copper wire and teflon insulation are suitable for operation to 200 °C. For higher temperature operation, the magnetic core, the conductor metal (Ni instead of Cu) and insulator must be selected to be compatible with the higher temperatures [16, pp. 651–652] Specially designed transformers can be used to 450 °C to 500 °C, however, they are limited in operating frequency.

Crystals are required for clock frequency generation for microcontrollers. Crystals with acceptable frequency shift over the temperature range from -55 °C to $+200$ °C have been demonstrated [22]. However, the selection of packaging materials and assembly process for the crystal are key to high-temperature performance and reliability. For example, epoxies used in assembly must be compatible with 200 °C operation.

Substrates: Thick-film substrates with gold metallization have been used in circuits to 500 °C [21], [23]. Palladium silver, platinum silver, and silver conductors are more commonly used in automotive hybrids for reduced cost. Silver migration has been observed with an unpassivated PdAg thick-film conductor under bias at 300 °C [21]. The time-to-failure needs to be examined as a function of temperature and bias voltage with and without passivation. Low-temperature cofired ceramic (LTCC) and high-temperature cofired ceramic (HTCC) are also suitable for high-temperature automotive applications. Embedded resistors are standard to thick-film hybrids, LTCC, and some HTCC technologies. As previously mentioned, thick-film resistors have been demonstrated at temperatures $>$ 200 °C. Dielectric tapes for embedded capacitors have also been developed for

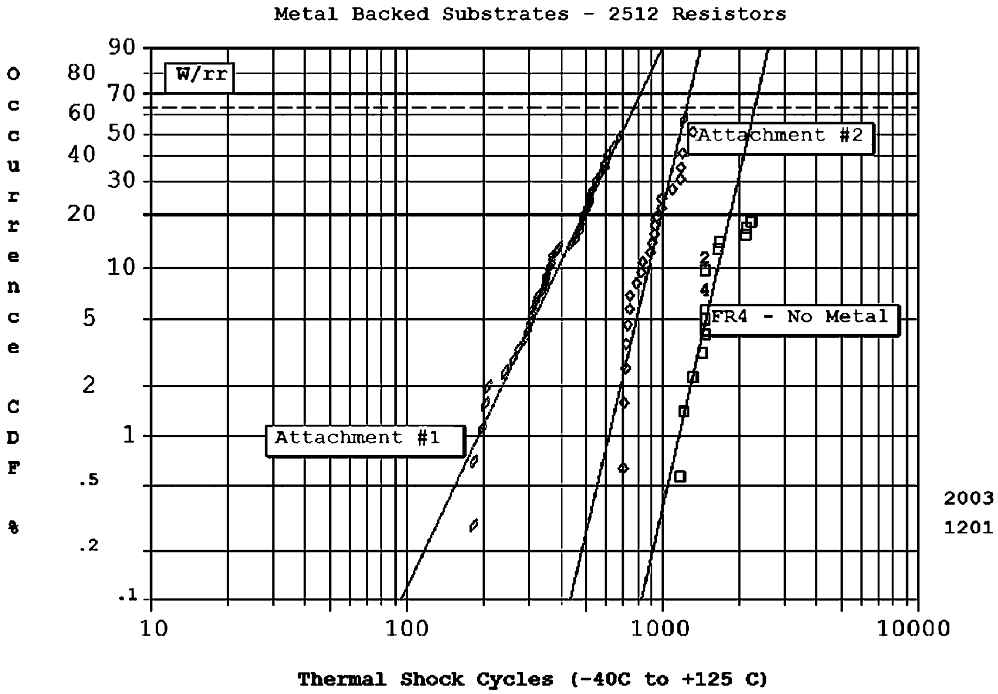

Fig. 9. Weibull plot of 2512 chip resistors with metal backed laminates. [27], [28].

LTCC and HTCC. However, these embedded capacitors have not been characterized for high-temperature use.

High-T_g laminates are also available for fabrication of high-temperature printed wiring boards. Cyanate esters [$T_g = 250\,^\circ\mathrm{C}$ by differential scanning calorimetry (DSC)], polyimide ($T_g =$ 260 °C by DSC), and liquid crystal polymers ($T_m >$ 280 °C) provide options for use to 200 °C. Cyanate ester boards have been used successfully in test vehicles at 175 °C, but failed when exposed to 250 °C [26]. The higher coefficient of thermal expansion (CTE) of the laminate substrates compared to the ceramics must be considered in the selection of component attachment materials. The temperature limits of the laminates with respect to assembly temperatures must also be carefully considered. Work is ongoing to develop and implement embedded resistor and capacitor technology for laminate substrates for conventional temperature ranges. This technology has not been extended to high-temperature applications.

One method many manufacturers are using to address the higher temperatures while maintaining lower cost is the use of laminate substrates attached to metal. The typical design involves the use of higher T_g (+140 °C and above) laminate substrates attached to an aluminum plate (approximately 2.54-mm thick) using a sheet or liquid adhesive. To assist in thermal performance, the laminate substrate is often thinner (0.76 mm) than traditional automotive substrates for under-the-hood applications. While this design provides improved thermal performance, the attachment of the laminate to aluminum increases the CTE for the overall substrates. The resultant CTE is very dependent on the ability of the attachment material to decouple the CTE between the laminate substrate and the metal backing. However, regardless of the attachment material used, the combination of the laminate and metal will increase the CTE of the overall substrate above that of a stand-alone laminate substrate. This impact can be quite significant in the reliability performance for components with low CTE values (such as ceramic chip resistors). Fig. 9 illustrates the impact of two laminate-to-metal attachment options compared to standard laminate substrates [27], [28]. The reliability data presented is for 2512 ceramic chip resistors attached to a 0.79-mm-thick laminate substrate attached to aluminum using two attachment materials. Notice that while one material significantly outperforms the other, both are less reliable than the same chip resistor attached to laminate without metal backing.

This decrease in reliability is also exhibited on small ball grid array (BGA) packages. Fig. 10 shows the reliability of a 15-mm BGA package attached to laminate compared to the same package attached to a laminate substrate with metal backing [27], [28]. The attachment material used for the metal-backed substrate was the best material selected from previous testing. Notice again that the metal-backed substrate deteriorates the reliability. This reliability deterioration is of particular concern since many IC packages used for automotive applications are ball grid array packages and the packaging trend is for reduced packaging size. These packaging trends make the use of metal-backed substrates difficult for next generation products.

One potential solution to the above reliability concern is the use of encapsulants and underfills. Fig. 11 illustrates how conformal coating can improve component reliability for surface mount chip resistors [27], [28]. Notice that the reliability varies greatly depending on material composition. However, for components which meet a marginal level of reliability, conformal coatings may assist the design in meeting the target reliability requirements. The same scenario can be found for BGA underfills. Typical underfill materials may extend the component life by a factor of two or more. For marginal IC packages, this enhancement may provide enough reliability improvement to

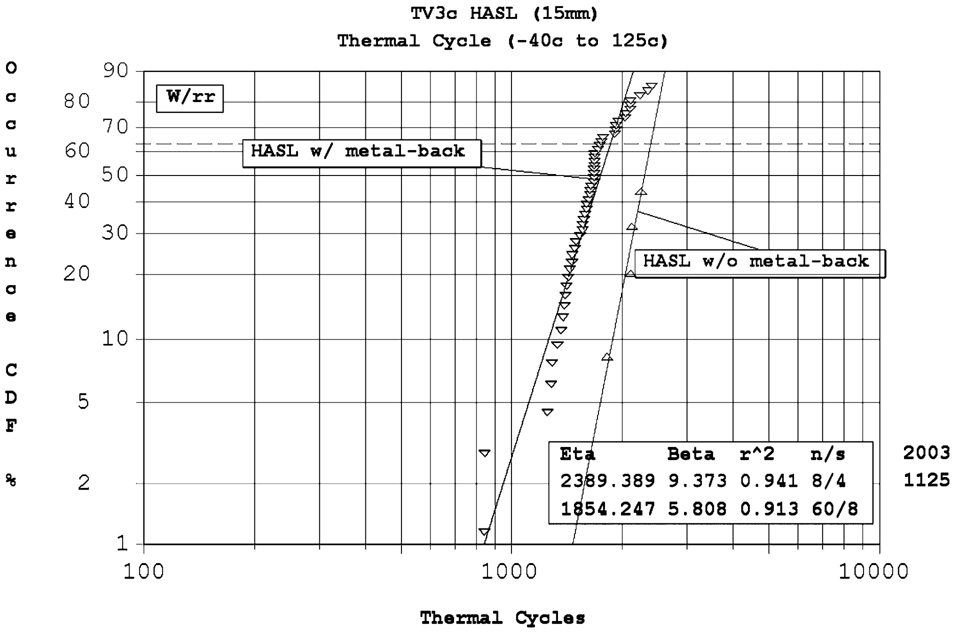

Fig. 10. Weibull plot of 15-mm BGAs with and without metal backing. [27], [28].

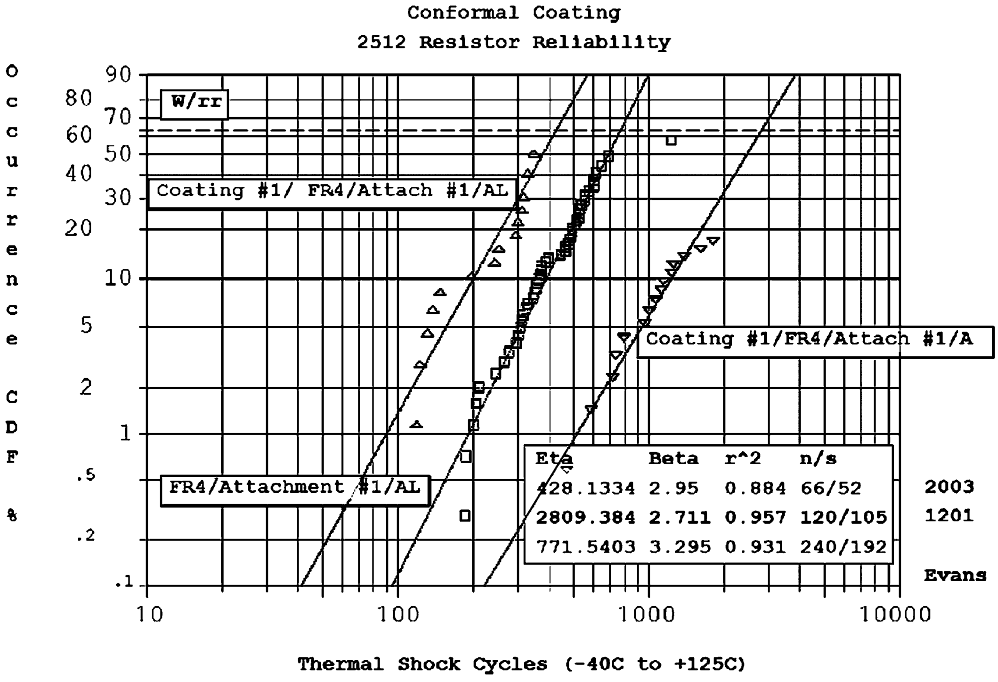

Fig. 11. Weibull plot of 2512 chip resistors using conformal coating. [27], [28].

all the designs to meet under-the-hood requirements. Unfortunately, the improvements provided by encapsulants and underfills increase the material cost and adds one or more manufacturing processes for material dispense and cure.

Interconnections: Methods of mechanical and electrical interconnection of the active and passive components to the board include chip and wire, flip-chip, and soldering of packaged parts. In chip and wire assembly, epoxy die-attach materials can be used to 165 °C [29]. Polyimide and silicone die-attach materials can be used to 200 °C. For higher temperatures, SnPb ($\geq$ 90% Pb), AuGe, AuSi, AuSn, and AuIn have been used. However, with the exception of SnPb, these are hard brazes and with increasing die size, CTE mismatches between the die and the substrate will lead to cracking with thermal cycling. Ag–glass die attach has also been used with Si die, but the die stresses are high [30]. The processing temperatures (330 °C to 425 °C) required for the hard brazes and the Ag-glass are not compatible with the laminate-based substrates.

Small-diameter Au and Pt wire bonding can be used to 500 °C on thick-film Au with Au pads on the SiC die [22].

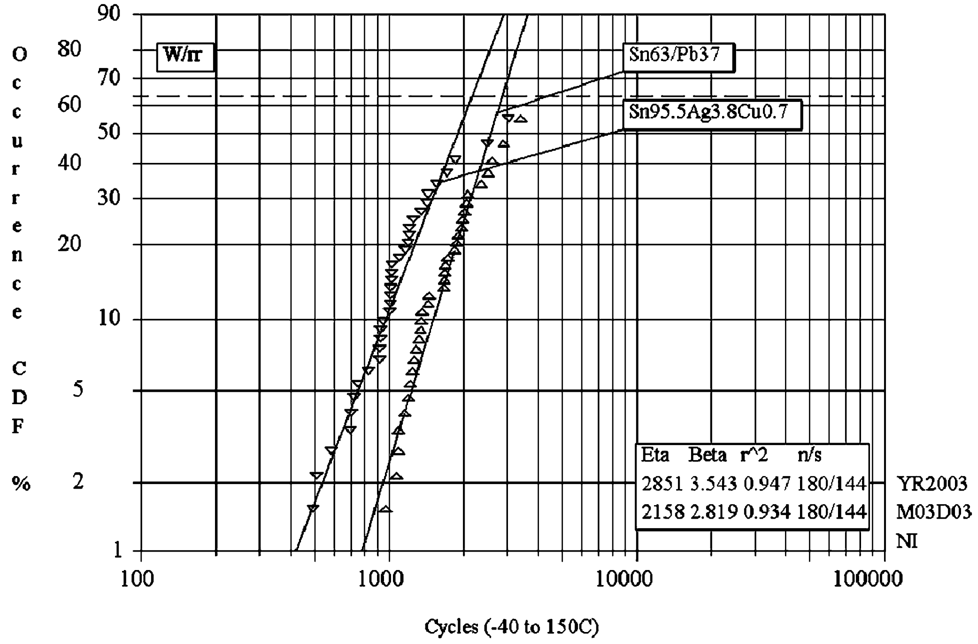

Fig. 12. Weibull plot of thermal cycle data (-40 °C to $+150$ °C) for 2512 chip resistors. [34].

However, most Si die have aluminum metallization and the use of Au wire is limited to 180 °C to 200 °C due to Au–Al intermetallic formation and Kirkendall voiding. Use of Al wire creates a monometallic bond at the die interface. Pd-doped thick-film Au conductors have been developed for compatibility with small-diameter Al wire to 300 °C [31]. While Al wire can be bonded to silver bearing thick-film conductors, the primary concern is corrosion due to the galvanic potential between Al and Ag [32]. Chlorine contamination in the presence of moisture is the primary corrosion mechanism. Increasing the Pd content of the PdAg conductor, extreme care in the cleanliness of the assembly and potting in silicone gel can be used to reduce the risk of corrosion. Au wire can be bonded to pure Ag thick films, but the Ag migrates along the surface of the gold wire at elevated temperatures [33].

On laminate substrates, Ni/Au finishes over the copper are compatible with Au wire (thick Au finish) and with Al wire (thin Au finish). In the case of Al wire, the Au layer must be thin so the Al wire bonds to the underlying Ni. Intermetallic formation and voiding will occur if the Au layer is too thick. If a phosphorus containing Ni is used, the phosphorus content should be limited to $< 6\%$–8%. Al–Ni bonds are potentially reliable to 300 °C, but further study is required [32].

For wire bonding to power devices, large-diameter Al wire bonding is used. In some cases the Al wire is bonded directly to the thick-film PdAg conductors (the potential for Al–Ag corrosions exists) or to Ni-plated slugs soldered to the metallization.

For solder assembly of passives, flip-chip die and packaged semiconductors, alternate solders are required above 135 °C to 140 °C to replace eutectic SnPb. High-lead solders can be used if the substrate and component can withstand the assembly temperature. At intermediate temperatures, lead-free solders are being considered. The SnAgCu eutectic alloy has been selected by the general electronics industry to replace eutectic SnPb. However, the performance of this alloy with 2512 chip resistors and 1206 chip resistors arrays on high-T_g laminate over the -40 °C to $+150$ °C thermal cycle range is significantly worse compared to eutectic SnPb (Figs. 12 and 13) [34]. As seen in Fig. 12, fourth-element additions such as Bi to the SnCuAg alloy improve the thermal cycle performance.

The NCMS report on lead-free, high-temperature, fatigue-resistant solder recommends Sn3.35Ag1Cu3.3Bi and Sn4.6Ag1.6Cu1Sb1Bi for -55 °C to $+160$ °C applications [35]. The performance of the NCMS-selected solders over the range from -55 °C to $+160$ °C is still less than the reliability of SnPb over the -55 °C to $+125$ °C range. Thus, extending the temperature range with these alloys will be less reliable than the current SnPb assemblies at 125 °C. With the push in the automotive industry to 150 000 mile/10 year design goals, this will pose an issue for high-temperature electronics acceptance. Amagai *et al.* have evaluated the effect of Ag and Cu percent composition as well as the addition of various fourth elements on reliability with a goal of optimizing thermal cycle and mechanical shock performance [36]. Nowottnick *et al.* have proposed using liquid solders for high-temperature applications [37]. In this approach, Sn–Bi solders are used. At elevated operating temperatures, the solder alloys melt, but maintain electrical contact. A polymer encapsulant is used to maintain mechanical integrity when the solder is molten. Work continues to find better high-temperature soldering solutions for automotive applications.

Flip-chip assembly on thick-film ceramic substrates with high Pb-containing solders has been used for many years. With increasing die size and thermal cycle range, underfills will be required to improve the thermal cycle reliability on ceramic. Underfill is definitely required on laminate substrates. Most commercial underfills have a T_g less than 150 °C and are not suitable. Higher T_g underfills are being developed for higher temperature automotive applications on both ceramic and laminate substrates.

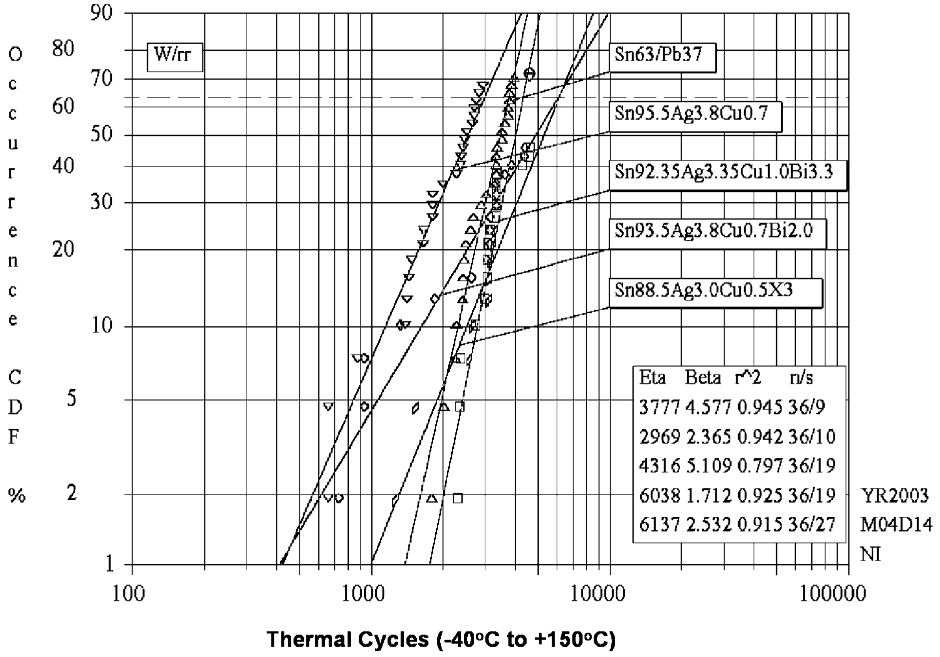

Fig. 13. Weibull plot of thermal cycles data. ($-40\,^{\circ}$C to $+150\,^{\circ}$C) for 1206 chip resistor arrays. [34].

Electromigration and underbump metallurgy diffusion at elevated temperature are also issues with flip-chip solder bumps. Electromigration can contribute to consumption of the underbump metallurgy and joint failure. The allowable current density (current/area of passivation opening) decreases with increasing temperature. Elenius [38] and Zhou [39] have reported that Au surface finishes on the substrate are detrimental to the SnPb eutectic solder bumps and underbump metallurgy. Zhou recommends Ag as an alternate PWB surface finish. The SnAgCu eutectic alloy is reported to be less prone to failure due to electromigration and underbump metallurgy (UBM) diffusion than eutectic SnPb [38].

Housings/Connectors: If chip and wire assembly is used, mechanical and environmental protection of the assembly must be provided. In automotive applications, this is commonly achieved using a molded plastic housing, silicone gel, and a cover. Lead inserts are molded into the housing to provide an electrical I/O. Silicone gels are available rated to 260 °C. The temperature limit is established by the selection of material used in the molded housing. With laminate-based surface mount technology (SMT) and flip-chip assemblies, a cast aluminum housing is commonly used. Sealed hermetic packages commonly used in military applications are considered too expensive for automotive modules.

High-temperature issues with connectors include thermal limits of the housing polymer, and the base metal and plating finish of the connector contacts. The spring force exerted by the receptacle on the contact pin must be maintained over the temperature range. This is particularly true for on-engine and in-transmission applications where vibration levels are higher, increasing the potential for fretting corrosion. This impacts the selection of base metals. BeCu and BeNi can be used for higher temperature applications. Gold can provide a nonoxidizing and corrosion resistant pin finish, but is more expensive.

V. SUMMARY: AUTOMOTIVE HIGH-TEMPERATURE CHALLENGES

The challenges for high-temperature automotive electronics are significant. First is volume. With one engine controller per vehicle and approximately 55 million vehicles sold in the world per year, if all engine controllers were high-temperature, the volume is still not high. In terms of microcontrollers, this volume might be significant if all of the manufacturers used a common microcontroller—they do not. In terms of passive components, the volume is very small compared to applications such as cell phones.

The lack of an industry-wide definition for "high temperature" limits the ability of the supplier base to address the needs. Each application is unique—mounting location, vehicle model, thermal management, and power dissipation. Thus, the temperature requirements from Delphi Delco, DaimlerChrysler, and Toyota vary as discussed in the introduction. A second question from the component suppliers is "How long will the device see the maximum temperature?" Assuming an average speed of 72.4 km/h, 241 350 km is 3334 h. Does this mean the component has to function for 3334 h at the maximum temperature or is there a temperature profile: A hours at $T_{\max}$, B hours at $T_{\max} - 10\,^{\circ}$C, C hours at $T_{\max} - 20\,^{\circ}$C, and so on. As shown in Fig. 3, the nominal transmission temperature was $< 110\,^{\circ}$C with a peak to 143 °C for a worst case situation. This would require a transmission controller that would function in a 143 °C environment, but how many hours would it need to operate in a 143 °C environment? Clearly, it would operate at $\leq$ 110 °C most of the 3334 h. The requirements on the semiconductor manufacturer are significantly different for 50 h at 143 °C compared to 3334 h at 143 °C.

Cost is a driving factor in automotive electronics. The industry works under the paradigm that with time electronics become less expensive or have increasing functionality at the same price. In general, consumers are unwilling to pay for increased fuel economy or lower emissions. Thus, it becomes difficult to pass increased costs to the consumer. Silicon-on-insulator technology exists for fabricating high-temperature semiconductor devices, but is too expensive to be considered.

Reliability is a significant concern. Reliability impacts safety, customer loyalty, recalls, and litigation. Increased temperature decreases the time to failure for many failure mechanisms, such as time dependent dielectric breakdown of gate oxides and electromigration of metals such as aluminum interconnect lines. An increased thermal cycling range, decreases the number of cycles to failure for solder joints due to fatigue and creep. The trend in the automotive electronics industry is toward 10 year/150 000 mile designs. Thus, more robust designs will be required to achieve improved reliability with high-temperature operation.

REFERENCES

[1] G. Leen and D. Heffernan, "Expanding automotive electronic systems," *IEEE Computer*, no. 1, pp. 88–93, Jan. 2002.

[2] *OEM Automotive Electronics in North America*, The Freedonia Group, Inc., Cleveland, OH, 2004.

[3] M. R. Fairchild, R. B. Snyder, C. W. Berlin, and D. H. R. Sarma, "Emerging substrate technologies for harsh-environment automotive electronics applications,", SAE Technical Paper Series 2002-01-1052.

[4] D. S. Eddy and D. R. Sparks, "Applications of MEMS technology in automotive sensors and actuators," *Proc. IEEE*, vol. 86, no. 8, pp. 1747–1755, Aug. 1998.

[5] M. Hattori, "Needs and applications of high-temperature LSIs for automotive electronic systems," in *Proc. HITEN High-Temperature Electronics Conf.*, 1999, pp. 37–43.

[6] R. W. Johnson, J. L. Evans, P. Jacobsen, and R. Thompson, "High-temperature automotive electronics," in *Proc. Int. Conf. Advanced Packaging and Systems*, Reno, NV, Mar. 10–13, 2002, pp. 77–87.

[7] "Personal Communications with DaimlerChrysler," unpublished, Jun. 2002.

[8] R. Thompson, *Proc. SMTA/CAVE Workshop Harsh Environment Electronics*, Dearborn, MI, Jun. 24–25, 2003.

[9] [Online]. Available: http:// public.itrs.net

[10] B. A. Myers, J. H. Burns, and J. M. Ratell, "Embedded electronics in electro-mechanical systems for automotive applications,", SAE Technical Paper Series 2001-01-0691, Mar. 5–8, 2001.

[11] J. R. Thompson, M. Christopher, J. Evans, and R. W. Johnson, "Meeting environmental challenges for advanced automotive mechatronic applications," in *Proc. IMAPS Ceramic Interconnect Technology Conf.*, Denver, CO, Apr. 26–28, 2004, pp. 35–40.

[12] J. L. Evans, E. Crain, and J. Suhling, "Component reliability for high-temperature substrates," in *Proc. SMTA Int.*, Chicago, IL, Sep. 24–26, 2002, pp. 189–202.

[13] J. C. Suhling, R. W. Johnson, J. L. Evans, R. W. Knight, N. Islam, J. Liu, S. Gale, Y. Elkady, and J. R. Thompson, "Use of underfill to enhance the thermal cycling reliability of small BGAs," in *Proc. APEX Conf.*, Anaheim, CA, Mar.–Apr. 2003, pp. S03-3-1–S03-3-10.

[14] R. M. Nelms and R. W. Johnson, "200 °C operation of a 500-W dc-dc converter utilizing power MOSFETs," *IEEE Trans. Ind. Appl.*, vol. 33, no. 5, pp. 1267–1272, Sep./Oct. 1997.

[15] R. W. Johnson, G. B. Weir, and J. R. Bromstead, "200 °C operation of semiconductor power devices," *IEEE Trans. Comp., Hybrids, Manuf. Technol.*, vol. 16, no. 7, pp. 759–764, Nov. 1993.

[16] R. Kirshman, Ed., *High-Temperature Electronics*. New York: IEEE Press, 1998.

[17] K. L. Lee, C. K. Hu, and K. N. Tu, "In situ scanning electron microscope comparison studies on electromigration of Cu and Cu(Sn) alloys for advanced chip interconnects," *J. Appl. Phys.*, vol. 87, no. 7, pp. 4428–4437, 1995.

[18] R. Moazzami, J. C. Lee, and C. Hu, "Temperature acceleration of time-dependent dielectric breakdown," *IEEE Trans. Electron Devices*, vol. 36, no. 11, pp. 2462–2465, Nov. 1989.

[19] J. von Berg, R. Ziermann, W. Reichert, E. Obermeir, M. Eickhoff, G. Krotz, U. Thoma, C. Cavalloni, and J. P. Nendza, "Measurements of the cylinder pressure in combustion engines with a piezoresistive β-SiC-on-SOI pressure sensor," in *Proc. 4th Int. High Temperature Electronics Conf.*, Albuquerque, NM, Jun. 14–18, 1998, pp. 245–249.

[20] J. B. Casady, W. C. Dillard, R. W. Johnson, and U. Rao, "A hybrid, 6H-SiC temperature sensor operational from 25 °C to 500 °C," *IEEE Trans. Compon., Packag. Manuf. Technol. A*, vol. 19, no. 3, pp. 416–422, Sep. 1996.

[21] J. E. Naefe, R. W. Johnson, and R. R. Grzybowski, "High-temperature storage and thermal cycling studies of Heraeus-Cermalloy thick film and dale power wirewound resistors," *IEEE Trans. Comp. Packag. Technol.*, vol. 25, no. 1, pp. 45–52, Mar. 2002.

[22] J. S. Salmon, R. W. Johnson, and M. Palmer, "Thick-film hybrid packaging techniques for 500 °C operation," in *Proc. 4th Int. High Temperature Electronics Conf.*, Albuquerque, NM, Jun. 16–19, 1998, pp. 103–108.

[23] R. R. Grzybowski, "Long-term behavior of passive components for high-temperature applications—An update," in *Proc. 4th Int. High-Temperature Electronics Conf.*, Albuquerque, NM, Jun. 16–19, 1998, pp. 207–214.

[24] ——, "Characterization and modeling of ceramic multilayer capacitors to 500 °C and their comparison to glass dielectric devices," in *Proc. 13th Capacitor Resistor Technology Symp. (CARTS)*, 1993, pp. 157–162.

[25] R. R. Grzybowski and F. P. McCluskey, "High-temperature performance of polymer film capacitors," *Int. J. Microelectron. Packag.*, vol. 1, pp. 153–158, 1998.

[26] J. E. Naefe, R. W. Johnson, R. Richard, and Grzybowski, "High-temperature storage and thermal shock studies of passive component attach materials," in *Proc. 4th Int. High Temperature Electronics Conf.*, Albuquerque, NM, Jun. 16–19, 1998, pp. 68–78.

[27] E. Crain, "Optimal material selection for a specific harsh environment application of metal-backed technology on an FR4 substrate," M.S. thesis, Auburn Univ., 2003.

[28] J. Evans, P. Lall, R. Knight, E. Crain, T. Shete, J. R. Thompson, and D. Naylis, "System design issues for harsh environment electronics employing metal-backed laminate substrates," *IEEE Trans. Compon. Packag. Technol.*, submitted for publication.

[29] R. W. Johnson, S. Pan, M. Palmer, and R. Dean, "Conductive adhesives for under-the-Hood automotive applications," in *Proc. 5th Int. High-Temperature Electronics Conf.*, Albuquerque, NM, Jun. 12–15, 2000.

[30] Shun-Tein, J. T. Benoit, R. R. Grzybowski, Y. Zou, J. C. Suhling, and R. C. Jaeger, "High-temperature die-attach effects on die stresses," in *Proc. 4th Int. High-Temperature Electronics Conf.*, Albuquerque, NM, Jun. 16–19, 1998, pp. 61–67.

[31] S. J. Horowitz, D. J. Gerry, and R. E. Cote, "Alloy element additions to gold thick-film conductors: Effects on indium/lead soldering and ultrasonic Al wire bonding," in *Proc. 27th Electronic Components Conf.*, Arlington, VA, May 16–18, 1977, pp. 358–366.

[32] G. G. Harman, *Wire Bonding in Microelectronics: Materials, Processes, Reliability, and Yield*. New York: McGraw-Hill, 1997.

[33] J. Aday, R W Johnson, J. L. Evans, and C. S. Ramanczuk, "Thick-film silver multilayers for under-the-Hood automotive applications," in *Proc. Int. Symp. Microelectronics*, Dallas, TX, Nov. 9–11, 1993, pp. 126–131.

[34] J. C. Suhling, H. S. Gale, R. W. Johnson, M. N. Islam, T. Shete, P. Lall, M. J. Bozack, J. L. Evans, P. Seto, T. Gupta, and J. R. Thompson, "Thermal cycling reliability of lead free chip resistor solder joints," *Soldering and Surface Mount Technol.*, vol. 16, no. 2, pp. 77–87, Jun. 2004.

[35] ——, "Lead-free, high-temperature, fatigue-resistant solder," National Center For Manufacturing Sciences, Ann Arbor, MI, Final Rep. 0096RE01, Project 170 503-96 034, 2001.

[36] M. Amagai, Y. Toyoda, and T. Tajima, "High solder joint reliability with lead-free solders," in *Proc. 53rd Electronic Components Technology Conf.*, New Orleans, LA, May 27–30, 2003, pp. 317–322.

[37] M. Nowottnick, W. Scheel, K. Wittke, and U. Pape, "Liquid solders for high-temperature solder joints," in *Proc. APEX Conf.*, Anaheim, CA, Feb. 24–26, 2004, pp. S13-2-1–S13-2-7.

[38] P. Elenius, "Failure mechanisms due to current and temperature," in *Proc. Int. Microelectronics Packaging Society Flip-Chip Workshop*, Austin, TX, Jun. 18–20, 2001.

[39] J. Zhou, "The reliability study of flip chip assembly with NiAu and Ag surface finishes," in *Proc. APEX Conf.*, San Diego, CA, Jan. 19–24, 2002, pp. S17-1-1–S17-1-7.

R. Wayne Johnson (F'04) received the B.E. and M.Sc. degrees from Vanderbilt University, Nashville, TN, in 1979 and 1982, respectively, and the Ph.D. degree from Auburn University, Auburn, AL, in 1987, all in electrical engineering.

He has worked in the microelectronics industry for DuPont, Chestnut Run, DE, Eaton, Athens, GA, and Amperex, Slatersville, RI. He is currently a Ginn Professor of Electrical Engineering at Auburn University and Director of the Laboratory for Electronics Assembly and Packaging (LEAP). At Auburn, he has established teaching and research laboratories for advanced packaging and electronics assembly. Research efforts are focused on materials, processing, and reliability for electronics assembly and for high-temperature electronics. He has published and presented numerous papers at workshops and conferences and in technical journals. He has also coedited one IEEE book on MCM technology and written two book chapters in the areas of silicon MCM technology and MCM assembly and one book chapter on high-temperature packaging. He was the 1991 President of the International Society for Hybrid Microelectronics (ISHM).

Dr. Johnson received the 1997 Auburn Alumni Engineering Council Senior Faculty Research Award for his work in electronics packaging and assembly. He received the 1993 John A. Wagnon, Jr. Technical Achievement Award from ISHM, was named a Fellow of the Society in 1994 and received the Daniel C. Hughes Memorial Award in 1997. He is a member SMTA and IPC. He is an Associate Editor of the IEEE TRANSANCTIONS ON ELECTRONICS PACKAGING MANUFACTURING.

John L. Evans received the M.S. degree in electrical engineering from Auburn University, Auburn, AL, and the Ph.D. degree in manufacturing systems engineering from the University of Alabama, Huntsville.

He is an Associate Professor of Industrial and Systems Engineering and Associate Director of the National Science Foundation's Center for Advanced Vehicle Electronics (CAVE) at Auburn University, Auburn, AL. Before joining Auburn University in 2001, he spent 17 years at DaimlerChrysler Corporation, Huntsville, AL. During his tenure at DaimlerChrysler, he worked as a Design Engineer, Lead Engineer, Financial Specialist, Electronics Packaging Supervisor, and Technology Manager. His most recent position was as Manager of Strategic Business and Advanced Technology for DaimlerChrysler Huntsville Electronics. He also served as an Adjunct Assistant Professor (1991–2001) in the Department of Industrial and Systems Engineering and as a Lecturer in the Administrative Science department at the University of Alabama, Huntsville.

Peter Jacobsen received the B.S. in electrical engineering from LeTourneau University, Longview, TX, and the M.S. degree in electrical engineering from the University of Michigan, Ann Arbor.

He is a Technical Specialist for Eaton Automotive in the Advanced Product Development Department, Southfield, MI. He was the Technical Leader and Program Manager of Eaton's effort to develop a competency in high-temperature electronics. His current efforts include developing electronics for camless engines and closed-loop transmission control. He has a total of 25 years of automotive experience.

James R. (Rick) Thompson received the B.Sc. degree in chemical engineering and the M.Sc. degree in mechanical and aerospace engineering from the University of Alabama, Huntsville, in 1986 and 1992, respectively.

He is currently with Siemens VDO Automotive Electronics Corporation, Huntsville, where he is currently involved in new business development and technical marketing. His previous experience includes materials research and development and advance product and process development with DaimlerChrysler Corporation as Supervisor of the Advanced Materials and Product Development Group. He was responsible for advanced propellant development as Supervisor of the Materials Research and Development Laboratory with the Thiokol Corporation, Hunstville Division, Huntsville, AL

Mark Christopher received the B.S. degree in electrical engineering from the University of Alabama, Huntsville, in 1988.

He is currently a Program Manager for Siemens VDO Automotive Electronics Corporation, Huntsville. He has responsibility for powertrain control modules associated with World I4 engine and transmission platforms within DaimlerChrysler. His technical background includes advanced products development for automotive application and advanced packaging development for automotive electronics. Prior to his work within the automotive electronics community, he did radiation-hardened electronics development work for the Department of Defense and the Department of Energy.