Evaluating the Performance and Reliability of Embedded Computer Systems for Use in Industrial and Automotive Temperature Ranges

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Dear Colleague:

As we head further into the 21st century, embedded applications are taking on new challenges to deliver products faster, and more efficiently. Within years, if not months, we will see new heights reached in wireless technologies, USB proliferation, and ruggedized capabilities. Applied Data Systems (www. applieddata.net) has been excited to work with an organization considered by many to be the "gold standard" in evaluating systems for ruggedized requirements: the University of Maryland's CALCE (Computer Aided Life Cycle Engineering)as part of a project funded by the Maryland Industrial Partnership program (MIPS). Together, we have been able to overcome several critical challenges limiting SBC utilization in the harshest environments. The following White paper shows only the tip of the iceberg for collaborations between organizations such as Intel, the University of Maryland, and Applied Data Systems.

Introduction

Many next generation products, including automobiles, aircraft, and industrial automation equipment, are making increasingly widespread use of embedded computer systems to assist in performing their functions more easily, accurately, and cost-effectively. Introduced over 25 years ago, on-board computer systems have now replaced the navigator and flight engineer on aircraft, the carburetor and timing belts on automobiles, and the machinist on automated milling machines. These systems are continually growing in complexity, with the most advanced having 206 MHz, 32-bit RISC microprocessors and 32 Mbit DRAM along with support for PCMCIA cards, and Ethernet links. In addition, new embedded computer systems are expected to include elements that interface the computer with other high tech innovations such as global positioning systems (GPS) and the internet, and to display information via liquid crystal displays. Furthermore, the applications in which these systems are used are multiplying. For example, in the construction and mining industries, it is now possible to find earth moving equipment which uses embedded computer systems to match plans for the site, provided by CD-ROM or internet, with maps of the location, provided by GPS, to identify the precise location to dig. The market for embedded control systems is expected to be over $4 billion this year.

Because of the very nature of these applications, embedded computer systems are expected to perform in environments that are significantly harsher than the typical home computer. The classic example of this type of environment is that encountered in automotive use, where temperatures can range from –40°C when unpowered on a cold winter day to 165°C under the hood when powered on a hot summer day. In addition, to extreme temperatures, the environment includes severe shock and vibration, and high humidity, along with road salt, sand, dirt and other ionic and organic contaminant's. While this is an exceptionally harsh case, most systems are expected to perform over a wide range of temperatures. In order to build systems that can withstand these environmental conditions, it is necessary to evaluate the capability and reliability of the board materials, the case materials, and the attachment materials or solders at those temperatures.

Component Issues

The performance of electronic components are typically specified by their manufacturer over one of the following four temperature ranges:

Commercial:	0°C to 70°C
Industrial:	-40°C to 85°C
Automotive:	-40°C to 105°C
Military:	-55°C to 125°C

Early semiconductor devices were often specified over the military range because of the relatively large number of military and space applications. However, over the last twenty years, the market has shifted, so that today over 92% of the

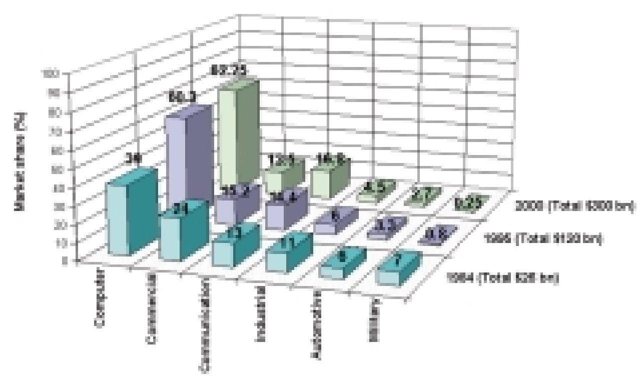

Figure 1: Estimated Semiconductor Market Share by Sector [Solomon, 1999]

applications for semiconductor devices are in the computer, commercial, and telecommunication areas. As these sectors have grown in market share (shown in Figure 1) relative to the industrial, automotive, and military markets, it has become increasingly difficult for manufacturers to economically justify supplying components in temperature ranges exceeding the standard commercial range (0°C to 70°C).

For this reason, most major semiconductor manufacturers have eliminated their military product lines, while some others have significantly scaled back their efforts. This has resulted in a significantly decreased availability of components that are sold for use over the wider temperature ranges. In particular, it has led to fewer new product introductions, which means there are fewer available functions, technologies, and package styles available in parts rated for wider temperature ranges [Pecht 2000].

There is a need for semiconductor parts that can operate beyond the commercial temperature range, primarily for the military, aerospace, automotive, and oil exploration industries. However, demand is not large enough to attract or retain major semiconductor part manufacturers to continue to manufacture or release parts in these wider temperature ranges. At the same time, products for these applications need to keep pace with leading-edge technological development in functionality, size, weight, and cost. The challenge for these industries is to determine what should be done if parts cannot be found whose documented specifications meet the life cycle application environment and operating conditions. Several approaches exist to address this challenge as shown below.

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• Re-evaluate the actual operational temperature conditions in the vicinity of the individual component. Often the stated temperature range for equipment comes from a "boiler plate" requirement and does not truly represent the actual operational conditions.

• Try harder to find parts whose specifications meet the life cycle environmental conditions. Many manufacturers provide industrial temperature range components, and military temperature range components are still available from manufacturers in the qualified manufacturer list (QML), emulation services, and aftermarket suppliers, such as Lansdale Semiconductor and Rochester Electronics.

• Use thermal management techniques to lower the temperature in the vicinity of the critical components.

• Use or invest in special part processes where necessary. Government laboratories (ONR, Sandia) and some manufacturers (Boeing, UTMC) have semiconductor manufacturing facilities which can be utilized for fabricating wide temperature range parts or for post-processing commercial dies.

• Lastly, consider using parts whose data sheet temperature limits are not broad enough to meet the life cycle conditions of the application. This should be considered only as a last resort.

While it is recommended only as a last resort, many companies have resorted to using components outside datasheet range to produce cost-effective, high performance electronic systems. Commercial avionics industry leaders such as Boeing and Airbus are working with their suppliers and the CALCE Electronic Products and Systems Center (EPSC) at the University of Maryland to develop and implement best practices for this approach. The International Electrotechnical Commission Quality Assessment System for Electronic Components (IECQ) Certification Management Committee (CMC) authorized the IECQ-CMC Avionics Working Group at the IEC Annual Meeting in October 1998 to develop and maintain industry procedures for electronic component management, reliability assessment, and extended temperature range assessment in the avionics industry. The IECQ Avionics Working Group is now providing documentation to assure aviation regulatory agencies (FAA, JAA) that all electronic parts used in avionics meet the agency standards. [Pecht 2000] The FAA currently accepts the use of parts outside the manufacturer's specifications, stating that "If the declared installation temperature environment for the EEC is greater than that of the electronic components specified in the engine type design, the applicant should substantiate that the proposed extended range of the specified components is suitable for the application." [FAA 1997] Further information on the techniques used for uprating components are available in the open literature.

Assembly Issues

In addition to understanding the effects of temperature on active devices, it is also important to consider passive components and the assembly processes as well. Passive components are typically sold for use at temperatures to 85°C, and, in most cases, do not suffer much loss in performance to 125°C. Above 125°C, capacitors may show a decrease in capacitance (dielectric constant) and an increase in parasitic losses, while magnetics will show an increase in core loss. Resistors usually have a stable increase in resistance up to and above 125°C that can be accounted for in design using the thermal coefficient of resistance. Assembly issues also are relatively insignificant at temperatures below 125°C, where standard FR4 boards and eutectic lead-tin solder have been used extensively and reliably for many years.

Nevertheless, full assembly testing is necessary to complete the process of ensuring part functionality in the system-level thermal and electrical environment. It also provides application specific functional coverage, ensures that products built with components used outside data sheet temperature range meet the product specifications, and assesses assembly level interactions. Results of assembly testing need to be used carefully. To isolate the cause of a problem, one may have to go back to part level testing. Success in assembly test is unique to the assembly and does not mean that the part can be used in other assemblies without additional assessment and testing. Re-testing is necessary when a part is replaced for maintenance and/or upgraded and when new assembly level functionalities are introduced. [Pecht 2000]

Reliability and Durability

The above discussion has centered on performance over a wider temperature range and not on reliability or durability. It is generally established that reliability is not a concern at temperatures below 125°C. The manufacturers qualification test schemes are typically not based on the part's temperature rating and commercial and industrial temperature range parts pass the same military-like qualification tests. [Wright 1997] Furthermore, no additional failure mechanisms have been reported for commercially available plastic encapsulated microcircuits over the temperature range –40°C to 85°C, with the exception of freeze-thaw cycling [McCluskey 1998] and the reliability of plastic encapsulated microcircuits has been shown to be equal to that of ceramics for up to 2000 hours of life at 155°C. [McCluskey 2000]. Reliability assessment is, however, an application specific process. Physics-of-failure based integrity tests, virtual qualification, accelerated testing or a combination thereof should therefore be used for each new assembly or system to assess reliability in each potential application.

A Test Case: The GCP2520 Embedded Computer System

A reliability analysis was performed on Applied Data Systems GCP2520 Graphics Client Plus System. This analysis consisted of thermal and vibrational analysis. Experimental methods were also used to validate the analysis.

Thermal Analysis

CALCE PWA was used to determine the printed wiring board temperature for the GCP2520. The temperature profile for the top side of the board can be seen in Figure 2. The board temperatures correspond to an ambient of 85°C. The maximum board temperature was 92.7°C.

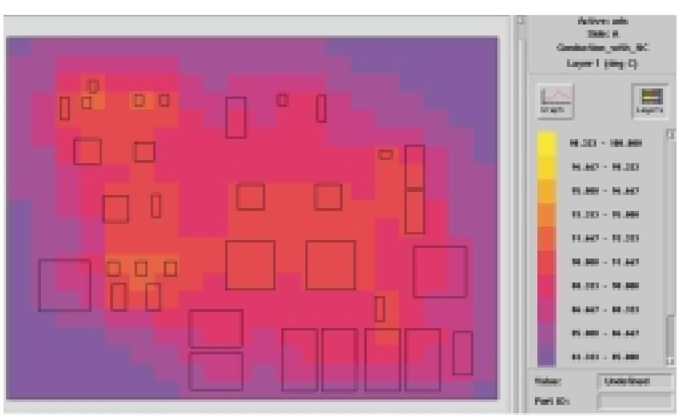

Figure 2: Temperature Profile of the Top Side of the Board

A thermal infrared camera was used to determine the surface temperature of the board and components to validate the CALCEPWA results. Thermocouples were also attached to the board during the test. The calibrated thermocouples agreed with the IR images to less than a degree.

After 16 minutes of supplying power to the system, the board and components increased in temperature due to the heat dissipated by the components. The thermal profile can be seen (Figure 3).

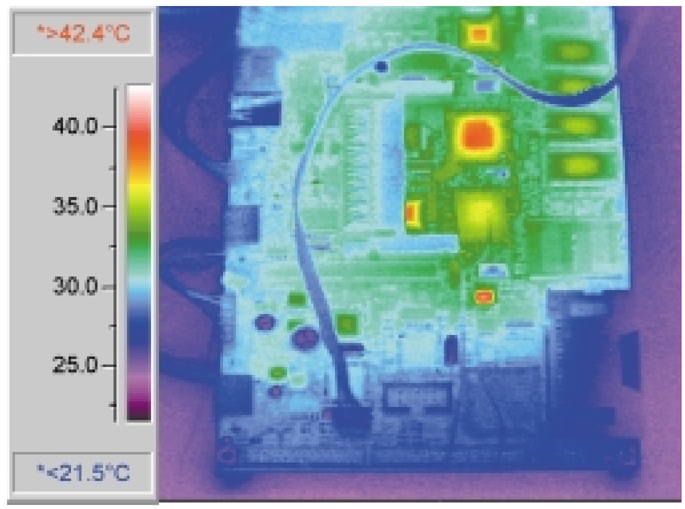

Figure 3: Thermal IR Image of Board After 16 Minutes of Operation

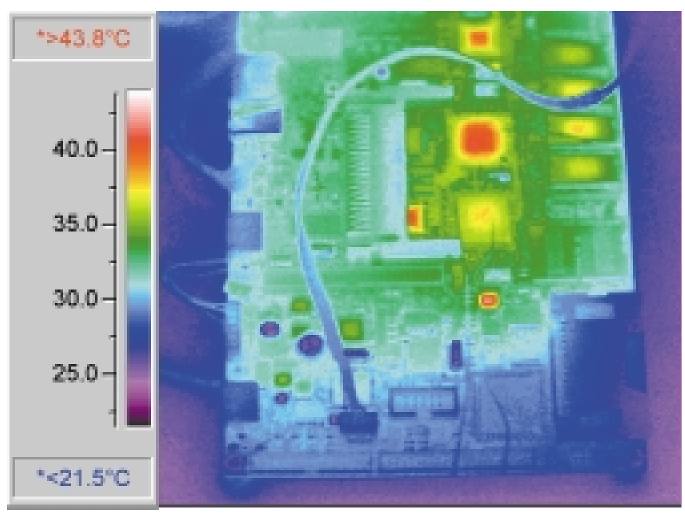

Figure 4: Thermal IR Image of Board After an additional 14 Minutes of Operation with Polygon.exe at Room Temperature.

After an additional 14 minutes of executing the program "polygon.exe", the board and components attained a steady-state temperature. The steady-state thermal profile can be seen (Figure 4).

The maximum temperature occurred on the Intel® StrongARM* Processor. The thermal camera indicated a temperature of 40°C while the thermocouple indicated a temperature of 39.1°C. The board temperature near the Intel® StrongARM* Processor was roughly 34°C as indicated by the thermocouple and 35.9°C from the IR image.

If the thermal measurements at room temperature are adjusted for a higher ambient temperature of 85°C, the results correlate well with the CALCE PWA results. The datasheets for the components were evaluated to ensure that they were qualified for use at the temperatures observed. While the Intel® StrongARM* Processor was not initially recommended for sale at the intended temperature, a low power dissipating component such as the Intel® StrongARM* Processor should not have a problem operating only 15°C above its maximum recommended temperature.

Vibration Analysis

In the vibrational analysis, the first three natural frequencies for the board were found to be 129 Hz, 256 Hz, and 318 Hz .

Reliability Analysis

The results from the thermal and vibrational analysis were used to determine the component solder joint reliability of the ADS GCP2520 Graphics Client Plus System. A first order thermal fatigue model was used. The results are shown in Table 1.

The components are arranged in ascending cycles to failure. Components U33, U24, U27, and U34 have the least cycles to failure, which is 3090 cycles in each instance. This is equivalent to a field life of 8.5 years. The expected field life increased by almost 1.5 years from the previous analysis performed by CALCE on an earlier prototype which had an expected 7 years of life.

Component	Board Temp	Case Temp	Cycles to Failure
U33	89	97	3090
U24	89	97	3090
U27	89	97	3090
U34	89	97	3090
U4	89	100	4431
U43	91	98	4712
U23	91	100	4840
U38	89	94	5057
U22	87	87	5705
U37	87	94	6024
U5	91	90	7841
U11	91	90	7841
U10	86	90	12032
U42	89	91	13555
U8	91	90	76259
U55	91	90	76259
U35	91	94	80379
U2	91	100	87080
U7	91	94	251822

Table 1: Cycles to Failure for Microcircuits

Experimental Verification of Results

In order to ensure that the virtual qualification was indeed correct and that the ADS GCP2520 Graphics Client Plus System would function at extreme temperatures, the unit was placed in an 85°C oven and a –40°C cold chamber.

The unit was placed in an oven at 85°C and allowed to come to thermal equilibrium. After 30 minutes, the program "polygon.exe" was executed for 10,000 GDI operations. The time to execute this operation was recorded for ten trial runs. The average time was 22184 milliseconds.

The unit was then placed in the cold chamber and allowed to reach -40°C. The same program was run. The average time to execute 10,000 GDI operations at -40°C is 20682 milliseconds.

At room temperature, the time it takes to execute 10,000GDI operations is 21528 milliseconds. There is less than 3.04% and 3.93% difference between operation at room temperature and 85°C and -40°C, respectively. Thus, the unit can perform reliably at such extreme temperatures.

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