High Temperature Electronics for Sensor Interface and Data Acquisition

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Introduction

High Temperature designs need components rated to operate in the harsh environment in which they will be used. This paper will discuss the more common types of applications needing these devices.

Guidelines are given for type and use of commercially available components and materials. Also included is a discussion in some detail of actual applications using HT Electronics. A demonstration of HT Electronics has been prepared, showing what can be done with these tools. Information has also been included about other components and materials needed to make a complete High Temperature System.

Why are HT Electronics Needed?

The industries most interested in designing products using HT Electronics today can be broken along application lines as follows:

- **Downhole Instruments**, used for drilling, formation, and product quality measurement of deep wells in oil and geothermal fields.
- **Turbine Engines** used in aircraft and stationary power generation need HT Electronics to implement more modern control techniques and monitoring systems
- **Internal Combustion Engines** need HT Electronics as engine compartments get hotter and control strategies are refined to meet reduced emissions standards.

In addition, markets needing HT Electronics are forming in the areas of integrated motor controls, industrial process controls, building fire safety controls, environmental test equipment, and other areas.

A number of recent requirement changes have pushed the upper operating temperature range limit higher, including:

Requirement **Effect on Product**

- increased depth of oil reserves => instruments exposed to higher temperatures
- increased cost of down-hole drilling => more reliable & durable instrumentation required
- improved performance in aircraft => tighter coupling of controls, distributed engine controls
- reduced fuel consumption => lighter controls and monitors, smaller more restricted enclosures
- removal of cooling apparatus => hotter operation of electronics without airflow or heat sinking

Standard, commercial off the shelf (COTS) bulk Silicon processed semiconductors, however, are not able to handle these increased demands. They are designed for a service range of –55°C to +70°C for commercial, +85°C for industrial or +125°C for military temperature range. Use of these components beyond their intended range is not specified or recommended by their manufacturers.

Commercial passive components are also usually limited in operating temperature. Plus, often, high temperature designs will derate the component’s power rating to prevent significant self-heating from damaging the part. It is also true that if the requirements include a large amount of thermal cycling, the difficulty of creating a stable design increases a lot.

Some high temperature users are willing to do extra work in characterizing standard components to find the most durable brands, but this is a costly venture, requiring burn-in equipment and test expertise. The results are also not always repeatable, since the component manufacturer can make changes to the process as simple as doing a “die shrinkage” which could degrade the temperature performance. The designer should beware that, unless statistically valid data is shown for high temperature operation over time, that part may be the one which fails and takes out the whole system.

As an example of a common problem, Figure 1 shows one of the dominant failure mechanisms in electronics exposed to high temperature environments. Electromigration of metals causes failure of conventional components to occur much more quickly than for specifically designed HT Electronics (demonstrated reliability data for Honeywell HTMOS products). From Figure 1, it is seen that a 1% failure rate can be expected for components operated for 1 year at 160°C. This same failure rate can be expected within 2 1/2 months of operation at 200°C, whereas an HTMOS component will survive **over 10 years of continuous operation at 200°C**.

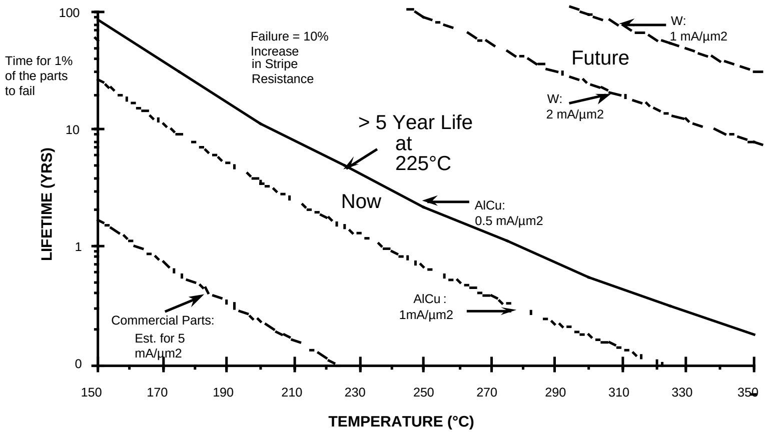


Figure 1—Electromigration Lifetime

The total potential market for HT Electronics is conservatively estimated to reach nearly $15B in the next couple of years. The actual market is quite a bit smaller—about $1B, however. Components are now appearing on the marketplace to enable a complete system to be made. Some issues which slow the development of new HT Electronics products include:

- Lack of commercially available components designed to operate reliably above 125°C
  - Incomplete set of HT Electronics available. i.e., lack of just one critical component is enough to avoid using HT Electronic design approach.
  - Weak commercial base due to few manufactures making products specifically for high temperature use
- Lack of capital equipment for fabrication and specialized test facilities to make HT Electronics
  - Vast majority of semiconductors still use bulk silicon process and test equipment
- Immaturity of certain material technologies and processes needed
  - Weakness of packaging and interconnection technology
- Process of designing devices for high temperature not well understood
  - Shortage of high volume applications willing to help fund the expense of new device development
- Some markets waiting for demonstrated reliability of HT Electronics
  - Cost sensitive markets not willing to pay premium for HT Electronics
- Longer product development cycles
  - More issues with materials, processes, test
- Perception that lower temperature electronics can “conditionally” perform at elevated temperatures
  - While component vendors do not specify their parts above 125°C, they don’t discourage their use there either, saying such things as “others have successfully used these parts at higher temperatures”. Pressed for relevant data, of course, they usually cannot produce any.

The goal of this paper is to present the designer with both examples and tools to design electronics for high temperature. If this information becomes common knowledge, designers will become more comfortable with high temperature design, many new high temperature products will emerge, and end product users will benefit from improved performance, efficiency, and lower cost.

Who Uses HT Electronics?

Table 1 shows several markets and their temperature ranges, expected life, product time to market, and quality requirements:

Market	Temp (°C)	Life(KHrs)	TTM(Yrs)	Quality Requirements
Down Hole Instruments				
- MWD & Gages	175-225	> 2	1-2	Data Sheet
- Perm. Monitoring	150-225	40	1-2	Data Sheet
- Geothermal	250-300	Up To 8	2-3	Data Sheet
Turbine Engine				
- Aircraft	200-300	40-80	5-10	SCD
- Power Generation	225-250	8-40	2-5	SCD
Int. Comb. Engine				
- ABS Sensor	> 150	5	4	
- Drive Train Module	> 150	5	4	QS9000
- Heavy Engine	> 150	20	4	QS9000

Table 1—High Temperature Electronic Markets

Downhole Instruments

Drilling for oil has presented electronics with a challenging environment. Locating an instrument for pressure or flow measurement at the end of 3 miles of wire, poses problems for electronics including temperatures ranging from extended periods at 185°C to shorter periods at 250°C. Geothermal wells push continuous operating temperatures to 300°C, with survival to 350°C required (7). Traditional limits of several hours to 100 hours are being pushed out to several thousand hours, and in the case of permanent gages, to several years of continuous operation. Three types of instruments, depicted in Figure 2 are typical:

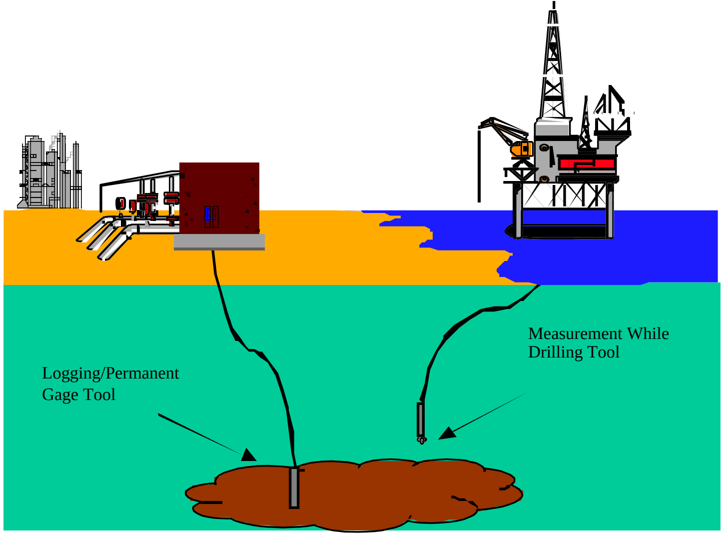


Figure 2—Downhole Instruments

Logging tools deployed for gathering snapshot information revealing the quality and potential production of the well. These can be wire-connected (wireline tools, receiving power and communications from the surface) or steel cable connected (memory tools, which are self-powered and contain memory which is retrieved with the tool).

Measurement while drilling tools used for directional drilling information such as hole inclination, hole azimuth, and the tool face direction. In addition, other measurements are now performed including resistivity, natural gamma, and neutral density. Downhole weight on bit, torque, vibration levels, accelerations are sometimes also incorporated into the measurement. This environment is extremely rugged requiring endurance of high vibrations and shock and thermal cycling every several days as the bit is pulled up and changed. Because of the high cost of drilling operations ($20k to $100k per day) these instruments need to be highly reliable. In some cases, the drilling operation is allowed to continue without operating instrumentation.

Permanent gauges are installed in producing wells and monitored at the surface periodically over several years time. Temperature, pressure, flow and different chemical sensors are deployed. These devices must have good long term stability without susceptibility to premature wearout mechanisms such as electromigration mentioned above.

Turbine Engine

Studies done at the Air Force Research Laboratory show that better regulation of engine thrust can result in a doubling of the thrust/weight ratio, 40% fuel burn reduction, at the same time as providing a 35% decrease in engine life cycle costs (8). To achieve these goals, control logic must be designed to use a broad array of hundreds of sensor/actuators operating over a wide operating temperature range to control thrust while protecting against aerodynamic, thermal, or material strength limitations.

The engine case is a significant source of radiant heat, approaching 560°C at high mach numbers and altitudes. However, based on typical jet fighter engine flight characteristics at mounting sites inside the engine, HT Electronics operating at junction temperatures of 300°C will handle worst-case thermal environments.

Aerospace control scientists have developed sophisticated distributed architectures which will improve performance, power output, or fuel economy if the electronics are able to be located close to the control target as seen in the FADEC system shown in Figure 3 below. Conventional uncooled electronics cannot be used here because of thermally induced wear factors leading to degradation and premature failure. Although fuel cooling has been very effective at improving the electronics environment, this approach favors a centralized control architecture as well as the added weight and space required for the cooling pumps, heat exchanger, and piping.

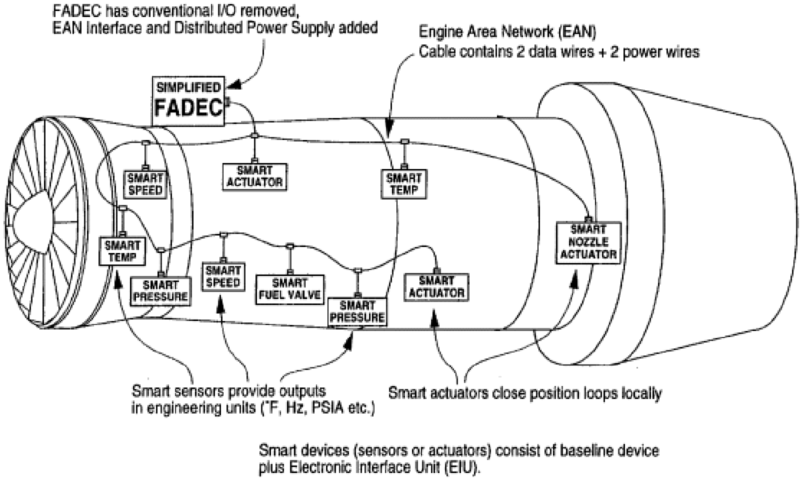


Figure 3—Advanced Turbine Engine Controls

In this application, the strategy is to perform low level functions in distributed modules, retaining complex calculations in the simplified FADEC (supervisor). It is simpler than the traditional centralized design because it contains a small fraction of the I/O. SOI technology will be used in most areas, while SiC technology is used in the most hostile temperatures.

In 1996 the Defense Advanced Projects Agency (DARPA) sponsored a $19M program to develop, demonstrate and commercialize High Temperature Electronic capabilities for use in turbine engine and industrial applications. A consortium of leading companies in aerospace, jet engines, specialized integrated circuit manufacture and specialized packaging was created to develop the active components, passive components, printed wiring boards and smart actuator electronic modules needed for this demonstration. Honeywell, Allied Signal and United Technologies Microelectronics Center (UTMC) developed all the active components required for all demonstrations. Proprietary interfaces for sensors and controls for different engine applications such as a smart actuator and a vibration monitor have also been developed by Honeywell.

Aircraft systems usually are man-rated, and as such have reliability units expressed in FITs or failures per billion operational hours. The term demonstrated reliability has new meaning when it comes to avionics in flight critical areas, such as components which are part of the flight control system. Due to the high profile nature of aircraft safety, liability for accidents is a huge factor. In fact, design related failures can force a major aircraft subsystem supplier out of business.

Internal Combustion Engine

High Temperature Electronics and Sensors are becoming increasingly necessary for automotive control applications such as engine control units (ECUs), in-cylinder pressure sensing and camshaft position sensing because of government requirements to rapidly reduce engine emissions. Reducing emissions, for example, depends on more precise and local control of valve timing, which in turn depends on primary (not inferential) sensing of cylinder pressure and camshaft position. To improve the precision of these measurements requires the sensors and signal conditioning electronics to be mounted as close to, or in some cases inside, the engine itself. Engine control units, typically mounted on the firewall of the engine compartment, can also contribute to reducing emissions by being mounted on the engine itself. The shorter control loops to/from the ECU lead to more precise control.

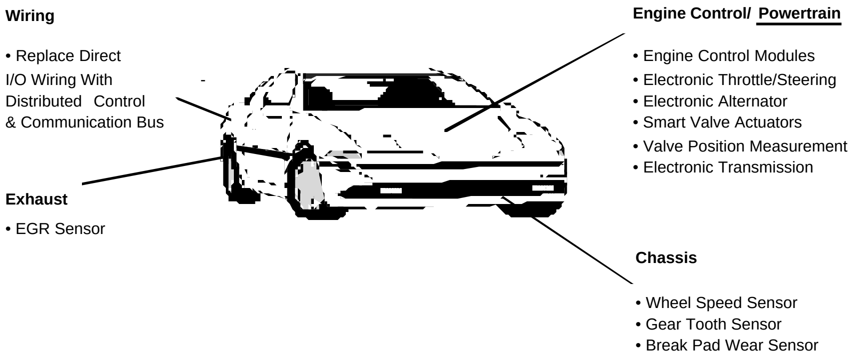


Figure 4—Automotive Use of High Temperature Electronics

Other Applications

Integrated Motor Control

Recent studies sponsored by the DOE on the use of HT Electric Actuators/Motors have show the feasibility of integrating the motor drive electronics with the motor. Product needs driving this integration include:

- Avionics hydraulic actuators with motors for lower weight and smaller size
- Military Hybrid Vehicles with both electric and diesel drive for stealth, use of regenerative braking, sharing of electric power for gun turrets, and other big motors. HT Electronics is also a plus for Operations in the hot Desert environment
- Military ship-based electric power generation, motors, and actuators for gun turrets, missile launchers, etc.
- Commercial Hybrid vehicles with requirements for high efficiency and very low emissions.

The Product Design goals for designing an integrated motor/drive include: local control (which is faster), compactness and reduction/elimination of cooling apparatus. Conventional single or multiple controlled motor 100°C via long heavy cables which carry high current PWM switching currents.

Future control architectures will use a smaller supervisory controller operating at 50°C connected to the array of motors & local controllers operating at 100 °C via lightweight Fault Tolerant Bus in a star configuration. The control and power switching electronics are contained at the back of the motor housing.

A primary issue to deal with in the integrated motor/drive, is the fact that the motor enclosure must dissipate power from both the drive and the motor, resulting in the need to de-rate the maximum continuous torque rating by up to 25% if conventional electronics are used. Heat sinking can take care of some of the added heat, but one goal is to reduce the cost and size, so this is undesirable. Thus, use of conventional electronics requires 1/2 the package size to be heat sink&drive electronics Figure 5 shows a motor drive built using a combination of Honeywell and other HT Electronics.

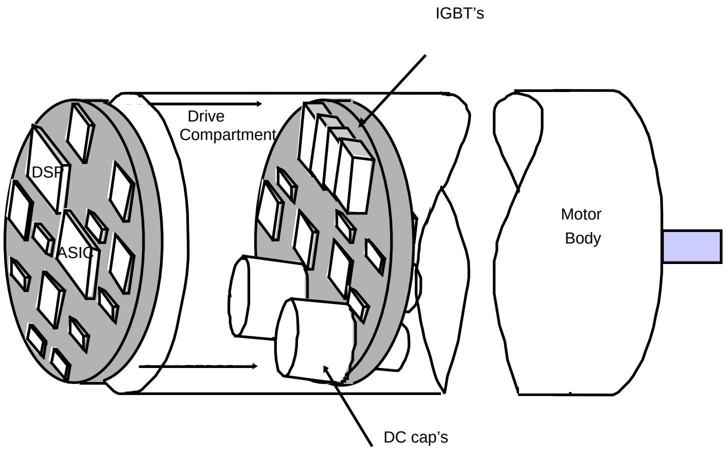
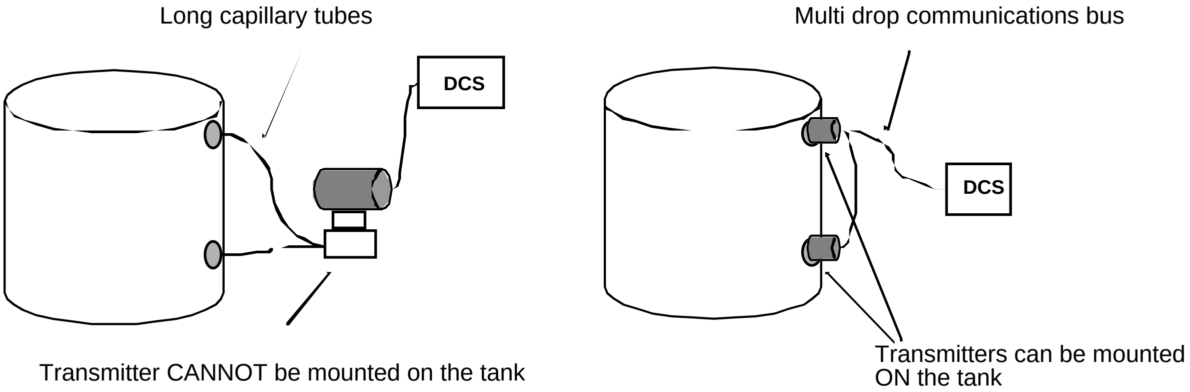


Figure 5—Integrated Motor and Drive

Some Industrial processes are carried out under very high heat conditions. A popular measurement, for example, is to compute process flow or fluid level in a tank. Which, under high temperature conditions, presents a problem for pressure transmitters doing the measurement. The conventional scheme is to locate the transmitter at some distance from the process and use “remote seals”. Large diaphragms located at the high temp process pressurize long capillary tubes containing low compression fluids which are sensed all the way back at the transmitter. If high temperature sensors and electronics are used for the transmitter design, this physical separation would not be required, resulting in a more accurate, stable measurement, and a more direct connection to the system supervisor as shown in Figure 6.



Without HT Electronics **With HT Electronics**

Figure 6—Industrial Process Monitor

Environmental Testing

Environmental Testing is a challenge when measurements are made inside an oven containing units being tested or burned in. High Temperatures and thermal cycling will degrade the integrity of monitoring electronics and present the test engineer with ambiguous data. The only option available with conventional electronics is to mount the monitors outside the oven and use shielded cable into the oven to the product being tested. Problems arise here as well due to long cabling & interconnection issues and exposure of raw signals to a noisy environment prior to signal conditioning. An example of this is when sensors are being characterized over temperature in the oven. If the sensor signal is a digital PWM or frequency one, critical timing measurements are distorted by cable capacitance caused by shielding and extra length. Bridge type sensors have millivolt level analog signals which are compromised by ambient noise, which can arrive at the monitor as large as the signal itself.

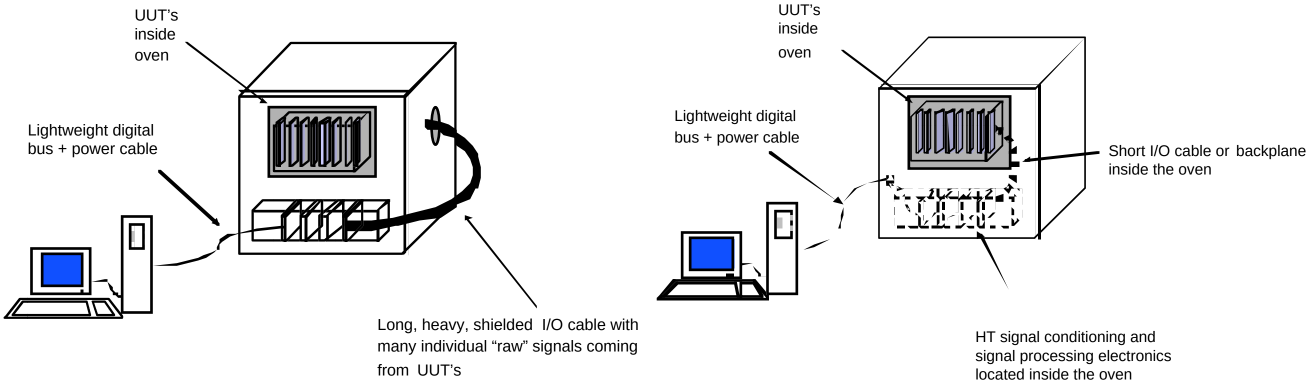


Figure 7—Use of High Temperature Electronics in Environmental Testing

The use of HT Electronics inside the oven allows the test to be conducted with as little distortion and noise as possible. Burn-in and characterization fixtures can be designed to contain all the electronics needed to do signal conditioning, and even the entire signal processing job, inside the oven. Thus, sensitive measurements and processing are carried out right at the sensor, before noise can corrupt it.

High Temperature Semiconductor Technologies (6)

There are few commercially available semiconductor choices available for use at high temperatures. In fact, as Table 2 shows, Si is the only technology with good high temperature characteristics, that is mature enough for production use.

Technology	Maturity	Temp Range	Source	Products
Si CMOS	Production	-55 to 150 °C	Multiple	Sensor I/F, Logic, Memory, Power
SOI (silicon on insulator)	Production	-55 to 300 °C	Honeywell and Allied Signal	Sensor I/F, Logic, Memory, Power
E/D GaAs	Production	-55 to 150 °C	Vitesse	Logic, Memory
Complimentary GaAs	Development	-55 to 350 °C	Honeywell	Logic, Power
SiC (Silicon Carbide)	Early Development	-55 to 600 °C	CREE	None
Diamond	Early Development	-55 to 1000 °C	Research Labs	None

Table 2—HT Semiconductor Technologies (HiTEN, London England)

As temperature increases in a semiconductor, there are challenging issues to resolve.

- Intrinsic carrier density increases
- Junction leakage current increases
- Device parameters vary
- Electromigration of interconnection traces increases
- Chemical reactivity of ohmic contacts increases
- Dielectric breakdown strengths decrease
- TCE mismatches stress the die mechanically

The most important physical properties for a good high temperature semiconductor material are a wide bandgap and high thermal conductivity.

- Bandgap, because it determines the amount of leakage current flowing across the junction.
- Thermal conductivity, because it determines the semiconductor's ability to dissipate heat to the ambient environment.

With some modifications, discussed later, Si has very good thermal properties, theoretically reaching temperatures of 400°C , and low power Si devices have been widely demonstrated to operate to 300°C. Since by far, most applications operate under 300°C, Si based technologies dominate the field now and will for many years to come. It is also true that packaging and interconnection problems present some of the biggest challenges for HT Electronics at temperatures above 250°C as discussed below, often providing more of a barrier to successful HT Electronics operation than the intrinsic material issues.

Si is suitable for power devices running at up to 200°C. Above that temperature, the choice is less clear. The three main technologies being SiC, GaN, and diamond. The latter two, though superior in performance due to wider bandgap and lower thermal conductivity, are in such an immature development state, that it will take several years for their importance to equal SiC. Another major selling point for Si is that the manufacturing technology is already in place for high volume, low cost products.

In summary, temperature ranges for HT Electronics can be broken down into 3 ranges as shown in Table 3. Market usage is also shown for relative importance:

Temperature Range	Percent of Market	Recommend for lo-pwr	Recommend for hi-pwr
Up to 200°C	90.2%	SOI	SOI
200 to 300°C	8.6%	SOI	SiC
Above 300°C	1.2%	SiC	SiC

Table 3—Recommended Technologies for GivenTemperature Ranges (HiTEN, London England)

SOI Technology

Standard Si CMOS material has intrinsic limitations when temperatures rise above 150°C including :

- Low threshold voltages due to thermal drift
- Excessive leakage currents due to reverse thermal junction currents
- Increased latchup and thermal runaway
- Reduced transistor mobility due to thermally induced carriers

Of all these factors, leakage currents present the biggest problem. They can be reduced by decreasing the area of interaction between devices and by using smaller geometry's, but then latchup becomes a worse problem.

A more cost effective solution is called SOI or Silicon On Insulator. Here, N and P type CMOS devices are isolated from each other by a layer of insulating substrate formed in the bare wafer material. Besides having very low leakage device capacitance's are also lower, increasing bandwidth, and reducing power consumption, which is very important for the large commercial IC vendors looking for better performance. A number of companies make these SOI wafers called SIMOX or BESOI, and the premium for the material is falling toward the standard material level. Increased usage thus drives the starting material cost down. Other advantages include very low voltage operation and increased radiation hardness. In fact, Honeywell makes radiation hardened Gate Arrays, ASICs and memories for use in Space, where radiation can damage standard bulk silicon devices.

Figure 8 shows a standard or "bulk" cross section in comparison to SOI. Note that the vertical dimension is not to scale. In fact the SOI active layer can be 100X thinner than bulk Si because SOI devices don't rely on vertical structures as do the bulk devices. This translates into much lower leakage currents due to the interfacial area between devices being reduced even more than if the thickness were the same.

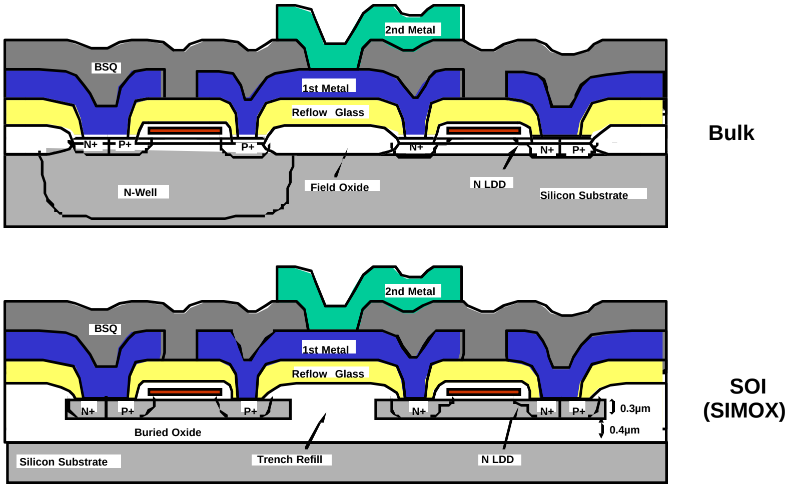


Figure 8—SOI Verses Bulk Technology Cross Section

Electromigration and Poor Ohmic Contacts

Probably the most significant limiting aspect of a HT Electronic component's lifetime at high temperature is the ability of the thin film interconnections to carry currents for extended periods of time (4). Over years, or even months of time, with (enough) current density, metals tend to dissipate. Lifetimes can be improved by reducing current density. HT Electronics are specifically designed to eliminate this issue by use of design layout rules which require 1/4 the current density of conventional bulk Si design. Another approach under development at Honeywell is to use metals with higher melting points, like tungsten. Research done for the Air Force has shown that tungsten films can handle at least 35 times the current of aluminum film. Figure 1 shows the effects of metal migration on lifetime.

Another issue at high temperatures is the increased chemical reactivity of metal to Si junctions. Unfortunately, metals with high electrical conductivity don't form stable ohmic contacts at semiconductor interfaces. HT Electronics solve this problem by using intervening layers of materials called diffusion barriers which is chemically neutral to the interconnect metal and the semiconductor contact. In Honeywell HT Electronics, this barrier is typically TiW, and it prevents a phenomenon called "metal spiking" from occurring. A significant amount of study is devoted to researching ohmic contacts in SiC.

Packaging and Interconnections for Components and MCM's (3)

When HT Electronics are exposed to high temperatures for extended periods of time, the materials used for substrates, die attach, wire bonding, and metal interconnects all have to be chosen carefully and should have good high temp properties. Substrate materials can warp and de-laminate, mis-match of thermal expansion coefficients can cause die to crack or come off, bond wires come off. These failure modes are in addition to more subtle life or performance issues like gradual thermally induced wire bond resistance increase due to formation of inermetallics, or increased leakage of packaging substrate materials due to dielectric strength degradation.

Some of the important properties for HT Electronic packaging and interconnections include:

- Materials used should have matching TCE's
- Interfacial materials used should be chemically inert
- Interconnect metals should not be mixed if possible
- Substrates should have high dielectric strength at high temperature.

In general, Ceramic substrates and Gold Eutectic Epoxy attach materials work better above 250°C. Cyanate Ester and Polyimide PCB's and polyimide or silicone attach materials work well only below 250°C.

If the materials have large CTE differences, and significant thermal cycling is expected, silver filled silicone can work well as a conductive attach adhesive, however, the upper temperature range should be limited to 250°C. An example of this CTE mismatch is the use of Cyanate Ester PCBs with SMT caps and resistors. For higher temperatures, ceramic substrates are recommended, especially if thermal cycling is expected.

A new low cost plastic package is being developed now for use with Honeywell HT Electronics products. This package will be designed to work in environments up to 225°C, and will be used in cost sensitive automotive and commercial applications.

High Temperature packaging materials research is an on-going "hot" topic, and there are still unclear choices in many areas. If you are interested in materials that are typically used in HT Electronics, please contact us at Honeywell and we will be glad to assist you.

Types of Devices Available in SOI

Please note that Honeywell SSEC has data sheets all of the following products. Application notes are also available, and more can be created if the application is explained in detail to the Honeywell applications engineer.

These parts have all been designed specifically for high temperature operation, and characteristic data is available for most of the device parameters. The process of manufacturing high temperature semiconductors is more complex and involves several process steps and tests not normally done, for example Burn In for 10 days at 250°C, and trimming analog parts for accuracy over the full 280°C operating temperature range.

Digital Devices

The following digital devices are available in SOI from Honeywell.

Part Name	Temp Range	Device Type	Features
HT83C51	To 300°C	Microprocessor	20MHz 80C51 compatible, 8K ROM, 256bytes RAM, 3-16bit timer/counters, UART
HT6256	To 300°C	SRAM	20MHz 32K x 8 Static RAM
*HT2007, HT2080, HT2160, HT2300, HT2400	To 300°C	Gate Array	20MHz Sea of Transistor Gate Array with from 5k to 200k usable Gate Count
HTCCG	To 300°C	Crystal Clock Generator	High Speed, up to 40MHz Oscillator

Table 4—HTMOS Digital Devices

The HT2000 Gate Array Library consists of:

- SSI and MSI cells for 1x,2x,4x drive strength
- 40 standard and complex gates
- 29 sequential logic elements
- tristate and 1149.1 Boundary Scan
- Macro cells for up to 16kbytes of SRAM
- Custom drop-in SRAM of up to 40kbytes
- Clock speeds of up to 20MHz at 225°C

Analog Devices

The following Analog Devices are available in SOI from Honeywell:

Part Name	**Device Type**	**Temp Range**	**Features**
HT1104	Operational Amplifier	To 300°C	Quad CMOS Op Amp, +/- 5 or 0/+10V Supplies, +/- 4.8V output switch
HT1204	Analog Switch	To 300°C	Quad bi-lateral switch, similar to CD4066
HT507/508	Analog Mux	To 300°C	8:2 and 16:1 Analog Mux
HTVREF05	5V Voltage Reference	To 250°C	+/-25mV drift over temperature.
HT574	11 bit A/D	To 250°C	15microsecond conversion rate SAR with parallel Microprocessor interface

Table 5—HTMOS Analog Devices

Custom Analog ASICS are available with support for Initial Feasibility, Technology Selection, Modeling, and Layout. Tools and support are available for Design Rules, Layout rules, Spice Models, Automated Test Program Development, High Temp Testing.

Power Devices

The following Power Devices are available in SOI from Honeywell:

Part Name	**Device Type**	**Temp Range**	**Features**
HTANFET	N Channel MOSFET	To 300°C	1 Amp Id, .2ohm ON resistance (RT)
HTPLREG	Positive Linear Regulator	To 300°C	+5, +10 and +15V Positive Linear Regulator, 0.5A output
HTNLREG	Negative Linear Regulator	To 300°C	-5, -10 and -15V Positive Linear Regulator, 0.5A output

Table 6—HTMOS Power Devices

Support Electronics & Materials Used in Making High Temp Circuits

Passive & Discrete Devices (1)

For passive components, packaging durability at high temperatures is of prime importance. Very often, joining, sealing, and package ruggedness are the main issues affecting the reliability of the components, whereas the basic property materials are very robust.

Traditionally, high temperature applications have chosen to use through-hole components due to greater availability. Their ability to withstand greater TCE difference between components and circuit board, than can leadless packages is attributed to the strain relief provided by component leads. Honeywell's HTMOS products are available in ceramic through-hole packages.

There is a strong desire to use SMT components for the space savings obtained. More passive SMT components are now available with high temperature terminations, making the decision to go to SMT easier. Leaded gull winged SMT IC's can also provide sufficient strain relief. In general, larger, leadless SMT components should be avoided because of the potential of cracking due to TCE differences in board and component materials.

For SMT components, standard eutectic Sn/Pb solder terminations are not recommended in the >200°C temperature range. End terminations should be either PdAg or Au above 240°C. Solders recommended for these terminations are 97.5Pb, 1.5Ag, 1.0Sn or Indalloy IND. 183 (88Au/12Ge) respectively. See discussion of solders later in this paper. A number of papers have been written, some cited here, which document thermal and aging tests of passive HT Electronics components.

Resistors (5)(2)(3)

Resistors, though less complex than other passive devices, are the largest utilized component in electronic design. Thus, failure modes, shifts, and thermal drifts all can have very adverse effects on a circuit designed for high temperature operation.

Wire wound resistors are designed for power applications, and thus are usually well suited to high temperature environments. To keep these parts from exceeding their potting material temperature limits, they should be derated significantly. Derating a resistor to 20% of room temperature power rating is recommended for operation at 200°C by the manufacturer, however, tests have shown that the part can be used at this derating factor for thousands of hours successfully. This only increases the case temperature from 300°C to 320°C. Both Dale and Caddock make wire wound resistors for which there is temperature test data available.
Thick film resistors have been designed for high temperatures. Heraeus-Cermalloy has made a special high temperature resistor ink which is printed on ceramic substrate with Pd/Ag termination suitable for temperatures up to 500°C.

Thin film resistors can be made for high temperature use. Honeywell has a process for making thin film chrome silicon on SOI integrated circuits. These films are deposited after underlayer processing and before the backend conductor films are deposited and patterned. Resistor values have trimmed accuracy's of +/- /2%. Some published test results demonstrate that:

- The nominal value of Dale 5W, and Caddock 0.1 to 1 watt wire wound resistors drifted typically within +/- 4% over several hundred hours.
- Some shifting of value can occur if the wire wound resistor is thermally cycled, amounting to a couple percent, which usually, but not always, returns to the previous value from before the shift occurred.
- Dale wirewound resistors have survived tests of 10,000 hours with 1000 thermal cycles from –55 to 225°C making them a good solution for medium power resistive needs.
- Temperature effects of 1% from 0 to 300°C are seen with the thick film printed resistors, however, aging effects show drifts of 3% in a couple hundred hours, making them good candidates for low power high temperature use.
- Drifts of the printed resistors were different for different shapes, with a square geometry having the least drift.

- Thin film resistors from Honeywell have drifted less than 0.7% over 1700 hours at 200°C. These resistors have a TCR which is typically –226ppm/°C with std deviation of 35ppm/°C. Power levels must be kept small, however, to avoid greater drift due to self-heating.
- Huntington Electric also manufactures wirewound resistors with very low (30ppm/°C) temperature effects.

Beware that manufacturers will sometimes adjust the value of a wirewound resistor by notching the wire. This will serve as a nucleation site for wire fatigue damage to collect, and is the usual cause of failure of these types of devices.

Capacitors (5)(2)(3)

Capacitance will often change significantly with increasing temperature due to temperature dependency of the dielectric constant. ESR and dissipation factor are also affected. High temperature capacitors usually have low capacitance due to mechanical breakage caused by thermal packaging stresses. Electrolytic caps don't operate above 150°C due to dielectric breakdown. Values of several tens of microfarads are typically wet slug Tantalum devices, but switching applications suffer due to higher values of ESR, and the capacitors will need to be paralleled to get high values with low ESR. Solid Tantalum caps are available in values of several microfarads. High Temperature ceramic caps tend to be very stable for long periods of time…exceeding 5000 hours in some tests, however, their values are usually smaller than 0.1 microfarad. Teflon electrostatic capacitors are being developed by Custom Electronics, which have very low TC of capacitance from room to 200°C, though the parts are usually small valued.

Some published temperature test results demonstrate that:

- Sprague and Transistor make wet slug tantalum devices. The loss of hermetic seal is the primary failure mode of these types of capacitors. Tests have shown that at 200°C there is a gradual loss of functionality above 2500 hours with these types of caps.
- At 200°C, Matsuo solid tantalum caps exhibit an initial aging shift in capacitance of a couple percent, but then stabilize for several thousand more hours. The TC of capacitance for these caps is about 350ppm/°C.
- X7R dielectric ceramic caps made by NOVACAP show some initial aging at 200, but then stabilize for several thousand more hours. Cycling temperature, however, produces a 2.5% temporary shift in value.

Crystals (3)

Drift tests of 5500 hours of crystals from CINOX, Anderson, and Q-Tech have shown that the crystal fabrication technology exists to make an oscillator stable to +/- 800ppm from –55 to 225°C. The packaging techniques used in high temperature crystals are a critical part of the overall component design. Mismatches in TCE between the internal structures can cause cracking and immediate failure or gradual degradation of performance. It is not sufficient to look only at the TC of Frequency for a given high temperature crystal without considering it's long term aging effects.

Circuit Construction Materials

Board Materials (3)

Circuit board materials should be carefully chosen to provide a stable platform for electronic components and or circuit die over temperature extremes. Some of the desirable properties of good packaging material include:

- Good Thermal conductivity
- Thermal shock resistance
- High electrical resistivity
- High mechanical and chemical inertness
- Thermal expansion which matches components & attachment adhesives used.

Depending on the type of application, the following temperature ranges are recommended for the given board materials:

1. Standard FR4	to 175°C, low power applications
2. Polyimide or Cyanate Ester	to 250°C, low power applications
3. Aluminum Oxide 96% alumina	> 500°C, low power applications
4. Aluminum Nitride	to 600°C, power applications

Wiring, Interconnections, and Solder (3)

TFE Teflon hookup wire is recommended for temperatures up to 250°C, such as Alpha 5848; above that, Dearborn's 311816 works well. It has nickel coated copper conductors having a double layer insulation of glass reinforced mica tapes overlaid with treated glass braid. Several solders may be used in making high temp circuits:

For temperatures below 250°C, a 97.5Pb, 1.5Ag, 1.0Sn can be used, with a melting point of 309°C. For temperatures above 300°C, Indalloy IND. 183 (88Au/12Ge) can be used, with a melting point of 356°C.

Adhesives and Epoxies (3)

Some good, high temperature epoxies and attach adhesive's include:

Product Name	**Material Type**	**Max Operating Temp**
EPO-TEK E3081	AG-filled epoxy	250°C
Ablestik 71-1	AG-filled polyimide	240°C
Indalloy IND. 183	88Au/12Ge Braze	356°C
Grace Specialty Polymers	AG-filled silicone	230°C

Table 7—Epoxies and Adhesives

Design Techniques for High Temperature Applications

Electronic Errors

Input amplifiers need to have low offset, high impedance, and high gain to minimize errors in a control loop. Unfortunately, bipolar amplifiers, which are typically used for these reasons, don't work well at high temperatures due to base current errors and reverse leakage problems at high temperatures. The base current of a bipolar input stage, for example, will fluctuate with temperature, and reverse leakage of a base/collector junction with open emitter doubles every 8°C.

Specialized amplifiers exist which incorporate bias cancellation, including the LT1001XH Junction Isolated and the HA7-2600 dialectically isolated amplifiers. These amplifiers have had some success at high temperatures. Another problem is thermal drift. One approach to removing the thermal drift in amplifiers is to use a chopper stabilized amplifier as shown below in Figure 9. The job of this circuit is to modulate the bridge, which is AC coupled to the input of the amplifier, and to synchronously demodulate the output of the amplifier, which is AC coupled. The output is then filtered in the final stage as shown (from Paine Instruments).

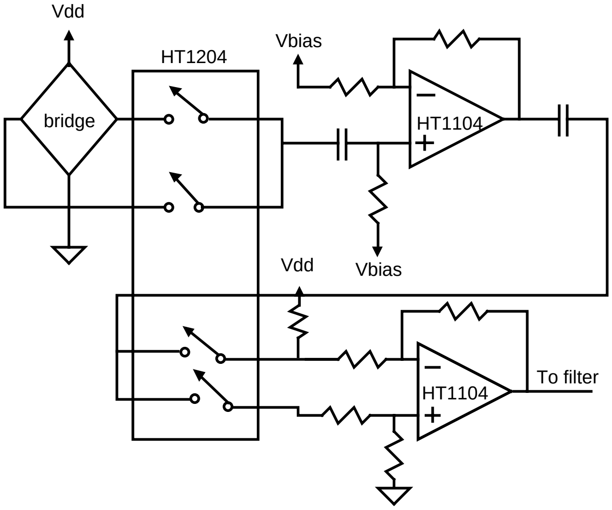


Figure 9—Chopper Stabilized Amplifier

Actuator Interfaces

Conventional actuator control techniques use a proportional analog signal generator. Thermal effects can influence the amplitude and frequency of the generator. PWM techniques can be used to overcome this issue. PWM signals are easy to generate if a microcontroller like the HT80C51 is used. This device has built in support for generating PWM signals at 19.6kbaud with a 20MHz clock.

Sensor Interfaces

In low temp applications, sensor outputs are amplified and converted to digital form using components like Instrumentation Amp's and A/D converters which may be ratiometric to power supply effects, but neglect inherent drift in the sensor due to temperature coefficients. High temperature approaches should include some way of scaling the instantaneous sensor output by an appropriate temperature sensitive mechanism like:

- Compensating the sensor with a resistor having equal but opposite temperature coefficient.
- Using constant current excitation for sensors in which current is the primary excitation mechanism.
- Measuring the temperature with a temperature sensor and digitally compensating the sensor.
- Ratiometric measurement, which produces a sensor output which is scaled in ratio to the *gain* of the sensor.
- Reducing the input range of the sensor or *nulling* the input signal by external feedback techniques. This technique is sometimes called *closed loop feedback* but is not easy to do with some types of sensors.

Thermally induced offsets can also be a problem with sensors. The problem can be exacerbated if the offsets are not correlated, but appear random from sensor to sensor. Ultimately, these of errors must be compensated for by direct characterization and correction.

Some applications require very high impedance circuits and materials. A very high impedance operational amplifier, like the HT1104HZ, can be used to amplify signals from high Z sensors like Accelerometers and Photodiodes. In these cases, low leakage ceramic board materials are recommended to maintain signal integrity.

Examples of Specific High Temperature Applications

Down-Hole Instruments

Essentially, most downhole measurements require a reliable, rugged data acquisition system which, MUST operate flawlessly when deployed. Here, the mission life may only be hours or days, but the price of failure can far exceed the cost of the instrumentation. For this reason, designers tend to be conservative, and often will characterize components and test their tools at temperature prior to deployment. Some tools developed several years ago can be re-furbished if *drop-in* replacements for components can be found. One of the goals of the Honeywell HTMOS standard product line is to such a replacement of older parts, like the ADC574 12-bit A/D converter or the DG508 analog mux.

Instruments are usually designed in long slender tubes. A directional tool, for example, may be several feet long and 1 to 1.5 inches in diameter. Often, the well casing may contain small side *pockets* for the tool in which to reside. Memory tools impose the added requirement of very low power operation, having to operate under battery power. Non-volatile memory is also a challenging requirement. The Xicor product line includes some 180°C rated memories, which are sometimes pushed beyond this. Wired Communication protocols are often proprietary, with bi-directionality of signals on a single line to conserve wires. Some instrumentation firms, however, have adopted aerospace buses, like the Mil-1553 synchronous communications bus. Another method is to actually modulate the pressure of mud being pumped into the wellbore. Here, the mud is pumped downhole and forced through a turbine-generator for power as well as providing cooling for the system.

Figure 10 shows architecture for a wireline permanent gage which utilizes a custom gate array and ASIC to interface to pulse width modulated pressure sensors and temperature sensors, and a single bi-directional communication line.

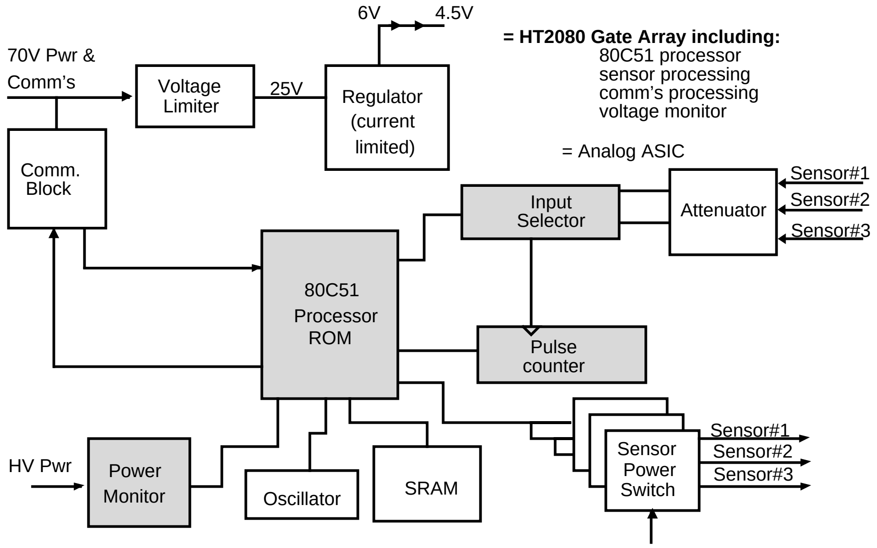


Figure 10—Downhole Tool Architecture

Custom gate arrays and ASIC's can solve some packaging and interconnection problems for the users, while reducing power consumption and overall size.

Turbine Engine

Distributed Engine Controls

Controls in an aircraft turbine engine can amount to nearly 20% of the cost of the engine, but can contribute 40% to the total life cycle cost due to high maintenance action required (8). Because the expected service life is as much as 80,000 hours, SOI technology is the appropriate technology to use. The amount of I/O required in modern jet engines has increased exponentially in recent years, leading to electronics being a higher percentage cost of the control system.

The following diagram, Figure 11, shows how multiple channels of sensors can be interfaced to a high speed 11 bit A/D converter, the HT574, to digitize and communicate signals to a supervisory processor located outside of the high temperature environment. This architecture is optimized for speed, allowing the three channels to settle through their input stage amplifiers independent of the mux .

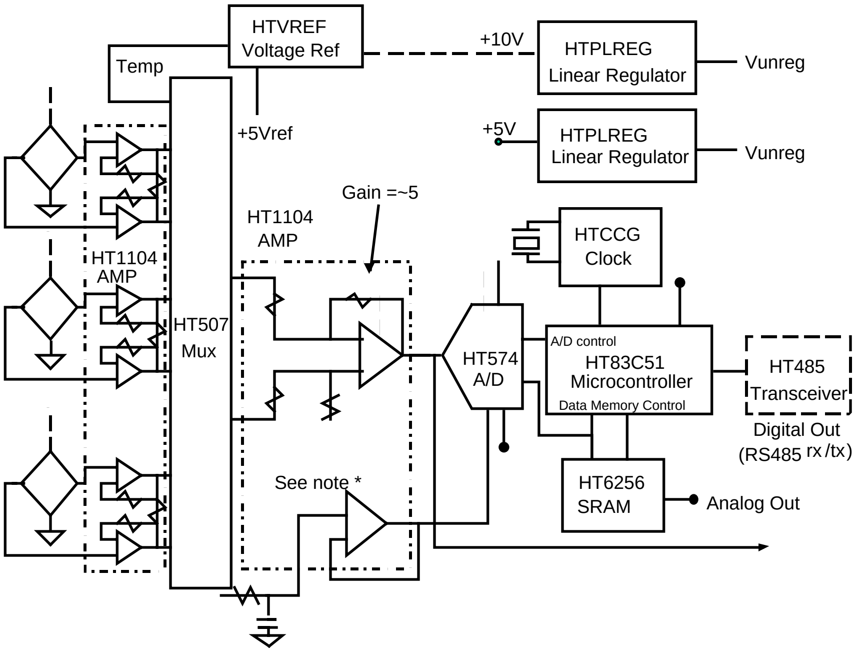


Figure 11—High Temperature Distributed Control Architecture

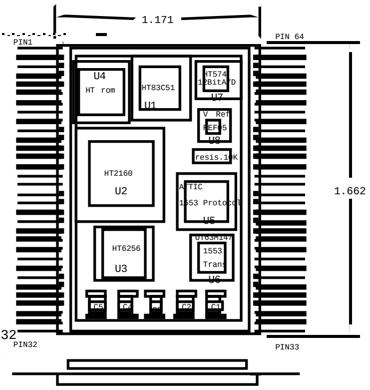
An architecture similar to this is used in a high temperature control MCM developed for the DARPA program mentioned earlier in this paper. The MCM layout, containing Honeywell HTMOS circuitry and packaging, is shown in detail in Figure 12.

COMPONENT LIST
14 TOTAL
8 ACTIVE COMPONENTS
6 PASSIVE COMPONENTS

U1 HT83C51 MICROCONTROLLER
U2 HT2160 GATE ARRAY
U3 HT 6256 RAM
U4 HT ROM
U5 ATTIC 1553 PROTOCOL
U6 UT63M147 1553 TRANSCEIVER
U7 HT574 12 BIT A/D
U8 HTREF-05 VOLTAGE REF.

C1 0.1UF CAPACITOR
C2 0.1UF CAPACITOR
C3 0.1UF CAPACITOR
C4 0.1UF CAPACITOR
C5 0.1UF CAPACITOR
R1 10K OHM RESISTOR

CRITICAL NODES:
DIGITAL PINS 31,32
ANALOG PINS 60,61



MULTILAYER CERAMIC PACKAGE

- 64 leads 32 per side .050" pitch
- Lead Width .017" .006" thick
- Co-fired alumina package
- Kovar seal ring
- Welded Kovar lid

Figure 12—MCM Layout for High Temperature Distributed Control (DARPA)

Internal Combustion Engine

Embedded Engine Sensors

HT Electronics is finding greater use in automotive applications as subsystem suppliers are asked to provide increase in temperature capability above 150°C in their products. This is an area where low cost goals will produce HT Electronic components with new packaging, processing, and techniques of ensuring product reliability.

Miscellaneous

Integrated Motor Controls

The advantages for integrating a motor with its drive electronics include:

- Smaller overall size
- Elimination of an external cable assy with it’s cost and technical problems:
  - EMI pickup
  - Added electrical resistance in the cable
  - Transmission line issues like voltage reflections
  - System inflexibility
- Less difficulty with installation, and setup than if two units are used

Typical drives operate with a maximum ambient temperature of 40 to 50°C. The heat dissipated by the power electronics will raise the operating drive temperature to 100°C.

An integrated motor/drive designed today could consist of round boards mounted on the back of the motor. Figure 4 is repeated here:

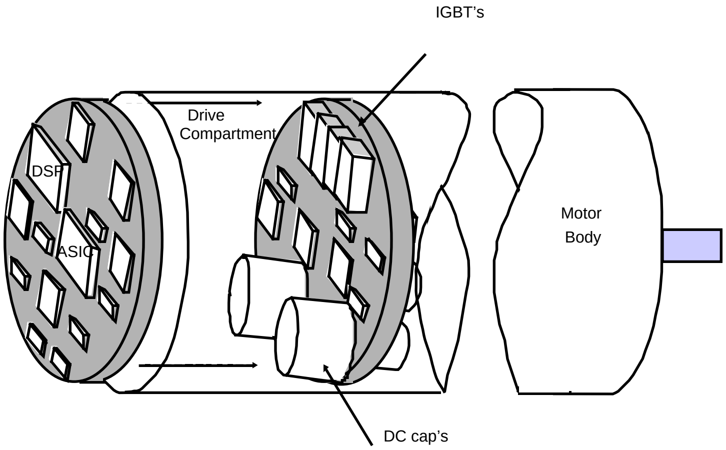


Figure 4—(repeated)

Board #1 = Control Logic with:

DSP (50Mhz, derated to 20Mhz)
HT2160 ASIC with 2 pwm generators, WDT, POR, A/D interface, etc.
EEPROM (rated to 180°C)
A/D, MUX, VREF,SRAMs (ours)
Comparator (derated)

Board #2 = Power Converter with:

Rectifiers, IGBT's (derated by 6x to allow operation at 160°C)

Some key challenges include:

- Motors have large (~200uF) DC caps to help in rectification (AC to DC to AC conversion) but no COTS parts exist for this, so the switching architecture should be modified to allow the use of lower capacitor values (<100uF) by implementing an "adaptive PWM bridge configuration"….thus reducing cap size by 70%. This requires 2x the number of switches however.
- High temperature switches are not available requiring derating and cooling
- High temperature non-volatile memory is not available
- Cooling approaches include mounting fans opposite the IGBT's on the heat sink.

Future, proposed approach:

- HT control logic—SOI
- HT power switches—SiC
- High efficiency switching architecture
- Power derated components
- HT MRAM for NVM
- DC cap reduction
- Efficient cooling

A High Temperature Demonstration

To demonstrate how effective the HTMOS components are at high temperatures, we have put together a few different sensor based boards, including position sensors, a heading sensor, and a current sensor.
The basic position sensor architecture is shown in Figure 13.

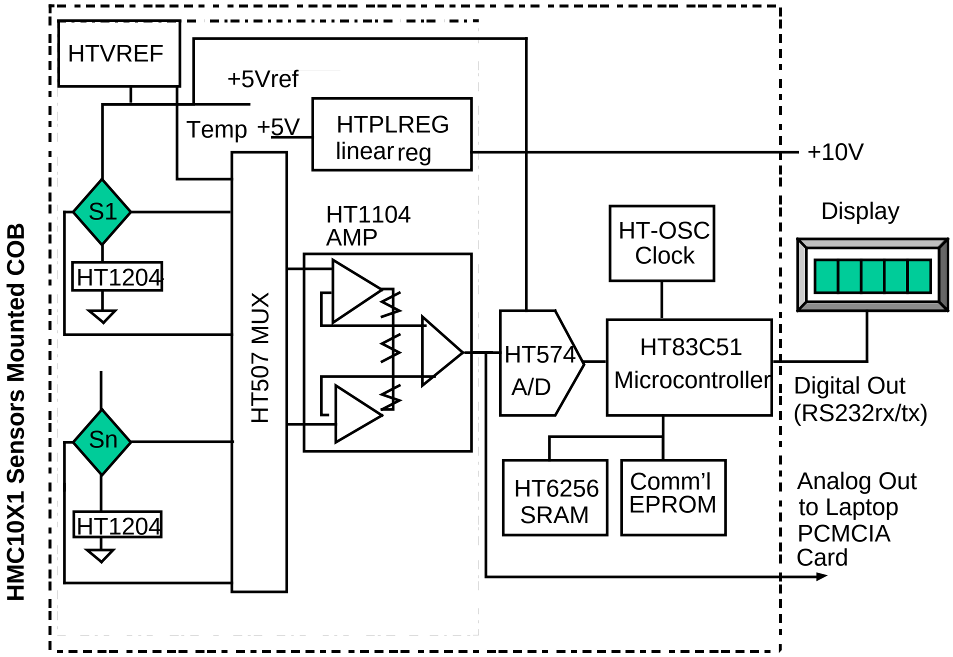


Figure 13—High Temperature Demonstration

Here, Honeywell HMC MR sensors are mounted Chip On Board style onto high temp Polyimide board material along with other HTMOS HT Electronics, including:

Analog Board:
- HT1104 quad op amp
- HT1204 analog switch
- HTPLREG Linear Positive Regulator
- HT507 analog mux
- HTVREF05 voltage reference

Digital Board:
- HT574 A/D
- HT83C51 Microcontroller
- HT6256 SRAM
- HTCCG

Parts are arranged on two boards, one analog and one digital. The digital board has not been built so a data acquisition card interfaced to a laptop provides the A/D conversion and display of the analog position signal.

The board is positioned over a hot plate and a Pyrex dish is placed over the board for visibility while holding the heat inside. A type K thermocouple is used to readout the temperature in Centigrade. A digital photograph of the demonstration is shown operating at 202.9°C.

Figure 14—High Temperature Electronic Demonstration

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