New high-temperature electronics may open doors for ultra-deep drilling, completions

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Above: A reservoir monitoring system using HT electronics was deployed in a Coso Naval Test Range well a mile from the Coso Geothermal power plant. The uphole reservoir monitoring system used to support the testing is seen above. The solar panel trailer is left of the well. The trailer provides power downhole and houses the satellite transmitter. Table 1 (below) shows basic industry requirements common between the auto, aerospace and drilling industries.

Industry	Temperature	Temp. Cycles	Operating Life
Automotive	125-160°C	Few thousand	~8,000 hrs (100K miles)
Aerospace	>200°C	10s of thousands	30,000 to 80,000 hrs
Well monitoring	up to 200°C	<50	40,000 hrs (5 years)

THE ELECTRONICS INDUSTRY is well known for "reinventing" itself. At the IC (integrated circuit) level, it's generally accepted that the industry redesigns ICs on a 4-6 year cycle. The electronics industry is constantly working to make ICs smaller, cheaper and faster. Long gone are the days of the 6 transistor radio. Consumers expect a lot of wiz-bang from their electronic gadgets. Unfortunately, within the continuing effort to make transistors smaller, faster and cheaper, the inherent reliability of solid-state electronics for operating within extreme environments has taken a back seat to consumer production.

This is no more evident than in the electronics needed for extreme environments of ultra-deep drilling. Today, "industrial"-grade electronic components are rated to 85°C without any manufacturer-qualified operating life. The old Mil-Spec (125°C) components started fading out of production in the 1990s, and few are left. The reliability buck is being pushed from the IC manufacturer toward the system design engineer to resolve environmental issues. For some engineers, this means running fans on top of electronic devices or creating large heat sinks to an external cold surface. For ultra-deep drilling applications, the design engineer has few practical options within an ambient temperature >100°C.

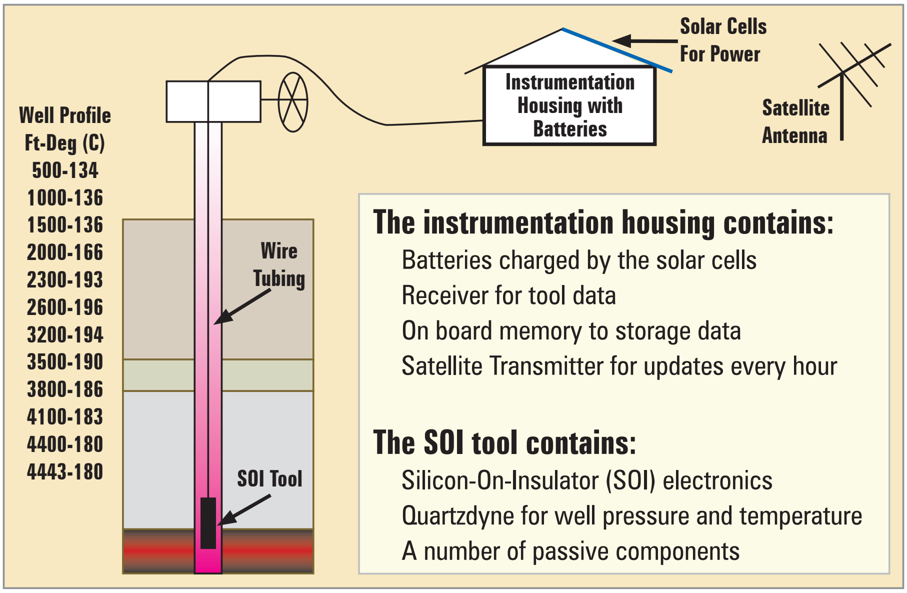
The good news is the ultra-deep drilling and well completion industries are not alone. The automotive industry is interested in expanding electronic engine and transmission controls while increasing auto warranties. The aircraft industry is moving toward more electric power to eliminate heavy hydraulic systems. These industries are even working on new semiconductors other than silicon to meet their needs. These new semiconductors are opening new doors for electronics in energy-efficient solid-state lightening, power converters and motor control electronics. Below are some discussions on new electronic devices addressing extreme environments.

SILICON-ON-INSULATOR

Silicon-On-Insulator (SOI) is the best known means for extending the performance of electronics toward higher temperatures. In standard commercial electronics, each transistor is built by doping pure bulk silicon to create positive or negative regions (called PN junctions) within the bulk silicon. As temperatures increase in silicon, an increase in thermally generated electrons are freed to run around the circuit, causing the PN junctions to function poorly or even fail to operate. In SOI, each transistor is built on an insulating (non-conductive) barrier. This action reduces the number of "thermally" generated electrons ~100X. SOI components can normally operate up to 250°C, with some operating up well over 300°C. At temperatures of 150°C, they operate with little or no functional degradation. Unlike bulk silicon, performance degradation can normally be seen above 125°C.

SOI doesn't by itself make the electronic device more reliable. One of the clear life-limiting factors for all electronic devices is the rate of metal migration. To connect transistors to the outside world, metal is bonded to the device. As it turns out, aluminum is a good match for silicon and is used in consumer electronics. Unfortunately, aluminum migrates into the silicon as a function of time, temperature and current density. Eventually, the loss of metal due to metal migration causes the device to fail. **Honeywell** uses AlCu alloy along with a reduced current density (of half that of standard commercial components) for a designed operating life time of 5 years at 225°C.

Others use heavier metals such as tungsten to greatly reduce metal migration. Both of these techniques enable elec-



The long-term demonstration testing at Coso installed the reservoir monitoring sytem at 3,100 ft using wire in tubing.

tronic devices to operate for 20 years or more at downhole temperatures between 100-150ºC.

SILICON-CARBIDE

New semiconductors are opening doors for the electronics industry. Silicon-Carbide is an example. Silicon-Carbide devices have major advantages over silicon for handing power. Silicon-Carbide has 5 times the voltage capability along with twice the thermal dissipation of silicon. In short, SiC power devices can be made smaller and require less cooling. And if that wasn't enough, it's a little more energy-efficient than silicon for switching large currents.

Future Silicon-Carbide-based motor controllers will be smaller and lighter and will save energy over existing silicon designs. Add reliable SOI and you can now build electronic systems with extremely high energy densities needed for a host of industrial applications.

The Sandia-designed mud turbine control electronics based on SOI-SiC technology is able to directly handle 100-300V from the turbine while operating at an ambient of 230ºC — and to do so for hundreds if not thousands of hours.

SiC is a new technology with only a few commercial power devices undergoing reliability testing. The market pull for SiC is very hot. Consider the following benefits for hybrid or electric vehicles to replace existing bulk silicon technology:

•A nominal size reduction of 30% — saving space.

•Improved thermal dissipation — saving weight.

• Energy efficiency improvement of 2%-4% — saving fuel or increasing distance.

The benefits listed above also benefit the aircraft industry, where weight reduction is a major cost driver. It's common within the aerospace industry to say, "It's not what it costs but what does it weigh?" The MEA concept eliminates all hydraulic systems from the aircraft for lighter electrical systems. Not only saving weight but also reducing aircraft ground support costs for people and equipment.

Table 1 shows basic industry requirements between the automotive, aerospace and drilling industries.

The high reliability requirements of the commercial airline industry and the extended temperatures, operating life times and high number of temperature cycles for aircraft engines exceed well monitoring requirements. In short, aircraft-developed electronics and sensors can solve many of the well monitoring reliability issues found within the drilling industry.

Although both industries can share the majority of components, there are differences in others. Aircraft electronics are used as control systems, whereas well monitoring and MWD electronics are more specialized and have more

Component	Aerospace	Drilling
A/D converter	8 to 10 bits	16 bits minimum
Processing (uP)	Basic	High level to support slow communication
Batteries	N/A	Required
Programmability	Minimum	Small market with diverse requirements drive high levels of programmability

Table 2 shows that while the aerospace and drilling industries can share the majority of electronic components, there are still some differences.

scientific-intent use. The A/D converter converts sensor signals to digital values. The aircraft control system doesn't need the high resolution of the well monitoring equipment. Table 2 lists some other differences.

The NETL Honeywell Joint Industry Partnership is directly working on improving A/D converters needed to measure sensor outputs within the well and programmability with a device called a Field Programmable Gate Array (FPGA). The FPGA is capable of software- reconfiguring its circuits to perform an infinite number of logic functions.

Sandia's Geothermal Research Department has designed a custom SOI chip to create a complete set of HT SOI electronics needed to build a basic logging and drilling tools. Sandia is working with a large number of component and sensor manufacturers to conduct drilling and logging tool demonstrations.

The Society of Automotive Engineers – Aerospace Electronics Chapter 7 is holding meetings to better define component manufacturing testing requirements for reliable HT electronics. By combining the electronics requirements for multiple industries, there is hope to greatly increase component available and reduce costs. For more information, please contact the author.

HT TECHNOLOGY DEMONSTRATIONS

The Sandia approach is simple: "Adapt and expand high-temperature electronics technology to downhole applications." Using hot geothermal and steam injection wells, Sandia has demonstrated reliable HT electronics in real field applications. To date, the Sandia HT SOI Pressure/Temperature (PT) logging tool has logged wells up to 256ºC without heat shielding. Plans are under way for monitoring a well for one month at an expected temperature of 300ºC.

PT WELL MONITORING

To date, three reservoir monitoring systems have been successfully deployed. The first two systems were funded by the USGS to help in their work in reliably monitoring volcanic unrest. Several examples of pre-eruptive groundwater pressure changes show that fluid pressure monitoring can be a valuable tool for detecting volcanic unrest. The third system was deployed in a Coso Naval Test Range well located a mile away from the Coso Geothermal power plant. The tool has been installed within the well at 3,100 ft using wire in tubing. At this point, the nominal temperature is 193°C (379°F).

Prior to the tool going into the well, the tool was oven-tested for one month at temperatures between 180 and 200°C. The purpose was to demonstrate the reliability gained when using manufacturer-qualified HT electronic components for long-term well monitoring. This system had been deployed for a total of 800 days, with three extrusions for inspection. Unfortunately the tool was lost when a Navy test required removing the tool, and the service operator dropped the tool and was unable to fish it out.

This demonstration provided Sandia the opportunity to learn more about tool hardware and assembly for long-term well monitoring. This information is used to provide manufacturers with a list of do's and don'ts. For example, an automotive capacitor rated for 200ºC used a standard lead-tin solder on an internal electrical connection. After time, the tin reacted with the copper wire to form crystalline bronze, which lost its mechanical strength. Sandia also found a loss of protective coating from high-temperature resistors. Micro leaks of well fluid passing the tools metal seals removed the resistors' protective coating. Sandia has developed new sealing technology and suggested using ceramic coated resistors for future well applications.

Overall this long-term demonstration provided many positive outcomes:

- At 193ºC, new HT SOI electronics have virtually unlimited operating life compared with conventional commercial grade electronics.
- Sandia learned to redesign existing metal seals and improve assembly materials to support HT SOI electronics.
- Electronic systems can be fully qualified and tested prior to well installation.

Perhaps the last is the most important. Because new electronics can operate for years at nominal temperatures of 150-200ºC, there is no real limitation on fully testing assemblies prior to field deployment. Keep in mind that commercial electronics lack life qualifications or performance data above 85ºC. Service companies might squeeze out 100 to 500 hrs of operating time at temperatures >150ºC. This limits the number of hours for burn-in testing needed to screen out infant mortality failures. In fact, at temperatures of 200ºC, the electronic devices might be degrading faster than systems can be accurately calibrated.

CONCLUSION

New industrial applications are pushing electronic manufacturers to improve the reliability of electronic components for extreme environments. The use of Silicon-On-Insulator technologies is enabling electronic to operate up to 250ºC. The use of improved metallization on silicon electronic components is enabling operating life times of 20 years at temperatures of 100-150ºC.

New semiconductors are opening doors for major changes within the electronic power industry. Silicon-Carbide is one of those new semiconductors. By combining SOI and SiC, motor controls and power converters can function more efficiently, be smaller in size and operate at temperatures well above 200ºC.

Acknowledgements: Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

References: B.L. Gingerich, SPE, and P.G. Brusius, "Reliable Electronics for High-Temperature Downhole Applications," 1999 SPE Annual Technical Conference and Exhibition, Houston, Texas, 3-6 October 1999.

This article is based on a presentation made at the 2006 DEA Workshop, 20-21 June 2006, Galveston, Texas.