WHY WELL MONITORING INSTRUMENTS FAIL

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ABSTRACT

This overview is intended to provide the reader with insight into basic reliability issues often confronted when designing long-term geothermal well monitoring equipment. No single system is looked at. General examples of the long-term reliability of other industries are presented. Examples of reliability issues involving electronic components and sensors along with fiber optic sensors and cables are given. This paper will aid in building systems where a long operating life is required. However, as no introductory paper can cover all reliability issues, basic assembly practices and testing concepts are presented.

BASIC INSTRUMENTATION OPERATING LIFE LIMITATIONS

There are a number of industries currently developing high-temperature (HT) instrumentation or control systems for a number of applications. Below is a short list of HT applications to give the reader a snapshot of the commercial HT instrumentation drivers and limitations.

Automotive
The automotive engineer designs are targeting 140-150°C with occasional temperature excursions to 170-200°C. The transmission is perhaps the hottest place for electronics. The transmission controller utilizes a microprocessor (16 bit), A/D (10 bit) and actuators.

Unfortunately, the automotive application only requires a lifetime of 150K miles/10 years of operation. The automotive industry targets transmission control electronics for 6Khrs (~8 months) of continuous service (150K/30miles/hr = 5Khrs). [Johnson (2003)]

Weapon Systems
Up until the 1990s, the weapon engineer designed systems using Mil-Spec components rated for long-term 125°C operation. Unfortunately, the US military was unable to justify the cost of maintaining a 125°C component infrastructure to support weapon systems when the vast majority of those systems operate below 85°C. Today, there is virtually no support for Mil-Spec electronic ICs.

Aircraft Engines
Electronic controls systems for aircraft engines have been demonstrated but not yet commercially produced. Under programs as the USAF More Electric Aircraft [Weimer, 2004] there is a real expectation that future HT commercial versions will be developed.

The aircraft-engine controller electronics use a combination of SiC (Silicon-Carbide) and SOI (Silicon-On-Insulator) technology. These systems are designed to operate for 5 years at 225°C without failure. These systems are designed to fail “gracefully”. Gracefully means to fail by falling out of specification while continuing to operate. For comparison, drilling industry instrumentation is lifetime temperature rated to failure. HT aircraft electronics have a calculated operating life of 20 years at 150°C [Gingerich (1999)].

Unfortunately, aircraft engine control systems and automotive transmission controllers use low-resolution measurement components for an 8-to-12 bit resolution. Most logging tools require 16 to 24 bits of resolution to take well-data measurements.

Oil & Gas Industry
The fossil energy industry is operating wells at temperatures as high as 225°C [Rountree (2002)]. At temperatures of 200°C, Measurement-While-Drilling (MWD) tools are limited to <100 hrs [Rountree (2002)] before refurbishment. Wells being drilled at temperatures above 200°C are drilled “Blind”. Schlumberger reports target operating life times of 400 hrs for 175°C logging tools, and 5 years for 150°C intelligent-well completions called smart wells. [Parmentier (2003)]
Smart-well electronics are used to control valves deep within multi-completion wells. A multi-completion well is like a tree with one trunk and many roots. In order to enhance production, the well owner can control flow at each branch in the well. Here smart-well electronics are primarily interested in monitoring wellbore pressure, temperature and flow. These valves are either hydraulically controlled from the surface or via electric motors located at the valve.

To qualify a smart-well measurement system for a reliable multi-year operating life at elevated temperatures, the major commercial service companies must design the system and freeze the design for years of testing and commercial production. This includes the following costly activities:

1. Establishing multi-year (3-5) reliability requires time/testing
   - Accelerated life testing (or HALT) within the oil patch is difficult because systems are complex and may have a known failure mode only a few (<25ºC) degrees above the targeted operating range.
   - Once oven and autoclave testing is completed, well testing is started.
   - Following successful initial testing, the engineers cannot continue changing the design without reevaluating the entire testing program.
   - For most systems, testing is the single greatest cost but not the only cost.

2. Perform a LIFE-OF-PROGRAM buy of system components and materials.
The vast majority of commercial electronics components have NO manufacturer-specified operating life. The service companies self-qualify electronic components.
   - Historically, the electronics industry re-invents itself every six years, so service companies MUST buy self-qualified components at the time they qualify them because they may never get a second chance.
   - Materials qualified for high-temperatures and a SLOW aging process must also be evaluated for potential well effects as fluid pressure, free hydrogen, potential HCl and other caustic fluids and gasses.

   - In short, the major service companies tie up MILLIONS OF DOLLARS in life of program buys to support their intelligent well completion instruments.

HIGH TEMPERATURE TECHNOLOGIES

Electronic Components
There are two potential component temperature rating of interest here, Industrial Grade and HT SOI.

Industrial-grade electronics provide specified performance at 85ºC. These are ‘bulk’ silicon devices using aluminum-to-silicon bonds and tinned aluminum leads connecting to the outside world.

The vast majority of these devices will not function above 125ºC because of thermally generated leakage currents inside the silicon. These thermally generated currents are not normally destructive, allowing the circuits to return to operation after cooling.

Leakage currents cause analog circuits to develop excessive measurement errors. Hardest hit are the DC measurements as strain, temperature or tilt. The digital circuits will continue to operate until a point is reached where the low logic ‘0’ in binary code can not be electrically produced. At that point, the digital system can not function.

Industrial-grade electronic devices that continue to function with increased leakage currents will exhibit a limited operating life of approximately 18 months at 150ºC. The main failure mode of these devices is the electromigration of aluminium metallization into the silicon chip resulting in a failed electrical connection. [Gingerich (1999)]

Electromigration is a well known aging process. It is a function of junction temperature, current density and time. It is important to keep in mind that junction temperature is always greater than well ambient temperature. The junction refers to the transistor. Transistors generate heat. Transistors are small. Transistor junction temperature can easily run 10-to-20ºC above ambient for small instrumentation devices to +100ºC for power devices. Care must always be taken to insure that electronic devices have a means for removing self generated heat.

HT SOI is new. Most HT SOI devices from Honeywell called HTMOS® and were designed for aircraft engine control applications. HT SOI uses silicon-on-insulator (SOI) technology to reduce thermally generated leakage currents ~100 times.
The reduction of leakage currents allows most HT SOI devices to continue operating up to 250-300ºC.

The electromigration process is better controlled using a 0.5 mA/um² current density where many Industrial Grade components use a 5 mA/um² design rule. [Gingerich (1999)]

**Fiber Optic Sensor and Cables**

Fiber optic systems and sensors offer a lot of advantages but also have some inherent disadvantages. A huge advantage of fiber sensors is the ability to connect fiber sensors in series, creating complete well sensor profile readings from a single fiber. Series fiber temperature and strain sensors have been demonstrated in a number of commercial applications.

The published operating life of fiber within oil wells has been very mixed. Fiber optic sensor and cable life appears to be highly dependent on well conditions and installation methods.

Fibers are normally installed within stainless steel tubing to protect it from wellbore fluids.

Fiber is affected by hydrogen (creating light lossy HO bonds) and by crystal growth in unprotected glass. [Normann (2001)] The effects of HO in fiber can be seen in Figure 1. Figure 2 shows fiber glass damage caused by supper heated water within a buffer defect. As such, the given well conditions along with fiber installation methods can greatly affect the fibers operating life.

**EXAMPLES OF FAILED MATERIALS OR COMPONENTS**

**Wire Breaks**

Wire breaks or failed solder joints are the most common types of well instrumentation failures. Figure 3 below shows a photo of a failed wire. The wire broke off a solder joint. Common solder is 60% tin and 40% percent lead. A common wire type is copper. In Figure 3, a manufacturer qualified 200ºC silver plated copper wire was tested at 193ºC. At elevated temperatures (>95ºC), the copper migrates through the silver to react with the tin (found in the solder) resulting in intermetallic growth: in this case crystalline bronze. The resulting intermetallic growth is structurally very week, easily broken.

At Sandia, we are using high lead-solder and nickel plated copper wires to greatly reduce intermetallic grow up to +250ºC. However, the instrumentation designer needs to validate their component selection. The capacitor shown in Figure 4 is 200ºC rated for automotive use. As can be seen in Figure 5, the manufacturer has an intermetallic growth problem at the device lead. This device failed after 3 months at 193ºC.

**Ceramic Capacitors**

Perhaps the most common electronic component ever produced is the ceramic capacitor; for example, the Sandia memory-based pressure, temperature and spinner tool uses over 30 ceramic capacitors.
Ceramic capacitors have a deadly flaw called dielectric breakdown. Dielectric breakdown is a function of time, temperature and applied voltage. Dielectric breakdown is deadly for two reasons. First, ceramic capacitors are used to reduce power supply ripple and common 60 hertz. As such these capacitors are placed across the circuits supply voltage. Ceramic capacitors fail at electrical SHORTS. The short is so hard, that traces on the printed wiring board will be burned off. Figure 6 shows a cut-away view of a short inside a ceramic capacitor. The physical damage to the capacitor is obvious.

The second deadly reason, extremely small defects within the ceramic capacitor’s dielectric can lie in wait for hundreds of hours before creating a dielectric-breakdown event. The majority of these defects are impossible to detect until millisecond before failing. Because of this fatal flaw, ceramic capacitors are not used on aircraft control systems.

**Chemical Interactions**

Geothermal wells contain more than hot water. They have a brine fluid containing dissolved minerals, noncondensable gasses and hostile chemicals. Among the more common notable hostile chemicals are chlorine (HCl), free hydrogen and H2S.

The image in Figure 7 is from a dissected quarter-inch 316L stainless steel tubing used to hold a fiber-optic cable. This damage was cause by a small amount of HCl found within a 250ºC geothermal well. This damage occurred within 16 hours. The weld to the left of the image may have sensitized the steel even more than typical 316L steel.

Free hydrogen affecting fiber has already been noted. However, it can also affect passive resistors used in electronics. The plot shown in Figure 8 shows the
effect of hydrogen on a manufacturer 250ºC rated resistor.

**FINAL COMMENT**

This paper can not cover all the issues found when designing a new test or monitoring equipment needed for a hot well. This report can help a new researcher or developer get a head start and perhaps prevent a few costly mistakes.

To conclude, a “short” outline of the “current” Sandia practices will be given below. These are some of the activities the Sandia Geothermal Research Department undertakes before installing a tool for a long-term test. For more information, please contact the authors.

**Outline of Sandia Installation Activities**

1. All metal housing parts are baked out at 250ºC for 48hrs to remove machining oils.
2. Electronics components are mounted on circuit boards while heated to a temperature about half the expected well temperature.
3. The assembled board is ‘burned-in’ under a constant vacuum to pull any VOC off during the curing process. The burn-in temperature is 10-to-25ºC hotter than the expected well temperature.
4. The burn-in is conducted for 2 to 4 weeks.
5. The tool is fully assembled within the lab.
6. The tool is evacuated and filled with Argon three times to remove oxygen and moisture.
7. The tool is installed on the cable or tubing and placed within the well.

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**REFERENCES**


