WELL MONITORING SYSTEM FOR EGS

Perma Works LLC
Grant DE-FG36-08GO18185
Feb 26, 2017

Control Number: PW-GO18185

Sub-Awards to:

Electrochemical Systems Inc. for HT Rechargeable Batteries

Frequency Management International for 300°C Clock Oscillator

This is the final technical report on this grant. The body of text was written by: Randy Normann, Dave Glowka and Charles Normann. There is a collection of technical papers assembled by Randy Normann and written by authors as given. These authors include: James Parker, Perma Works, Josip Chaja, Don Dunstan and Mario Caja, Electrochemical Systems Inc., Kouros Sariri, Frequency Management International Inc., Craig Beal, MajiQ Technologies Inc.

FINAL REPORT

WELL MONITORING SYSTEM FOR EGS

Perma Works LLC
Grant DE-FG36-08GO18185
Aug 10, 2014

EXECUTIVE SUMMERY

EGS (Enhanced Geothermal Systems) offers mankind a source of near infinite energy. To harness the earth's energy via EGS requires the expense of drilling deep wells and creating a subterranean heat exchanger for powering surface geothermal power plants. Under this grant, Perma Works LLC was the lead organization for developing geothermal well monitoring tools supporting EGS development. These tools are based on 15 years of high-temperature electronic technology development at Sandia National Labs. Perma Works is working a long list of high-temperature electronics suppliers who are also supporting the development of light weight commercial aircraft control systems. The aircraft and geothermal industry have very similar requirements for high-temperature electronics. Where the aircraft industry needs many years of system level testing before adaptation of a new technology on commercial aircraft the geothermal is ready today. Where the geothermal industry is a very small market the commercial aircraft industry is large enough to support commercial production of high-temperature electronic devices and sensors.

This grant is a collection of projects designed to move aircraft high temperature electronics technology into the geothermal industry. Randy Normann is the lead. He licensed the HT83SNL00 chip from Sandia National Labs. This chip enables aircraft developed electronics for work within a geothermal well logging tool. However, additional elements are needed to achieve commercially successful logging tools. These elements are offered by a strong list of industrial partners on this grant as: Electrochemical Systems Inc. for HT Rechargeable Batteries, Frequency Management Systems for 300C digital clock, Sandia National Labs for experts in high temperature solder, Honeywell Solid-State Electronics Center for reprogrammable high temperature memory. During the course of this project MagiQ Technologies for high temperature fiber optics.

Below is the list of the major objectives outlined in grant Go18185 with an overview of the outcome.

1. Commercial release of a 300°C, 40K psi analog tool for real-time pressure and temperature monitoring during hydraulic-fracturing and reservoir testing.

This is our greatest accomplishment. Perma Works has release a 275°C tool with operation up to 300°C and 30K psi for real-time pressure and temperature monitoring during hydraulic-fracturing and reservoir testing. A reduction in reservoir pressure rating was

done for two reasons: The highest pressure sensor at 300°C we could find was 30K psi from Paine Electronics. Discussions with well stimulation experts as Susan Petty revealed that geothermal hydraulic-fracturing is normally below 20K psi. This tool was tested and run in the 26,000 psi Australian EGS effort run by Geodynamics. This tool is named the PW-PT535A.

The Perma Works analog tool has demonstrated the capability of monitoring well stimulation during fracturing and monitoring well production and well injection during power production of the EGS plant.

2. Electrochemical Systems Inc. will start small scale production of sodium-sulfur batteries. These batteries greatly increase the safety while reducing the cost of geothermal logging tools.

Electrochemical Systems Inc. was a sub awardee. Electrochemical Systems worked at setting up a manufacturing process for sodium-sulfur batteries for 3 years under this grant. Their sodium sulfur battery technology is almost idea for geothermal. It would have been a significant gain to the industry, see Appendix F. However, they were never able to find a solution to a gas leak at the top of the battery. The commercial versions of the battery would leak at temperatures over 200°C. A number of potential solutions using better glass to ceramic seals and gold/titanium conductors were tried. Electrochemical System Inc. was offered for sale following the death of its owner and head chemist Josip Caja. No further work in this area is expected. A Josip Caja publication is included in the Appendix of this report. (Update April 2015 – Solid-State batteries show promise for 200C+, show later in this report.)

3. Perma Work will commercially release a fully digital 250°C PT-Flow tool based on the Sandia HT SOI HT83SNL00 IC with new HT SOI parts coming from the NETL Deep Trek project.

A complete electronic design has been completed using the Sandia develop HT83SNL00 chip. This work included the commercial development and release of the Honeywell EEPROM memory IC. This IC was a critical IC developed under the DOE NETL Deep Trek project but never released because of an error in an internal logic gate.

The EEPROM IC is an electronically programmable device which can store either microprocessor execution code and/or well data. Without this device, geothermal logging tools required programming on site before each log and if power was lost for even a second, the tool would stop functioning and any stored well data is lost. In short, the EEPROM IC is deemed as a major high temperature technology enabler for the geothermal industry.

Although an electronic design was completed using the HT83SNL00 chip which was licensed from Sandia National Labs, the HT83SNL00 license was returned to Sandia National Labs.

4. Eclipse NanoMed will start commercial production of a new type of high-temperature large value ceramic capacitor. This capacitor will reduce the size and increase the reliability of 300°C electronics used in geothermal environments.

Eslipse NanoMed was successful at producing a 300°C rated capacitor. These capacitors were tested in the first set of prototype electronics for the 300°C analog tool and at testing conducted by Sandia National Labs.

5. Draka Cableteq to complete testing of their upgraded 250ºC to 300ºC wire/fiber optic ¼ tubing for permanent geothermal well monitoring.

Draka Cableteq and Perma Works worked to develop a commercial version of wired ¼ inch tubing for permanent geothermal well monitoring. Today, 260°C wire/fiber tubing is commercially available from Draka Cableteq. A 300°C cable was built and successfully oven tested at 400°C. However, field testing suggests that over handling the 300°C cable can lead to wires shorting against the metal tubing. As such, this was not released as a commercial product. It should also be mentioned that Draka Cableteq received a second DOE Geothermal Technology grant to continue fiber optic testing.

Today, a geothermal well in Nevada has deployed both a 300°C well monitoring tool (first item in this list) and fiber optic DTS system from Draka Cableteq. This is the first successful deployment of system combining fiber optics and high temperature electronics.

6. Frequency Management International Inc. will start production of a family of 300°C digital crystal clocks needed to enhance the operating life and temperature range of the Sandia chip set.

Frequency Management International (FMI) was successful above expectations. They were able to solve the metal contact issues with the crystal which was generally believed to be impossible above ~225°C. FMI built and ran crystal clocks oscillators for over 2000 hours at 300°C. 300°C crystal clocks are commercially available from FMI. Now, that FMI had proven that metal contacts can be designed for 300°C; there are now secondary 300°C clock suppliers in the market place. That's life on the cutting edge of technology.

7. Perma Works to add an optical LED driver to the PT-Flow tool for use in conjunction with fiber optical distributed temperature systems (DTS) built into Draka Cableteq cables.

Efforts at Perma Works to build an optical LED driver for use in DTS failed. The light loss between the LEDs into the cable is too great. The loss of high temperature, multimode DTS fiber is also significant. Testing of off-the-shelf LEDs was successful. Perma Works contracted with MagiQ Technologies to study this problem in more detail. They are fiber optic experts. The light loss issue was not resolved. Portions of the MagiQ report to Perma Works is attached as an appendix to this report.

8. Perma Works to write feasibility report on moving HT SOI 300°C electronics for permanent well monitoring and control for EGS power production.

Under this grant, Perma Works has developed a much keener understanding of the technology challenges under this grant; realistically 300°C is not a possibility with commercially available technology. It is possible to design EGS well monitoring systems for a 10 year life below temperatures of 225°C. The number one limitation for EGS well control systems is the lack of a downhole flow control valve and the lack of large valued, high temperature capacitors.

9. Solid-State flow sensor for EGS well monitoring.

This was not listed as a major effort in the grant application. However, a solid-state flow sensors for EGS at elevated temperatures can enable well control systems needed for EGS. A solid-state, high temperature sensor was successfully built and lab tested. This work is covered in Appendix H of this document.

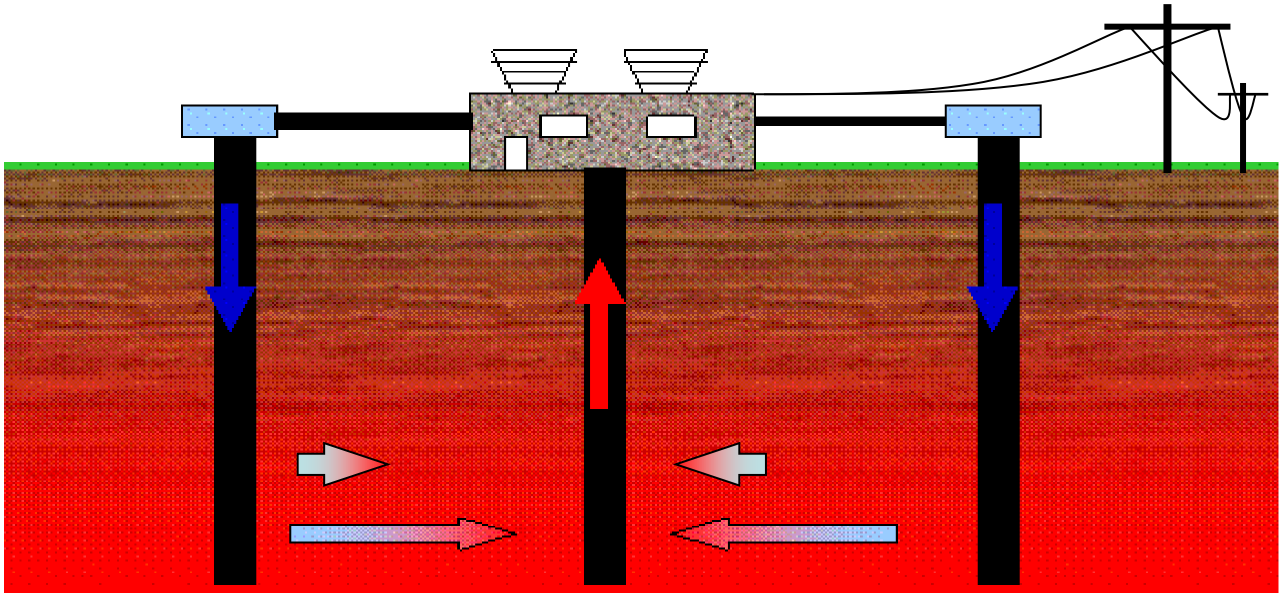
Final comment: As a result of this work, it seems possible to design EGS well monitoring systems for temperatures of 225°C to 275°C and life ~10 years. Perma Works developed internal compensation of electronic measurement circuits will aid in realizing these high temperature EGS resources. Operation for shorter periods of time is possible at temperatures of 300°C.

INTRODUCTION

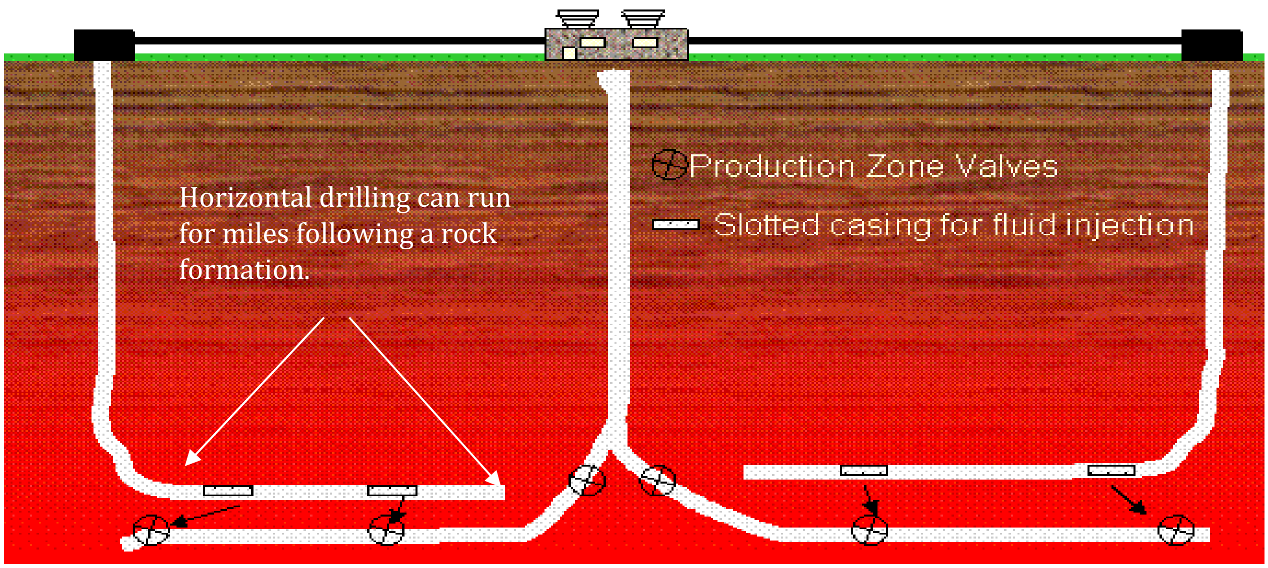
EGS (Enhanced Geothermal Systems) offers mankind a source of near infinite energy. To harness the earth's energy via EGS requires the expense of drilling deep wells, fracturing hot rock formations to create a heat exchanger for powering electrical power plants.

Future EGS wells will have multiple production and injection zones to maximize the value of each well drilled. This report envisions a well monitoring system supplying the reservoir pressure and temperature along with mass fluid flow.

Below are two illustrations of envisioned EGS wells with monitoring and control systems. The first one is simply an EGS system with two vertical wells intersecting two heat exchanger formations with differing flow rates. The second illustration is using long horizontal to exploit a favorable hot rock formation. In each case, the EGS fluid production is controlled from the power plant to optimize energy product from each well. Work under this grant is directed to solving the well monitoring system. A feasibility report discussing issues and potential solutions for full EGS downhole well controls was created and is included in the appendix.



Above is an illustration of future EGS wells with multiple production formations from vertical wells.



Above is an illustration of future EGS wells using horizontal wells to mine heat from a favorable rock formation.

This grant is addressing the immediate needs of the Geothermal EGS industry for monitoring hydraulic fracturing activities, reservoir testing, and production monitoring while creating the ability to build in future reservoir controls. All of these capabilities stem from the ability to build long-life electronic and fiber optic systems with the ability to operate deep in the well at the reservoir.

Perma Works proposed to commercialize 10 years of Sandia/DOE high-temperature research to build well monitoring tools needed for today's EGS projects. At the same time, Perma Works is targeting this technology for permanent installation in the well; behind production tubing or even behind well casing. This activity not only provides EGS power plant owners well monitoring systems but opens the door for electronic well controls enabling future EGS power plant owner's assurance of uninterrupted geothermal energy from their engineered reservoir.

Below is a list of commercialization objectives reached in this grant. Each item listed below will be a **new commercial product or enhanced commercial product targeting 300ºC** by manufactures here in the US.

- Perma Works commercially released a 300ºC, 30K psi analog tool for real-time, pressure and temperature monitoring during hydraulic-fracturing and reservoir testing.

- Perma Works has been supplying 300ºC test fixtures to electronic manufactures wanting to test their designs up to 300ºC. Companies as GE, RelChip and United SiliconCarbide have used our services.

- Eclipse NanoMed started commercial production of a new type of high-temperature large value ceramic capacitor. This capacitor reduces the size and increased the reliability of existing 300ºC electronics used in geothermal environments.

- Draka Cableteq completed upgrading 250ºC to 300ºC wired Incoloy tubing for permanent geothermal well monitoring.

- Frequency Management Inc. started production of a family of 300ºC digital crystal clocks needed to enhance the operating life and temperature range of the Sandia chip set. (Today, there is a second supplier.)

- Honeywell Inc. completed a commercially functional EEPROM memory chip. This one device is enabling all future geothermal well logging tools. (Today, there is now a second supplier.)

Below is a list of commercialization objectives which failed to reach commercial release.

- Electrochemical Systems Inc hoped to move their high temperature sodium sulfur battery technology from prototype to small scale commercial production. Josip Caja at Electrochemical Systems identified an issue with a battery gas leak at 200°C and over. Josip was unable to find a solution to a gas sealing problem. As such, after a few operations at temperatures over 200°C, the battery could not be recharged. (Update, Perma Works is working with a second battery supplier showing significant results at the time of this report. Also, we are sorry to report, Josip Caja passed away and we understand Electrochemical System may not exist anymore.)

- Perma Works failed to commercially release a fully 250°C digital tool for supporting EGS. Perma Works engineers did design the tool electronics, software and mechanicals. The solid-state flow sensor was laboratory tested in a flow loop and showed to work. Perma Works still has hopes of making a commercial version of this tool even with the loss of the HT83SNL00 license.

- Perma Works and Sandia National Labs failed to develop a high temperature solder for 300°C electronic circuits. Discussion provided in this report on the efforts of Perma Works will benefit future researchers on this topic.

PUBLICATIONS

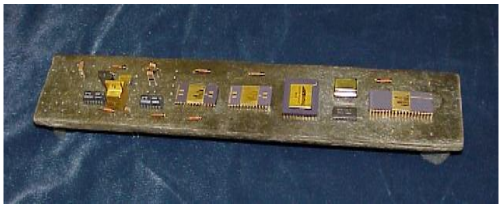
1. Randy A. Normann, Dave A. Glowka; Design Consideration for Geothermal Logging Tools, Geothermal Research Council Transactions, Vol. 34, 2010
2. Randy A. Normann, Dave Glowka; Designing Logging Tools for Future High Entropy Geothermal Power; Geothermal Research Council Conference, Portland, Or, September 28 - October 1, 2014
3. Randy A. Normann, Platform for Testing New HT Aircraft Sensors for Geothermal Logging, Geothermal Research Council Conference, Portland, Or, September 28 - October 1, 2014
4. Randy Normann, Practical Oil Field Requirements for High-Temperature Batteries, High Temperature Electronics Conference, Albuquerque, 2010
5. Randy Normann, Alastair Black, Charles Normann, James Parker; Universal High-Temperature (250°C) Test Fixture, High Temperature European Network Conference, Oxford, UK 2011
6. Randy Norman, Breaking Down Development Cost Barriers for Geothermal Reservoir Monitoring Systems 'Anyone' Can Program, Stanford Geothermal Workshop, Feb 13-15, 2017

TECHNICAL DISCUSSION

HT CERAMIC CIRCUIT BOARDS

High temperature circuit board was a major effort under this grant. Conventional circuit boards use a nonconductive fiber board with a thin copper layer glued to each side. The fiber board is strong and inexpensive. However, at temperatures above 235°C, the glues start to break down causing delamination of the copper.

The development of a high temperature circuit board along with a high temperature solder enables all geothermal well monitoring and well logging tools to use new HT electronics. This is true because the aircraft industry builds their engine control systems on square cold fired ceramic circuit boards. Cold fired ceramic technology is limited to 4 inch by 4 inch dimensions by the metal to ceramic thermal expansion miss match. Geothermal instrumentation is built in to 1 inch ID tubes. The geothermal circuit is 1inch by 10 inch or more. A new means for placing metal on ceramic is needed and developed under this grant.



The image to the left is from early HT electronics work done at Sandia National Labs in 1997. Here some of the first HT SOI electronic devices from Honeywell SSEC were mounted on machine able ceramic. The devices were connected using simple Teflon coated wire. There was no solder used, instead, the wires were attached to the device pins by laser welding. Clearly, normal geothermal tool builders cannot use laser welding; this was done simply to prove these circuits could run at 300°C. In fact, this circuit ran up to 317°C before the microprocessor locked up.

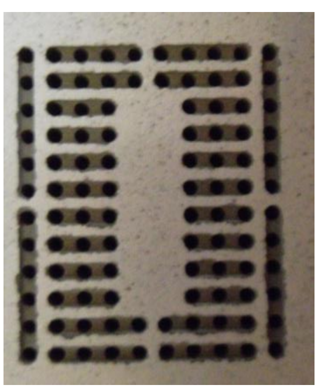
At Perma Works, we worked with a new means for creating circuit traces in machinable ceramic. Ceramic is clearly a high temperature, non-conductive material making it a good starting point. A lot of time was spent on this effort. In the end, we used a little know circuit board material (Rogers 4000) which is good if sealed in a dry atmosphere.   Documents on this topic are considered patentable so much of this work is not presented here.

In the work at Perma Works on new metallization of ceramic involved three types of metal.

Basic Properties of Potential Metal Layers
Zinc: Melting point 419°C,   Resistivity = 59.0 nΩ·m at 20°C, Thermal conductivity = 116 $W \cdot m^{-1} \cdot K^{-1}$
Nickel: Melting point 1455°C, Resistivity = 69.3 nΩ·m at 20°C, Thermal conductivity = 90.9 $W \cdot m^{-1} \cdot K^{-1}$
Copper: Melting point 1085°C, Resistivity = 16.8 nΩ·m at 20°C, Thermal conductivity = 401 $W \cdot m^{-1} \cdot K^{-1}$

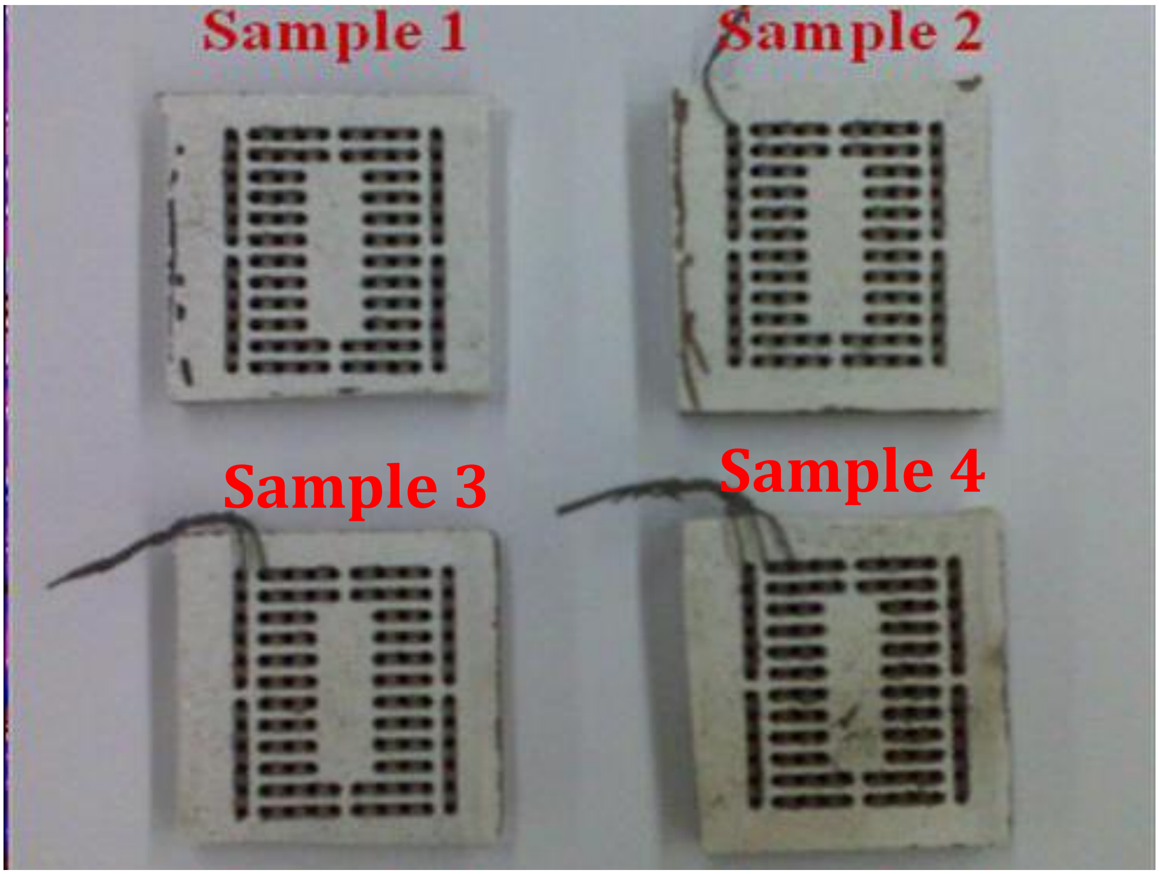
In the table above, Zinc and Nickel metal are compared to copper. Copper is the most common metal used for the metal layer of commercial circuit boards. Here we want a melting point above 300°C, a low resistivity and a high thermal conductivity. Clearly, copper is the better material. Unfortunately, copper is not good for our application. In testing our processes to create a metal layer on machine able ceramic both nickel and zinc attached directly to the ceramic. As such, this process is not dependent on organic glues to hold the metal in place.

It was determined in solder testing that nickel actually worked better at holding to ceramic when being repeatedly soldered. Here a technician, soldered a wire on to and then remove it to re-solder on again. After about 5 times one and then off, the nickel layer would break away from the ceramic. This test means the nickel metal layer is holding on to the ceramic well enough to allow for rework or repair of HT electronics in the field.

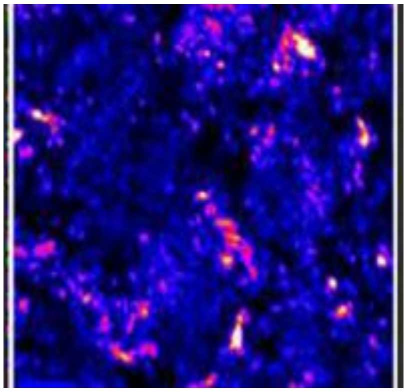


A common universal circuit board layout (see the image to the left) was created using machinable ceramic and nickel metallization. See Appendix B: "Ceramic Bread Boards" by James Parker. Using this layout, Perma Works tested several types of machine able ceramic from three US manufacturers. In short, after many hour of building and testing, all seemed to work similar results. It appears that the process of manufacturing machinable ceramic is roughly the same. Although, no manufacturer would tell us their process it appears to us machinable ceramic is a ceramic mixture of normal ceramic flakes and a weaker ceramic based bonding agent. Normally, metal carbide cutters cannot machine solid ceramic. However, the ceramic based bonding agent is mechanically weak. The carbide cutters are fracturing the ceramic flakes out by breaking the bonding agent. This works great until a cutter hits a solid ceramic flake larger than the cutter. While cutting out traces in machinable ceramic, if the carbide cutter was 0.02in or larger, we normally did not have a problem with broken carbide cutters. For smaller sizes at 0.012in, we occasionally hit a place in the machinable ceramic which would break the carbide cutter every time. For large though hole electronics of which most HT SOI parts are, this is not a major issue as traces of 0.02in are acceptable.

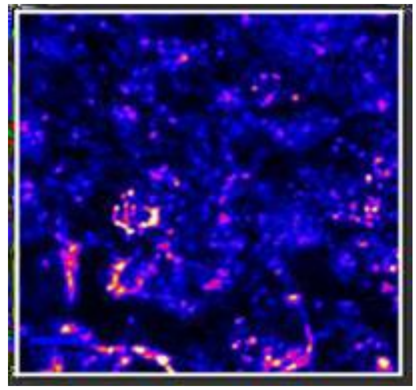
To demonstrate improved performance to thermal expansion differences between the metal and ceramic, four test samples were produced and subjected to extreme temperature and temperature shock. The four samples can be seen below.



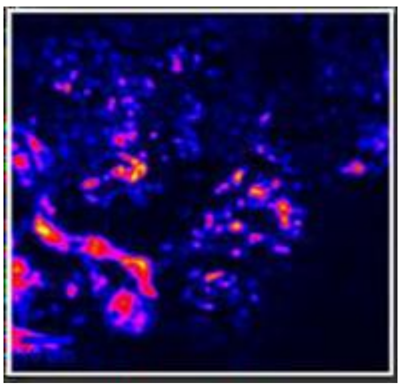
One sample was never heated. The other samples were heated to 300°C, 400°C and 550°C. Each was removed from the furnace without being given a chance to cool down; the poor man's temperature shock. Using a Confocal optical process (532.8nm laser) U of New York preformed non-destructive testing to look at the metal to ceramic bond. The results are shown below.



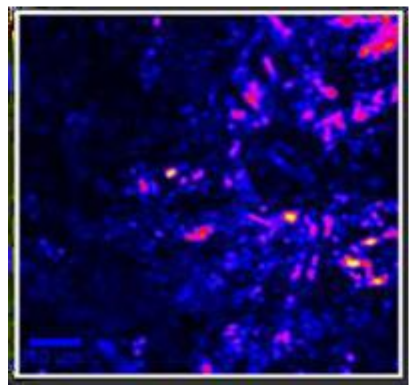
Sample 1



Sample 2



Sample 3

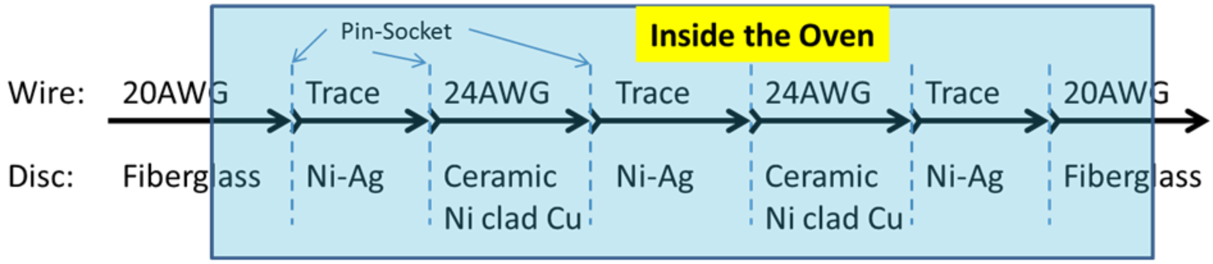


Sample 4

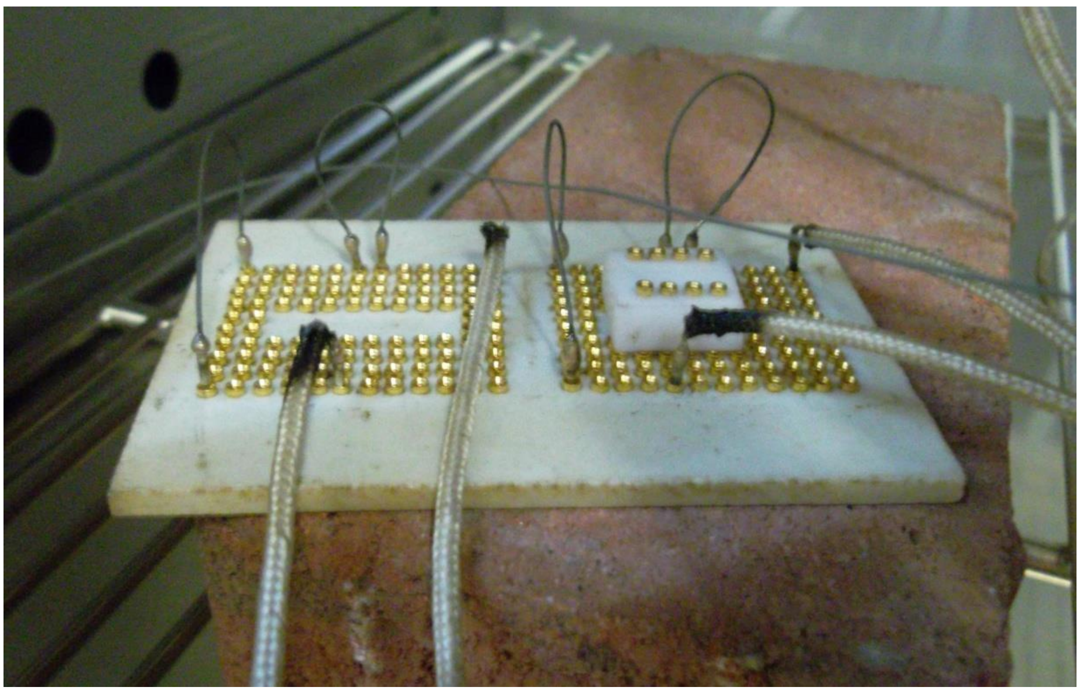
In the Confocal images above, the important detail is the change in marbling as each sample was heated to higher temperatures. The marbling is the mix of ceramic and metal which is needed to create a tight bond. The marbling has little change between the non-heated sample and the 300°C sample. There is some loss of marbling at 400°C and 550°C. Note, all samples lacked any visible surface features indicating loss of metal to ceramic bond. In short, all samples are still useable.

RESISTANCE TESTING CERAMIC TRACES

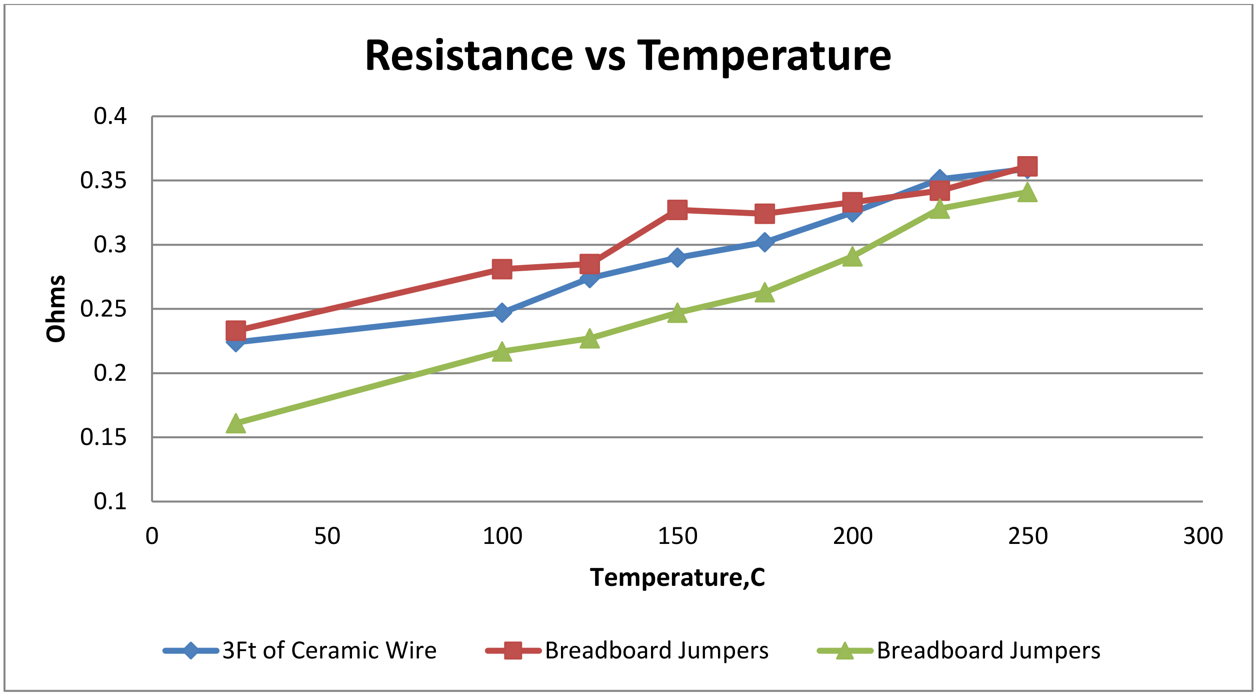
One of the universal ceramic circuit boards was fully populated with metal wire sockets. This allows testing of HT components without solder. Here, the test board is itself the object of a circuit resistance test. A simple resistance test of a series combination of wires, sockets, pins and circuit traces was conducted from room temp to 250°C. Two identical circuit connections (As seen below) were made plug into a protoboard. A third circuit was simply a 3ft loop of connection wire to compare against the two circuit board and jumper circuits.



The focus of this test is the resistance change due to increasing temperature on the smaller protoboard traces, jumper wires and solderless pin-socket connections. The larger 20awg connecting wires were tied to lab meters. Their change in resistance is minor. The jumper wires were nickel clad copper with pins brazed on the ends for plugging into the protoboard sockets. The pins and sockets are gold plated over nickel-beryllium and soldered to the circuit board using silver.



Each of the protoboard traces were ½ long and the jumper wires were 2inches long. The two circuits can be seen in the photo above.

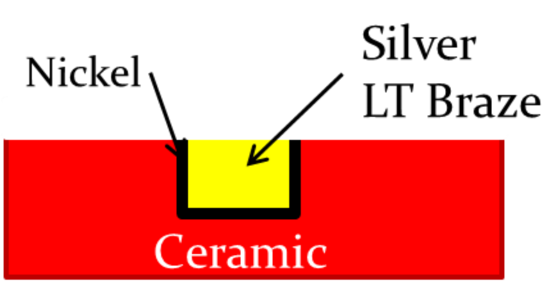


The results of this test are shown above. Along with the two series circuits, a simple run of 3 ft of ceramic insulated, 24AWG, nickel clad wire was also placed in the oven. As it turns out, the 3ft of wire was a good choice because the resistance of the wire fell in between the two circuits.

In the resistance testing, at no time was there a loss of electrical connection. No loss of connection is really good given that each of the two series element circuits has 6 sets of solderless plug in connections. A total resistance <0.4 ohms across all temperatures of our three circuits is good enough for most circuit application. In short, the high temperature protoboard is a success.

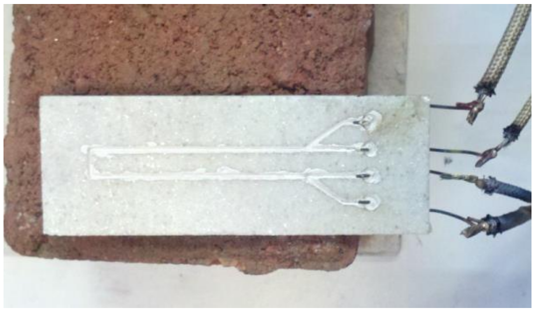
HIGH CURRENT TEST OF CERAMIC CIRCUIT BAORDS

An interesting benefit of building circuit traces inside the grove is that, we increase the bonding area with metallization both on bottom and the side walls. This attribute can be exploited for creating power circuits operating at very high temperatures. To this extent, we conducted a test using our circuit trace technology and low temperature brazing (~600^{0}C w silver wire) to fill the grove with nickel followed the silver. (LT silver braze is commonly used by the jewelry industry).



A test trace in ceramic was made. The trace was 4.45 inches long, 0.03inches wide and approximately 0.01 inches deep. The metal filled about 80% of the depth. A four wire voltage measurement was used to measure the voltage drop as 1.00A was conducted by the test trace.

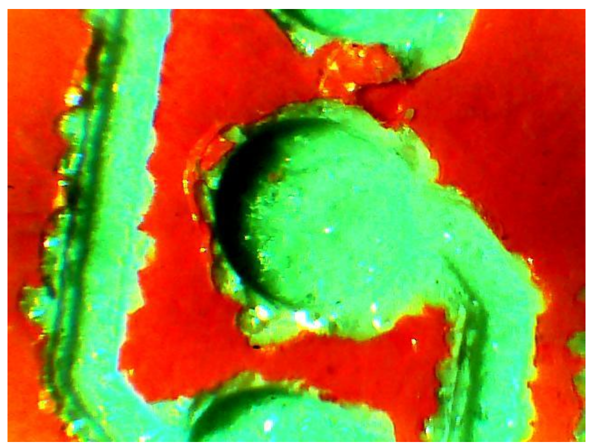
At room temperature (~23^{0}C), the voltage drop was 0.021V. At 250^{0}C, the voltage drop was 0.034V. Compared to calculated value for a 0.030 in wide, 2oz/ft^2 copper, these voltage drops are a little more than half the value of similar copper traces on conventional circuit boards. Also having survived brazing a metal conductor inside the grove, it seems every reasonable, this system will continue to provide very good performance at even much higher temperatures.



The image to the left is the ceramic test board. The 4 wires were connected to a high precision 4 wire resistance meter.

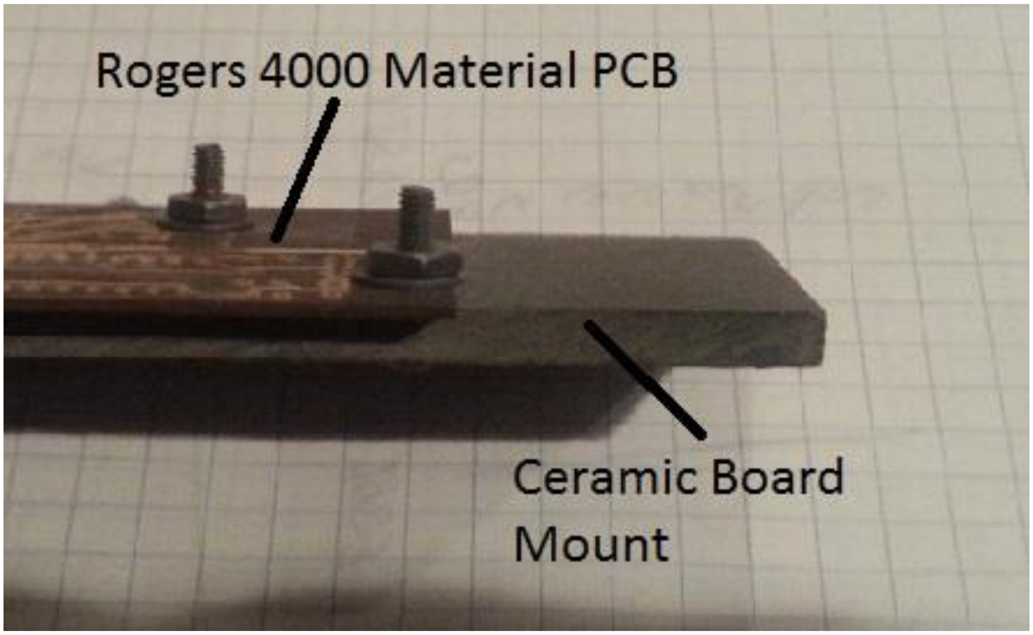
CONCLUSION OF HIGH TEMPERATURE CERAMIC CIRCUIT BOARDS

Machinable ceramic circuit boards developed within this grant are extremely robust and could enjoy commercial success for high temperature industrial power systems and future motor controls for geothermal power systems. For use in downhole logging and well monitoring tools, the machinable ceramic lacks the detailed machinability to support small electronic circuits. Most of the machining of machinable ceramic was done in house at Perma Works. Alastair Black was the lead programmer working with a CNC mill and carbide cutting end mills. Alastair tried painting the surface of the surface of the ceramic red to make inspection of the machine cut traces easier. The photo to the right is one such example. It is easy to see small surface flakes of solid ceramic are broken out along the edges of the milled trace. When traces become close, the chances for to traces being bridged (shorted) by rough edges becomes increasing likely. In creating analog circuits with large components and 0.02in clearance, shorting was uncommon. For higher density digital circuits and 0.012in clearance shorting was a significant issue.



Another small effort was to use a unique process from a local company called, Life BioScience. They have a very unique means for cutting very fine details through a glass like material of which could be heated and converted to a ceramic. At first this process seemed like the answer to our problem. However, the glass like material was thin and fragile. So, it required mounting to our machinable ceramic. The mounting process was never achieved. See Appendix A.

Finally, we had been using Roger 4000 material for building high temperature test boards for temperatures less than 300°C. These were simple 2-sided circuit board with large through hole electronics. However, Roger 4000 material can be processed using standard circuit processes.



In the image above, a Roger 4000 board without circuit components was hard bolted to a piece of ¼ machinable ceramic.

DEVELOPMENT OF HT SOLDER

The lack of a working high temperature solder for 300°C is a limiting factor for all geothermal tool development. Existing HMP (high lead) solders are extremely difficult to work with and require large circuit features and hand soldering. Tool production in geothermal is limited to small production. When soldering becomes difficult, the opportunities for a 'missed' or poor solder connection are increased, reducing reliability.

The high lead solders (>95% lead) are favored for high temperature soldering. These solders simply fail to flow (or wick) between the metal connections. So much so, the limited device pin pitch is ~0.1inch. Many modern electronic components have pin pitch values at 0.020 or smaller. These devices simply cannot be used.

Knowing this is an industry problem, Perma Works partnered with Sandia Nationals under this grant. Paul Vianco and Joe Henfling as Sandia Labs had the task of working on a new high-temperature solder. Paul Vianco is an expert in the field of solders. Paul has a number of concepts worth exploring to solve this problem. One of Paul suggestions was to work on a high-temperature solder flux to chemically attract the high lead solder to flow between the metal connections. However, Paul never received the Sandia grant funds expected under this grant.

Paul Vianco and Joe Henfling were lost. Effort was under taken to find a private industry partner manufacturing solder interested in such an effort. Randy Normann talked to several companies including the Indium Corporation. No private industry company could be found. However, these conversations, it appears that solders comprised of two or more metals (as lead-tin or Silver-Tin) to improve soldering for 300°C circuits has been exhausted. If a solution exists, it may lie outside of conventional solders.

Initial efforts to find a new high temperature solder started with Randy Normann obtaining a number of metal powder samples some the size of nano particles. These powders were mixed with an organic solder flux. The hope was to find a combination of metals what would melt together inside a furnace. The metal powders were mixed in a paste by adding generous amounts of solder flux. The furnace would burn off the flux and melt the metals together to create a solder like bond between circuit traces and components.

A new idea on soldering for high temperatures came from Dr. McClusky at the University of Maryland. Dr McClusky presented a paper on a high temperature soldering process at HiTEC, in Albuquerque 2010. His concept was to grow an intermetallic connection using silver and indium particles mixed in an organic flux. At ~250°C, the organic flux is burned off and the two metal particles form an intermetallic. Intermetallic are normally a problem for solders. Here the metals do NOT melt but grow together through a solid-state transition. The flux and the added heat accelerate this process. Once the two metals have become solid, they will not melt (or reflow) until temperatures over 600°C.

Dr. McClusky was funded to try his silver-indium mix on Perma Works high temperature circuit boards. The results were very good. However, silver and indium are very expensive metals to work with and rework is not possible at 600°C. The University of Maryland had applied for a patent on this concept. The licensing fee was $25K/year which is out of question. As such, we failed to develop a high temperature solder supporting 300°C HT SOI logging or well monitoring tools.

Why is high temperature solder for 300C electronics important? A brief discussion follows.

There were two outcomes of the Sandia National Labs two year HT SOI electronics test at the Coso Geothermal well: One that HT SOI electronics can operate for years at very temperatures and two soldering high temperature components is a major issue. Existing high lead solders work up to and over 300°C but they are very difficult to work with. With large devices as ceramic dip packed electronics developed in the early 70's and through-hole resistors and capacitors, high lead solders are not good but useable. For modern packaging as the new HT SOI, RC10001 microprocessor from RelChip, high lead solders are impossible. The new RC10001 is the first 32Bit microprocessor able to run at temperatures over 300°C!

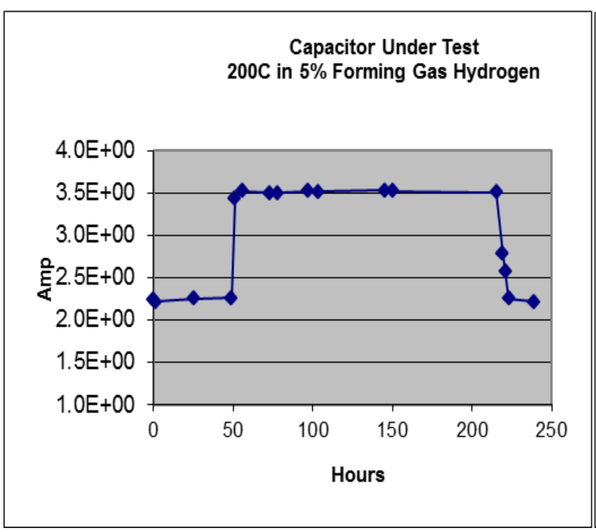
However, the RC10001 has 144 pins with only, 0.025in separation, old ceramic dips had 0.10in separation.

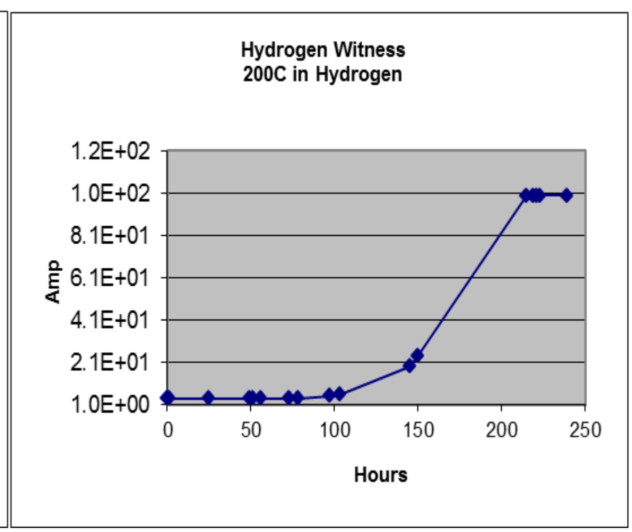
HYDROGEN TESTING

There is some small amount of free hydrogen in all wells including geothermal wells. One of the sources of hydrogen comes from geothermal brine interacting with steel as in the well steel casing or the steel of the logging tools pressure housing. The hydrogen atom is so small and so active at elevated temperatures that hydrogen will penetrate a tools high pressure steel housing and interacting with the logging tools electronics with 24 hrs at 200°C and within a few hours at 250°C.

Hydrogen is a bad actor for long term geothermal well monitoring electronics. First, it will combine with any oxygen (air) trapped inside the tool's pressure housing at the time it was assembled to create H2O inside the tool. Second, hydrogen damages some components, most notably resistors. Resistors are used to fix gain of signal amplifiers. When the gain changes so does the tool calibration. In early well testing at Sandia National Labs, a tool noticeably changed pressure calibration within 20 hrs inside a 240°C well.

As free hydrogen in the geothermal well is always there and unstoppable, Perma Works has to test all electronic components for unwanted hydrogen effects using the hydrogen test chamber shown in the photo to the left. Here, the round oven can heat electronics up to 400°C. The oven is completely sealed for low positive pressure gas. The hydrogen comes from hydrogen forming gas which is 5% hydrogen and 95% argon. A small tube (not shown in the photo) releases the gas through two inches of





standing water. By bubbling forming gas through the oven, the level of hydrogen inside the oven is held constant. If not for the slow bubbling of gas, the hydrogen trapped in the oven would simply escape through the ovens metal housing. The ability of the oven to hold a constant hydrogen level is shown in the capacitor test example given above using a hydrogen witness sensor.

In most all cases the effects of hydrogen are permanent. However, testing a new 250°C capacitor from Faradox showed an interesting reaction to hydrogen. In the test data, a capacitor and a sensor with known hydrogen sensitivity were placed in the Perma Works hydrogen test oven.

The devices were subjected to an oven temperature of 200C for 50hrs in local Albuquerque air in order to validate that there was no effect due to the elevated temperature for these high temperature devices. After 50hrs, the forming gas was released into the oven. For the first few minutes, a lot of gas was used to displace the local air already inside the oven. The response to the capacitors leakage current is immediate. The response by the witness resistors is also immediate but at a slower building rate. After about 200hrs the hydrogen forming gas was turned off and the leakage current in the capacitor drops back to normal and the witness resistors value stabilizes at it new peak value.

This sensitivity of the capacitor is unique and rarely seen. This data was shared with the engineers at Faradox and they determined the issue and corrected this problem in future production of their HT Polymer Capacitor.

In general, the list below is the result of hydrogen testing.

HT SOI Electronic Devices --- No Hydrogen effect

Ceramic Capacitors --- No Hydrogen effect

Polymer Capacitors --- No Hydrogen effect

HMP (High lead solder) --- No Hydrogen effect

Resistor Thick Film --- Unuseable

Resistor Thin Film --- Slow increase in resistance over time

Resistor Metal Film --- Little change

Resistor Wire Wound --- Stable (might also be the result of physically large)

In all the cases above, there is a possibility of hydrogen issues based on device packing which varies between manufacturers. In the case of ceramic capacitors, it seems that the ceramic material is not effected by hydrogen exposure however, if the packaging is a silicon based coating there is a strong possibility that hydrogen entering the tool will combine with free oxygen creating H2O. At geothermal temperatures, the H2O will interact with the silicon coating. This is also a strong possibility for resistors. Attachment 'D' is a test of resistors where the cheap resistors are run compared to high end temperature stable resistors in the hydrogen oven.

300°C TOOL FOR SUPPORTING EGS

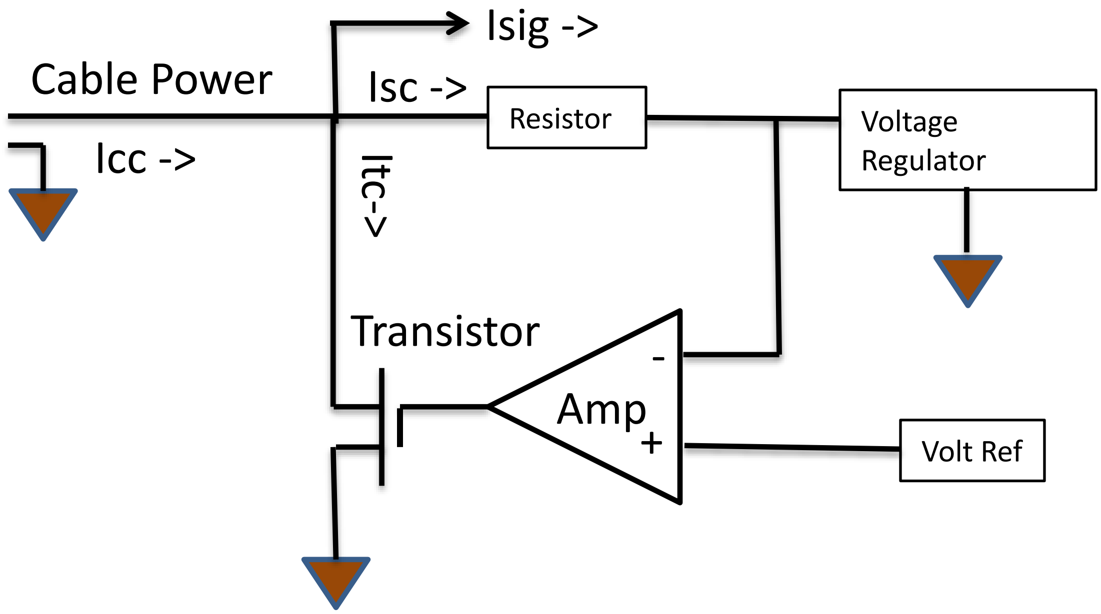
Most of the effort was applied to this simplest of tools. In the original program plan, it was assumed this tool had already been built and demonstrated at Sandia National Labs using electronics known to work up to 300°C. However, Sandia lacked circuit boards for testing a complete tool beyond 250°C.

There are several basic instrumentation concepts general used to approach this type of application. Each was built and tested until a working solution was found. These are listed below.

1. Constant Current. Generally, sensors are powered from a constant current circuit. The standard values are 2-20mA and 4-40mA which are independent of cable voltage. Here, the circuit draws a fixed supply current of either 2 or 4mA while the sensor amplifier draws the difference based on sensor value. So, a cable drawing 10.542mA on a 4-40mA circuit would be a signal of 6.542mA. Constant current removes cable voltage drop issues.
2. Voltage Controlled Oscillator, VCO. Here the downhole electronics draws DC power from the cable and provides a sine wave on top of the DC power based on sensor value. As such, 1KHz might mean 0C and 1.3KHz mean 300°C for a simple temperature measurement.
3. Digital. Here a microprocessor controls an analog-to-digital (AD) converter. The AD has a fixed voltage reference of which it compares to the sensor output. Based on this conversion, the microprocessor reads a binary code from the AD and transmits the binary code up the cable using standard long cable transmission methods as FSK (frequency skip key).
4. Multi-wire. Here each sensor located in the downhole tool has a wire leading to the surface.

Perma Works exhausted all of the above before coming to a reasonable hybrid solution. In general, most of the HT SOI parts were used to build complete tool circuits based on the list above. In general, Perma Works used known good circuits that work well at moderate temperatures. Given the difficulty of working at such elevated temperatures complete tool circuits allowed for meaning full testing of temperature induced error in the measurements. The following discussion on each of the methods above will be useful.

Constant Current. Complete downhole tool circuits based a constant current type circuit was designed. This method does work at 300°C. Perma Works was not able to use a standard 4-40mA because the circuits for measuring temperature and pressure exceeded 4mA. In fact, near 300°C the needed supply current was approximately 35mA. This means, the tools constant current independent of cable voltage or tool temperature would start at 40mA.



In the above circuit, the goal is to hold the supply current needed by the voltage regulator (HTLPREG) to operate the tools circuits as a constant value to the cable. While current created by the sensors (Isig) is allowed to change as needed. From above:

Icc = Isc + Itc + Isig

For the Icc (cable current) to be constant independent of cable voltage or tool temperature. For out tool, we needed a constant 40mA of current if the sensor current (Isig) is zero. The amplifier (HTOP01) senses the voltage drop in the resistor created by Isc (system current for the circuit) needed by the circuit voltage regulator (HTPLREG). If that voltage equals the voltage reference (2.5V, CHT-BG3M) then Itc (transistor current) is zero and cable current is 40mA. However, if the current is less (which is the normal case), the Itc = 40mA – Isc by design. Now, the surface electronics only needs to subtract 40mA to measure the sensor current and convert that value to a sensor reading as well pressure in psi or well temperature in degrees C.

Icc = 40mA + Isig

To generate Isig, a second power transistor (HTNFET) and second amplifier (HTOP) are used to amplifier the sensors electrical output.

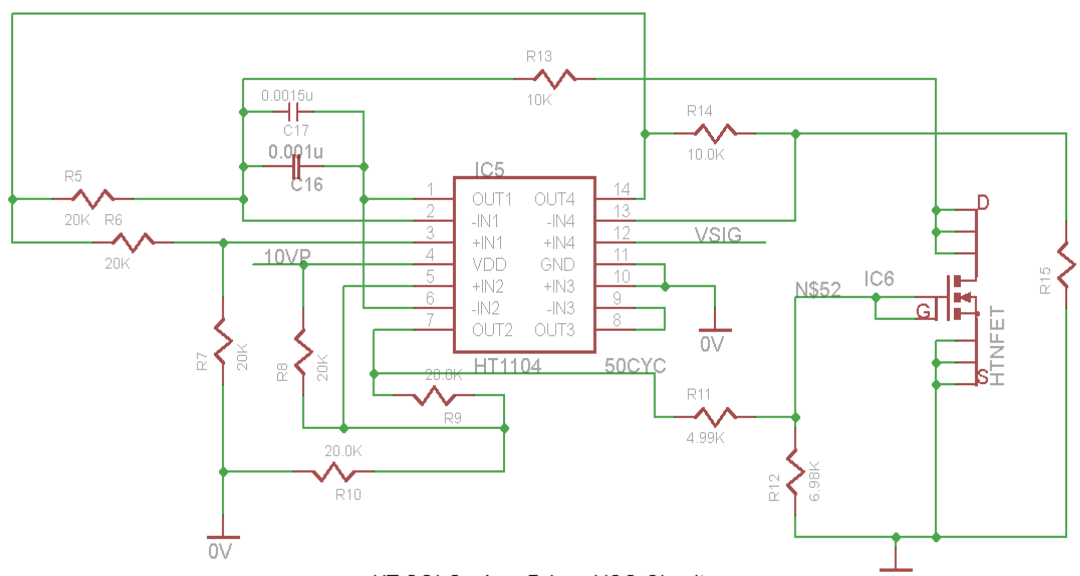
Why Perma Works did not go with this circuit design? There are two reasons. First, the circuit has three power devices; a voltage regulator two power transistors, one for holding a constant 40mA and another for creating signal current. These three power devices are heat generators inside the tool, increasing the tools internal temperature above the well temperature. In short, this tool draws maximum power at all times inside the well because currents can only add not subtract coming from the cable. This heat will lead to early tool failure.

Secondly, the voltage reference used by the amplifier to hold supply current at 40mA varies 2% over the temperature range. This variation is seen as signal noise. In standard 4-40mA circuits, the signal current is ~10X the supply (4mA) current. For our 300C tool with constant current starting at 40mA, to gain a 10X over noise implies 0.4A signal. This would never be practical.

Voltage Controlled Oscillator, (VCO). Here the sensor signal is amplified and applied to an oscillating circuit which has its frequency changed based on the signal's value. For example: a 1.000KHz oscillator with a 0C signal input from a temperature sensor might reach 4000KHz with an increase in temperature signal at 300C. A shift of 1Hz is a change in 0.1C.

There are two benefits of this type of circuit. First, like the constant current circuit, this signal transmission is independent of cable effects as the cable will not change the frequency. Also, counting frequency by microprocessors is simple task and normally of high accuracy. Second, multiple signals can be placed on one wire by ranging different frequencies of multiple VCOs. For example: 1.000KHz to 4.000KHz for temperature while 10.00KHz to 15.00KHz for pressure.

At Perma Works, we built two different VCO circuits using HT SOI parts. One was a op-amp driven design and the other a standard 555 chip design. Below is the op-amp design.



HT SOI Op-Amp Driven VCO Circuit

In the op-amp design, Vsig is the signal from the sensor. Op-amp 4 of the quad op-amp HT SOI chip is used only as an amplifier/buffer for the sensor circuit. C16 + C17 along with resistors R6-R10 set the nominal frequency of the VCO. Transistor IC6 was an improvement over the first design to speed up the discharge of C16 + C17 on the down cycle of the oscillator.

Perma Works tried both the Honeywell HT1104 op-amp and the Cissoid CHT-OPA. These are both HT SOI, quad op-amps. Unfortunately, the neither op-amp worked well above 225°C. The speed response of these op-amps degrades too much after about 225°C. At higher temperatures, the temperature effects on the nominal VCO frequency became more dominate than the input from the sensor. Adding the external transistor was of little help.

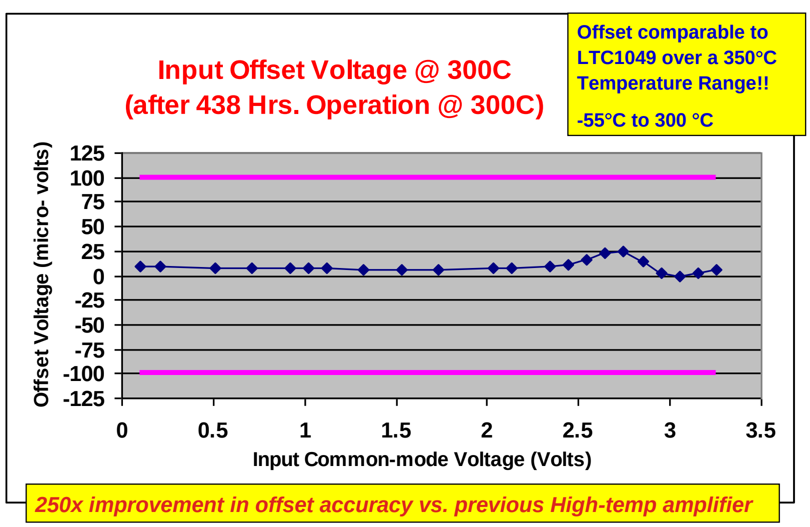
The 555 based VCO is a much simpler and cleaner design. The 555 chip is a classic IC used for many oscillating circuits. Its popularity is the reason Cissoid created a HT SOI version. Naturally, Perma Works acquired some of these devices for testing as a VCO. The 555 VCO works reasonably well up to 230°C, however, between 230°C and 250C, the device simple stops holding a nominal frequency. This device cannot be used for a 300°C tool.

Digital. For the first tool, microprocessor circuits were not an option. This section is covered in the fully digital 250°C PT-Flow tool development.

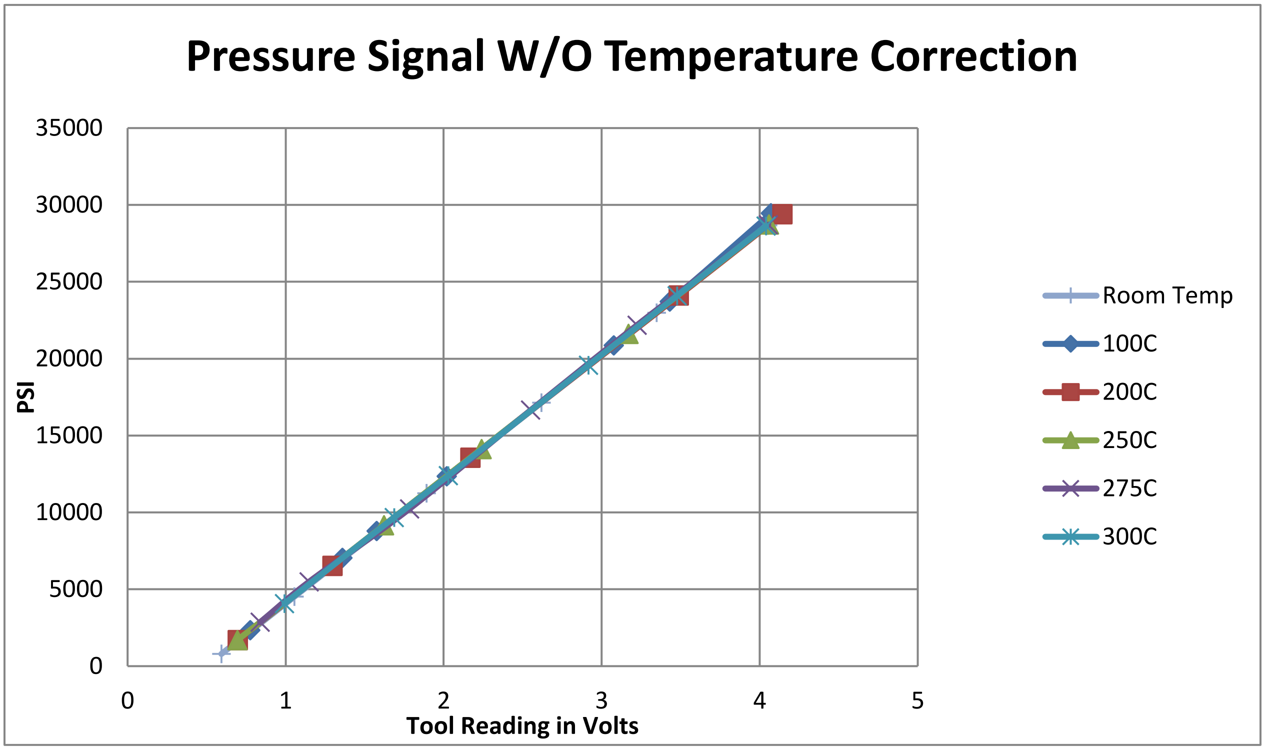
Multi-wire. Assuming a multi-wire cable where each sensor output has its own signal wire greatly reduces the complexity of the down hole electronics. However, discussion with PPS and Geodynamics quickly resulted in cost and availability of such cable for 300°C geothermal wells. The cost of such a cable is close to $300K and have a limited life.

THE FINAL 300°C TOOL SOLUTION

The technology enabling a 300°C tool is the Honeywell HTOP01 precision operational amplifier. This device has incredible DC accuracy for measuring static signals as pressure and temperature. The HTOP01 has a built in offset error correction process. The data plot to the right shows the offset error of a pressure amplifier circuit operating at 300°C. The error is less than 25uV as seen in the data plot to the right. This data was captured by Sandia National Lab prior to Randy Normann leaving Sandia.



At the 2010 DOE Geothermal program review, Perma Works presented pressure signal graph below. Here fixed values of pressure are input to an oven heated amplifier circuit made up of two HTOP01 chips. The gain is ~300 which is a lot of gain for any sensor. So the question is how to best get this signal to the surface?



None of the four means (Constant Current, VCO, Digital, or Multi-Wire) already considered were acceptable. The constant current actually does work but the noise levels from error in the circuit holding the current constant were too high. However, an idea occurred. The reason for the constant current is to determine the signal current as below.

Icc = 40mA + Isig; Where Icc (cable current) is signal current (Isig) plus a constant 40mA tool supply current as shown in the Constant Current section of this report.

If we remove the constant current transistor creating Itc and find a means to measure the tool supply current (Isc) at any time and temperature, we would simply subtract that measured value. So, we created an analog tool which could place up to 8 signals on the cable. One of the signals is a measure of the tools Isc. When this signal is placed on the cable, the surface electronics knows to record the cable current as the tool supply current, Isc.

Now Icc = Isc + Isig; Where we know Icc and Isc.

GENERAL TOOL OPERATION

Perma Works has modified the PW-PT535A analog tool to accept experimental sensors where sensor developers want to demonstrate their sensor in real-world conditions in a HPHT (high-pressure, high-temperature) well. In general, the 535A tool was designed for geothermal well logging at temperatures of 275°C and up to 30,000 psi to support geothermal well production testing and production stimulation (hydro-fracturing). There are additional markets in steam flood for increased oil production and well stimulation of natural gas wells.

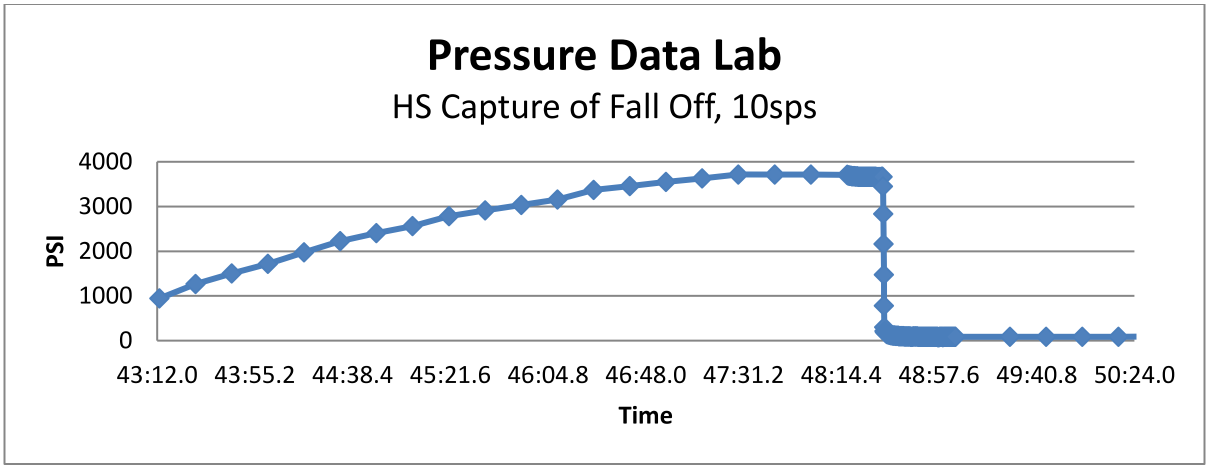
The modified PW-PT535A tool provides the sensor developer with a complete system for well logging using conventional wireline logging equipment. The tool provides regulated 5V power, a 2.5 voltage reference and a platform at the front of the tool for the user to modify as needed.

This tool can operate on either standard 300°C wireline logging cable or special cables containing an isolated signal wire. Standard wireline cable is an armored cable with an isolated center conductor as seen to the left. The armor is used as the tool ground and the center conductor as the power and signal. The tool housing and all metal parts are power ground and signal return to the surface.

For cases where there is an additional second wire inside the armored cable, we can run the signals independent of the power and ground wires. This improves the signal to noise ratio. For long term well monitoring a cable is made using ¼ inch solid tubing. In the cable images to the left, there are two wires protected by the tubing; one for power and the other for signal coming from the wired cable inside tubing. However, the best sensor results come from using the second signal wire.

The standard tool is responsive to the operator even while on 15,000 feet of standard logging cable. The tool can cycle through all the sensors or can stop on any one sensor to capture dynamic signals. In general, the tool cycles through all eight sensors in about 15 seconds. If it stops at any one channel, the sample rate is increased up to 50 samples per second. It's also possible to attach an oscilloscope to monitor tool output at the surface with >5 KHz bandwidth.

Below is an example of switching to a faster data collection mode for pressure readings during well fracturing. When the rock fractures, the reservoir engineer wants to know how fast the water moved into the fracture to gain insight into the size and volume of the newly created fracture. The tool pressure readings were every 15 seconds and then switched to 10 readings a second. In this example, the fluid standing in the pipe dumped in 6 seconds.

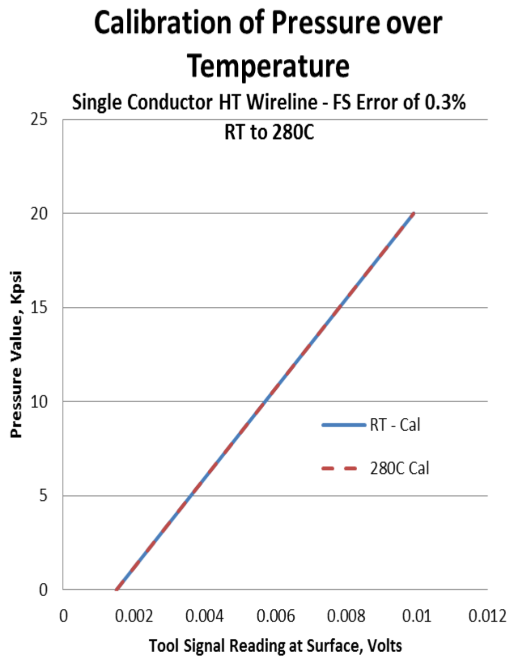


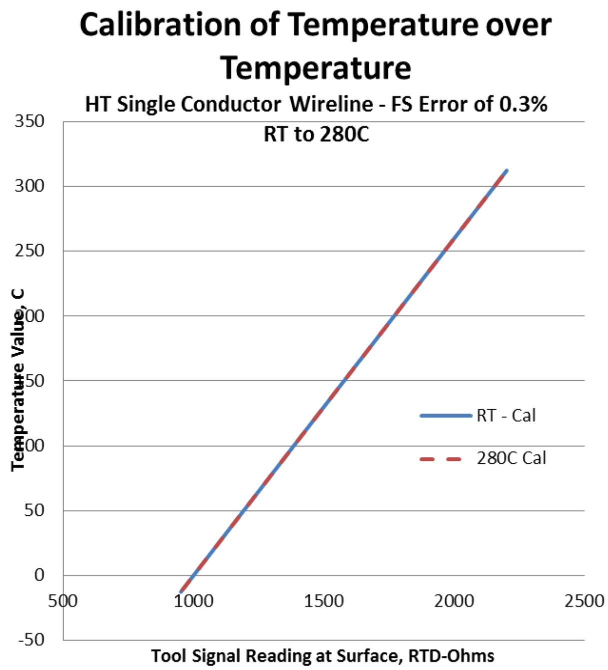
The photo below shows a woman holding the tool. A solar power surface box is to her left. A spool of high temperature wired tubing is to her right. Tubing is used for permanent tool well deployment.

HOLDING CALIBRATION OVER TEMPERATURE

The PW-PT535A analog tool transmits a number of internal signals that compensate for the extreme temperatures the tool must operate in. Compensation is needed for increasing temperature-dependent dark currents that change the offset voltages of the tool's voltage reference and signal amplifiers. Also needed is compensation for changes in the resistance of the logging cable caused by extreme heat and potential leakage currents.

Unfortunately, some of the compensation channels for the modified PW-PT535A tool have been dropped to provide up to three channels for the sensor under test. Perma Works engineers can help the sensor designer transmit the best signals for their test. Below are the pressures and temperatures measured by the unmodified 535A tool over the complete temperature range. These are raw tool readings using only the signals sent to correct for the sensor reading over the tool's temperature range.



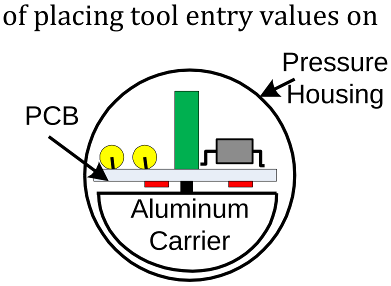


For these plots, the pressure sensor data (left) is in volts per Kpsi. The temperature sensor data is in ohms per degree C. In both cases, the room temperature plot sits on top of the 280 °C plot. Even as the 535A tool is rated to 275°C, testing is run to 280°C. In fact, the tool electronics can be run to 300°C for short periods of time.

MOUNTING CIRCUIT BOARDS (PCB) WITH COMPONENTS

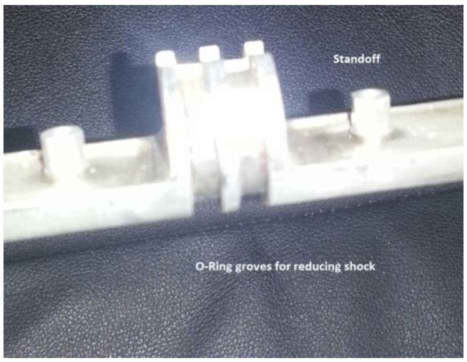
It's in the nature of the business that logging tools are built inside round pressure housings. The pressure housing is generally the most expensive part of a logging tool meeting three standard specifications: high strength (10 Kpsi and up), limited diameter (<2 inch) and tolerant of caustic fluids (HCl, H2S).

Pressure housings are made from high-grade stainless steel containing nickel. Our pressure housing is heat treated 17-4 ph. Standard 316ss is almost never used in geothermal because it is easily attacked by HCl while 17-4 is more chemically resistant and is twice as strong as 316ss allowing for thinner walls, leaving more room for electronics. The tool diameter size limitation comes from a long history of placing tool entry values on top of the well with a 2 inch ID in the oil industry. Thus, our tool has a 1.75 inch OD. For a pressure rating of 10 Kpsi, the tool's inside diameter only 1.1 inch, leaving a 0.3-inch wall for the pressure housing. In general, the tool electronics are on 1.0-inch-wide circuit boards.



The electronics are mounted on an aluminum chassis as shown in the drawing to the left. The aluminum chassis is half moon. The board standoff is placed in the middle of the circuit board; the threads can be screwed into the aluminum chassis at a thick location. The board mounts we use are 0.25 inch high. So there is room for small surface-mounted resistors and capacitors on the bottom of the circuit board.

Normally, we use a large board mount because our tools are in the field for 5+ years and used every day. They have to handle vibration. For those, we use a 0.157 inch (4.1 mm) hole with a "grounded" pad that's 0.3 inch (7.6 mm) OD. However, to save space, we have used 0.157 inch holes with 0.2 (5.1 mm) pads. In either case, we keep the mounting holes at a maximum of 3 inch (7.4 cm) between the mounts, and because of the moon shape of the aluminum carrier, it is best to place the board mounts in the center of the circuit board.



Any tall components must be less than 0.42 inch (10.1 mm) high and must be placed on top and in the middle of the circuit board.

A photo of a mounting chassis is shown to the left.

A pin header with standard 0.1 inch spacing and 0.04 inch plated holes is used for board wire connections. We use a HT Nickel Clad 28AWG wire for this type of jumper. At the board level, we solder with HMP MM01005. It’s easy to obtain and good to 290 °C. We have tried a number of HT solder fluxes. We are not able to see enough difference in HT solder fluxes to make a recommendation. We are currently using M-Flux AR-2 from Micro-Measurements. Circuit layout traces 20 mm wide and 12 mm clearance between traces to allow for hand soldering using HMP solder. Traces are copper/nickel/gold. We have a qualified manufacturer for high-temperature circuit boards if needed. However, if you’re only interested in 250°C or less, other options allow higher densities.

JP3 Pins (Pin 1 has the square solder pad)
Pin 1: 5V Supply (Honeywell HTPLREG 5.0v)
Pin 2: Gnd
Pin 3: 2.5VRef (Cissoid CHT-BG3M 2.5V Dip)
Pin 4: Gnd
Pin 5: Sensor1
Pin 6: Gnd
Pin 7: Sensor2
Pin 8: Gnd
Pin 8: Sensor3

The 5-volt supply is regulated but not current limited. In general, the system can support a 30 mA sensor supply current at temperature and unlimited capacitance. The voltage reference requires a high impedance with load <1 mA for proper performance.

ANALOG CHANNELS AND DATA FORMAT

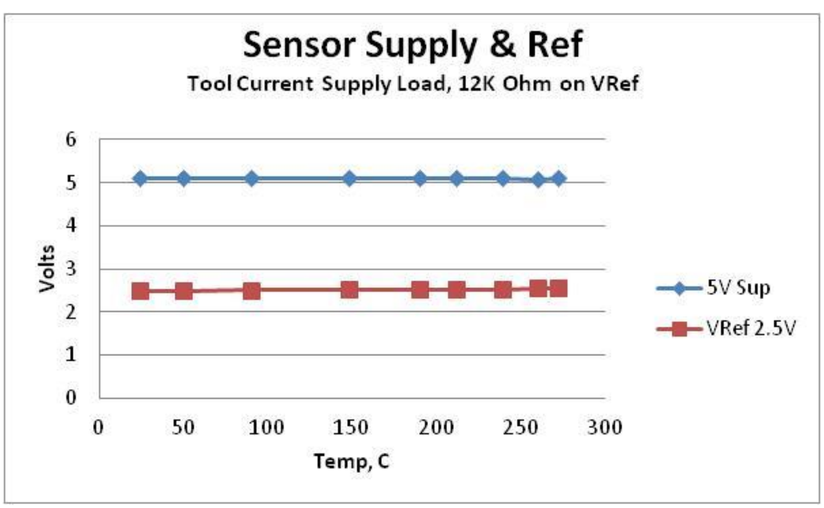
Three open data channels support testing new HT sensors. However, PW can increase that to four or even higher if desired. For going into a geothermal well, it is best to keep the Perma Works pressure and temperature sensors on the tool to validate the well pressure and temperature for the sensor. The PW sensors are mounted on top of the tool. The new sensors under test are often at the bottom of logging tool there because they see the fluid with the least disturbance.

<u>The 8 data channels going to the surface are:</u>
Channel 1. Well Pressure (Paine Electronics Pressure Transducer)
Channel 2. Well Temperature (1000 ohm RTD located inside the Paine Electronics pressure transducer)
Channel 3. Tool Cable voltage
Channel 4. Voltage Ref
Channel 5. Sync Signal
Channel 6. Sensor1
Channel 7. Sensor2
Channel 8. Sensor3

PW surface software triggers on the sync signal to mark data channel locations. Since high-temperature logging cable is a poor conductor at high temperatures, PW needs to track tool cable voltage to maintain the correct operational voltage at the tool. In short, channels 4 and 3 cannot be changed.

OVEN TEST DATA

The tool electronics were mounted on an aluminum board carrier with room for add additional sensor electronics at one end. The tool electronics were run inside the oven at elevated temperatures. Normally, a thermocouple is mounted on the actual circuit boards under test. For this test the thermocouple was mounted on the board carrier not the electronics. In this case, the electronics will be 5-15°C cooler on average than the board carrier as the oven heats up. For the temperature values below, the measured temperature of the board carrier is used.



The 3 sensor input signal cables were ~6ft long twisted pair and bought outside the oven along with the 5V supply and 2.5V reference voltage supplied to the sensor. Below is the plotted sensor 5v supply and reference voltage. The 5V supply is performing better than normal because there is only a

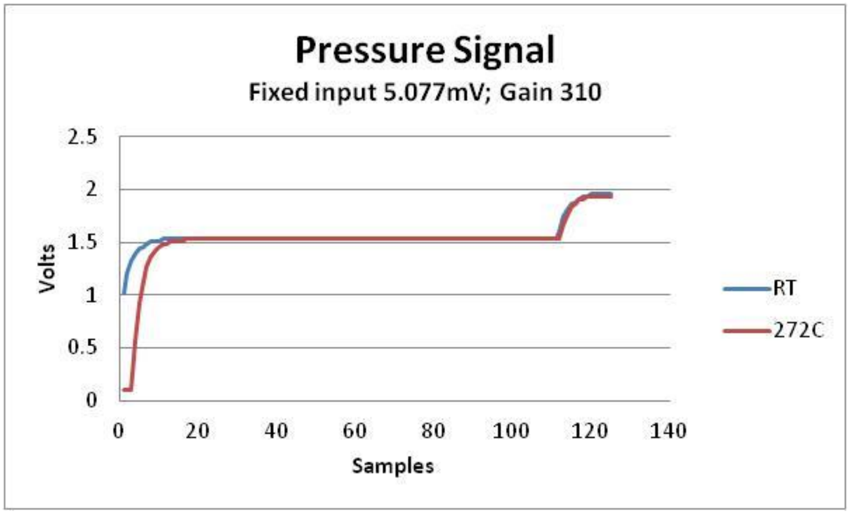
~15mA load. The reference voltage started at 2.4948V and finished at 2.543V.

Tool electronics quiescence current during this test started at 13.6mA and finished at 19.8mA.

3rd Wire IME Measurements					
Room Temp Calibration			260C Temp Calibration		
Input	Output		Input	Output	
0.499	0.502		0.502	0.505	
1.006	1.008		1.005	1.007	
1.505	1.506		1.506	1.505	
1.991	1.988		1.992	1.991	
2.51	2.52		2.5	2.49	
3	3.02		3	2.97	
3.5	3.52		3.5	3.47	

To provide an input to the sensor channels a 20K ohm multi-turn pot was placed across the 5V sensor supply with all three sensor channels tied to the wiper arm of the pot. A series of voltages were made at the wiper arm of the pot and compared to the receiver 2nd wire output.

The receiver output follows the sensor channel inputs nicely. In this case, the tool is only placing the sensor channel values on the 2nd wire of the logging cable after passing through an analog mux and unity gain buffer. The receiver passes the tool signals through a 1Hz low pass filter to reduce noise and 60Hz during bench testing as here. For the benefit of the sensor developer, this filter can be significantly opened. However, in the real world of well logging, high temperature logging cables have limited bandwidth. The sensor developer should consider a band pass of 7KHz or less depending on the well temperature and length of the cable installed on the logging truck.



Using an oscilloscope (8bit vertical resolution) some small effort was taken to measure signal noise. The measured noise on the sensor channels was below the limits of the oscilloscope. The tool electronics also have circuits for monitoring well pressure.   A standard pressure transducer normally has a full scale output of only 20mV. For this oven test, a fixed input of 5.077mV was used. The tool electronics have a gain of ~310. So, the noise levels on this channel are normally the highest of the tools data channels.

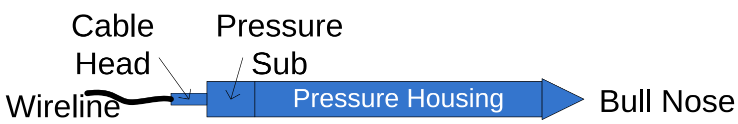
With a pressure reading of 1.53V the oscilloscope was still unable to measure noise variations in the signal. Again, these results are following the receiver which has a 1Hz low pass analog filter. No digital processing was done to the signal shown in this report.

BASIC MECHANICAL CONFIGURATION

The top of the tool, called with "Cable Head," has a wireline attachment and a sealed, high-pressure electrical feed-through. Depending on the cable, we have either a standard single conductor wireline cable head or a two conductor cable head. There is a third option of using a wired 0.25 inch tube. Tubing is better for extended logging runs of weeks or years.

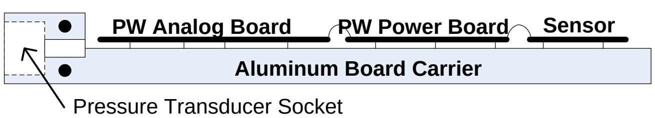
After the cable head is the "Pressure Sub". To make deploying sensor circuits easier, this tool is backwards. The pressure sub is normally located at the bottom of the tool. The pressure sub measures the well's pressure and temperature. This leaves the "Bull Nose" open for the sensor engineer to alter as needed for any number of sensors that need well access.

After the pressure sub is the "Pressure Housing," which holds the electronics. The pressure housing is normally the most expensive mechanical part of the tool. Following the pressure housing is the bull nose. The bull nose is where most sensors get access to the well fluids. The only requirement of the bull nose is to have a round shape to allow the tool to easily slide down the well.



FIELD DEPLOYMENT

To protect the expensive HT circuits, the circuit board is mounted on the same board carrier as used in the logging tool. A simple oversized protective steel tube is cut and drilled so that screws can be used to hold the board carrier inside.



SURFACE RECEIVER

The surface receiver provides tool power via direct connections to the logging cable. The effort for the surface receiver electronics was considerable and was a function of the tool development as a number of communication methods were considered. Most of the work on the surface electronics was performed by Charles Normann and Alastair Black. The initial surface electronics were based on an SOC (System-On-Chip) microprocessor with a built in 24 ADC.

The cable is also transmitting data back to the surface as a signal coupled on the DC power wire (standard mono-logging cable) or on a signal line wire using multi-wire cable. As mentioned elsewhere in this report, the use of a standalone signal wire reduces noise in the measured signal.

The data being captured by the surface receiver is time stamped. The surface receiver has an onboard battery backed, real time clock. Also, tool data can be passed to a PC is connected to the surface receiver via an USB port. The PC allows the user pass commands to the surface receiver and the logging tool. In general, when logging is started, the surface receiver clock is set to the same time as the logging truck or other surface equipment. This allows the reservoir engineer to coordinate tool data with activities occurring on the surface.

The surface receiver also has the capability of making well head measurements as pressure, temperature and flow. Well head data can be tied to the tools data as changes in flow often result in changes in well temperature and pressure.

As the tool moves down the well, the logging truck records depth vs. time. The surface receiver records tool readings vs. time. When the log is completed, Perma Works software called "Field Ops" merges the receiver tool data with truck depth data to make a well log of data vs. well depth.

As the surface receiver is a standalone system, taking data versus time, it is easily removed from the truck to simply log the well over periods of months or years as needed. The surface receiver and operate form 120 Vac, 240 Vac or 12-24VDC with an optional step up converter.

The Perma Works software is unique allowing the operator to change calibration as needed. This allows for the owner to change well head sensors or even replace sensors inside the logging tool. These field adaptions greatly reduce down time.

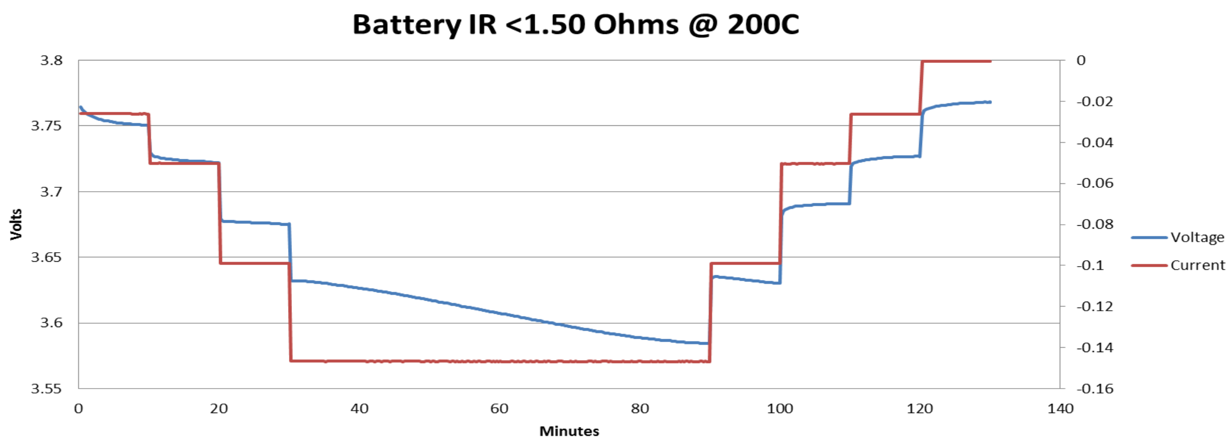
There are simple PC software data filters the user can define for any data channel received by the surface receiver. These filters are simple moving averages and median point filters or a combinations of median filter followed by averaging.

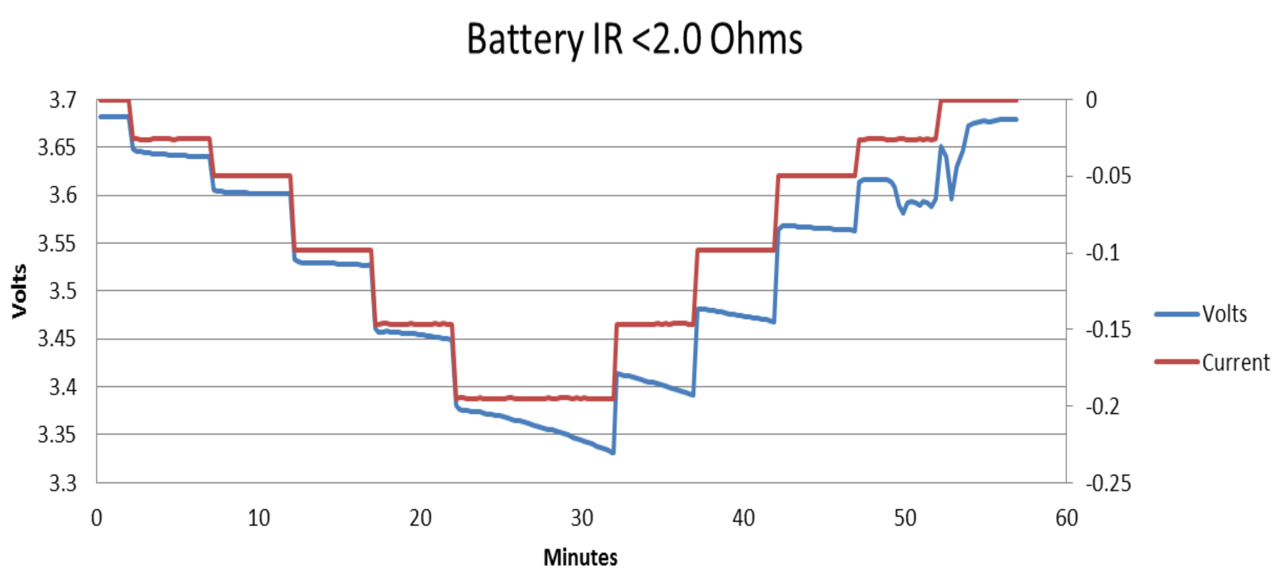
Update, April 2017. The surface receiver is undergoing another change. The original system was based on propriety software. As such, any change to the surface software required man hours by Perma Works engineers. The new system is based on the Arduino public domain processor system. This system is taught in ~90% of US high schools. There is huge public domain support and self-help books as "Arduino for Dummies" by john Nussey or "Arduino Programming in 24 Hours", a Sam's Teach Yourself book by Richard Blum.

By moving to the Arduino microprocessor system, future EGS well monitoring systems will be programmable by geothermal technicians or reservoir engineers to best meet their immediate need without going back to Perma Works.

Update March 2014. With the loss of a battery solution from ESI, testing was conducted on a new solid-state, rechargeable battery from Dr. Potanin. This technology is considered a safe battery because even at elevated temperatures, the battery materials are in a solid form, no danger for bursting because of increasing internal pressure with increasing well temperature. However, low temperature performance at room temperature is non-existent.

This test battery is a prototypes and very expensive to build. As such, we only had 1 battery for testing, so we started with a safe battery test at 200°C before moving to 250°C.





This battery developed an internal open circuit within the cell at 250°C, however, this battery is showing great promise at higher temperatures and it's rechargeable.

FIELD DEMONSTRATIN TESTING AT HABANERO 4(AN EGS WELL)

OVERVIEW

Habanero 4 is the fourth production well drilled by Geodynamics at Habanero in the Cooper Basin, Australia. This is a true EGS (Enhanced Geothermal System) project where well stimulation was undertaken to enhance the fractured reservoir of Habanero. The objective of Perma Works' effort was to support reservoir characterization by logging pressure and temperature just above the production zone using our PW-PT535A tool which was designed to support EGS well stimulation work under DOE Grant DE-FG36-08GO18185. The need for monitoring reservoir response is highly valued. Geothermal well stimulation is very expensive requiring multiple high pressure tractor-trailer sized pumps and large crews to operate them. It should be noted, the Cooper Basin is located in the central Australia outback making operations extreme expensive. All the equipment was shipped by trains (very large trucks pulling multiple trailers) from the populated parts of Australia. To support the Perma Works EGS tool, Geodynamics had to ship in a full sized logging truck and fly in a crew to operate it all the way from **New Zealand** plus shipping to the Australian outback well site. In short, the project lead for onsite well logging estimated the cost of real time data collection using the PW-PT535A to be over $325K USD in Australia plus operations in New Zealand. The photo below was taken from inside the logging truck. The large blue machine attached to the white diesel truck is one such pump for fracking the well.

The results from the actual Habanero well were excellent independent of our tool's operation. Geodynamics is leading the way for all future EGS projects. Unfortunately, the

PW-PT535A deployment was problematic with one tool having a pressure seal leak (assembly error) and the second tool a short circuit (assembly error). To support reservoir testing in Habanero 4, the PW-PT535A tool was modified to operate with a conventional mono-conductor wireline in place of the wired tubing used in permanent reservoir monitoring applications. Working with Tiger Energy Services, initial testing of the PW-PT535A on a conventional wireline in New Zealand was positive. Following the New Zealand test, a second set of circuit modifications were undertaken to ease operational issues found in New Zealand. Tiger Energy Services also performed the deployment at Habanero 4.

This report will cover both positive and negative results from the tool's deployment along with improvements already made and suggested future improvements. Many of these future improvements have already been initiated at the time of this report.

THE PW-PT535A

Two PW-PT535A tools were used to support this test. The pressure house built for these tools was rated for 30,000psi with Paine Electronics pressure transducers. This high of pressure rating was required because the Habanero wells in the Cooper Basin are deep at ~12Kft with a pressurized reservoir of ~2Kpsi at the surface. So, fracturing this reservoir requires significant downhole pressure. Adding up all the pressures which could be seen by the tool pushed our pressure rating.

As there were a number of well stimulations planned, the tool required operating from a 7/32, high temperature logging cable. The cable head was changed to accept 7/32" 300°C, braided cable from the original 1/4in wired tubing. The logging truck contained approximately 15Kft of cable. Running the PW-PT535A from this long of a cable created some difficulty.

In order to convert the tool for use in EGS, new surface equipment was designed enabling much faster data rates, more data channels (up to 8) and a programmable power supply. Geodynamics required proof the tool would work prior to funding the actual deployment at Cooper Basin. Geodynamics set up a well monitoring test in New Zealand.

This report contains the results of demonstration testing in New Zealand and Australia. There were a few months separating the two deployments so some changes were made between following the New Zealand deployment. It should also be mentioned, that both New Zealand and Australia were members of the IPGT (International Partnership for Geothermal Technology) with the USA Department of Energy.

TOOL OPERATION AS DEMONSTRATED

The tool operates in two modes:

1. Continuous cycling of readings: Pressure, Temperature, Zero P/T and Full Scale
2. Fast pressure mode

CONTINUOUS MODE:

In continuous mode the tool cycles through all readings starting with well pressure as outlined below.

- Pressure is the well pressure. In this case, the transducer is rated to 30,000 psi (~2,000 Bar) and 300°C
- Temperature is both the tool and well temperature. In this case to reduce the risk of a high pressure thermal well, the temperature RTD was located inside the tool
- Zero P/T is the zero reference for 0 psi and 0°C used by the tool
- Full Scale is the signal's full scale output. This and the zero reference enable the detection of cable losses.

Because of the 16,000 ft logging cable mounted on the logging truck, we set the cycle to 13 second intervals. This is a programmable option which can be made shorter when using a shorter cable. The people at Geodynamics believed 13 second intervals as more than fast enough for most EGS applications.

TESTING IN NEW ZEALAND

OBJECTIVE:

To demonstrate thePW-PT535A on a HT single conductor wireline for an extended period at 250°C. To work with the same logging truck, equipment and people as will be used in Australia supporting the EGS effort at Habanero.

RESULTS:

The PW-PT535A tool was modified to operate over a single conductor by coupling both tool signals coming from the tool and user commands going to the tool onto the same conductor as tool power. Because the tool is constantly transmitting data, the user commands must over drive the tool signals coming up the cable in order to change tool operating mode. These changes were manually hardwired on to the tools circuit boards prior to shipment to New Zealand.

In the New Zealand (NZ) testing, the tool monitored and logged the well from 200°C to 260°C for approximately a total of 30 hrs in two runs. In setting up the tool in the Tiger shop an issue was identified with a narrow operating range of tool supply voltages. This was improved by reducing the tool's output signal ~30%. However, this field 'fix' requires a better solution in the future.

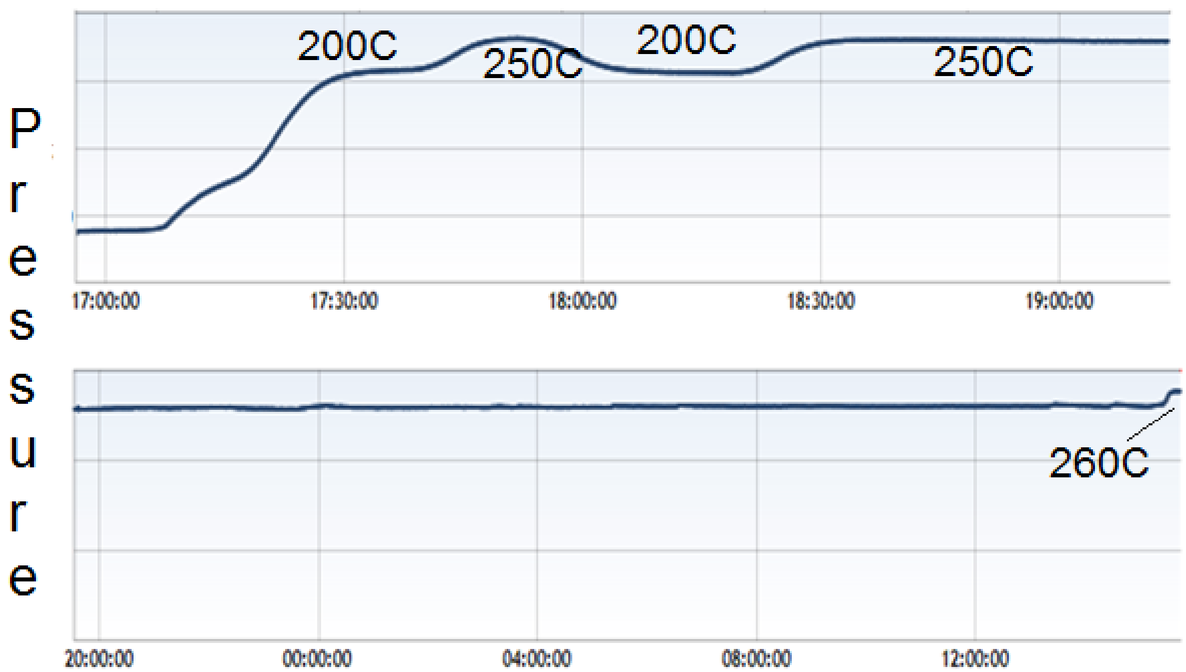
The tool worked in a 24 hr well monitoring test at ~250°C with a push down to ~260°C at the end of the 24 hrs prior to removing the tool. During the second logging run, all tool functionality was tested. The tool made pressure and temperature well monitoring measurements and switched to the high speed pressure only measurement all while in the well at geothermal temperatures.

At 30,000 psi, the pressure transducer is significantly overrated for the NZ test well (< 3,000 psi). The loss of ~30% of the tool's signal on the final day placed the surface receiver near its lowest level. This combination low sensor signal and low electronic data signal leads to noisier than expected results. The noise floor was approximately 30 psi (2 Bar). Future performance should improve in higher pressure wells where the full dynamic range is required.

24 HR WELL TEST:

Here the tool was monitoring pressure only in fast pressure mode. The surface equipment did not need to communicate with the tool. This was done to simply show the tool operating barefoot for an extended time at elevated temperature without risking a communication error.

The tool was lowered to a depth where 200°C well temperature was reached and then to a lower depth for 250°C and then back to the 200°C depth to demonstrate that the pressure measurement was working and consistent. Once the tool was returned to a 250°C well temperature it was left at that location overnight. The very tail end of the log is where the tool was lowered to a 260°C point in the well prior to removal.



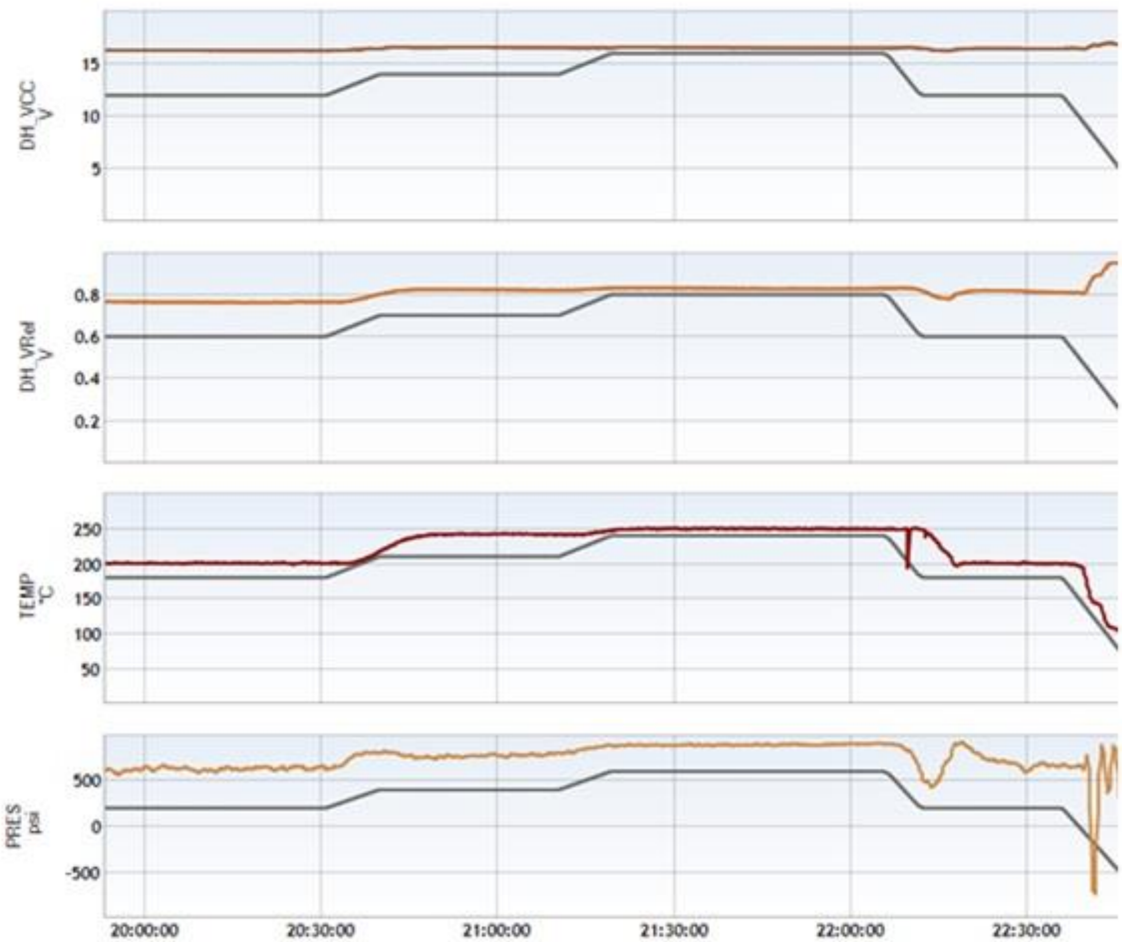
The downside to doing pressure only over such an extended time is that we do not have the corresponding temperature and P/T zero point data to help control drift or temperature related calibration changes.

Using conventional 300°C logging cable requires a cable head with HT rubber O-rings. The remainder of the tool uses only metal-to-metal seals. In short, the cable head is normally the first thing to fail in past testing with conventional logging cable.

SECOND LOG:

This log used the continuous measurement mode with the tool moving slowly down and up the well.

Significantly, the noise level decreased as the pressure went higher, thanks to the increased signal level. When the tool was coming back out of the well we see chaotic data. We believe the chaotic end was during a cable head failure.



LESSONS LEARNED AND ACTIONS TAKEN:

1. The communication with the tool over a long logging cable needs to be improved. After returning to the US, the electronics were manually modified to increase the tool operating voltage by 50%; from 12-18V to 9-18V. This allows the tool to work over a broader range of cable conditions.
2. Pressure range of the 30,000 psi transducer is better than expected. The NZ well was a low pressure well using less than 10% of the transducer's range. Even so, the noise floor looks reasonable. There is an opportunity to increase the pressure transducer gain to allow for greater sensitivity at low pressures. The tool's pressure transducer amplifiers were increased. Now, the pressure transducer is reading its full scale value for pressure at only 23,000 psi to better fit expected pressure testing in Habanero 4.
3. Mechanical damage during breakdown of the tool following the final logging run When the final run was conducted, the tool was removed from the cable while it was still hot. At that time, the wireline crew broke loose 'all' the tool joints. We believe

the tolerance is too tight at one of the joints because the O-ring groove was mechanically damaged. See the figure below. In order to have the tool repaired and support making the electronic changes listed above, the tool electronics were returned to the US and the tool's mechanical parts were taken to a local machine shop in New Zealand. Because of the high cost of shipping equipment between New Zealand and the US, the tools were delivered to Habanero 4 in parts. This contributed to the tool assembly failures at Habanero 4.

The image to the left is of the damaged O-ring groove. A large chip was actually broken out of the steel next to the O-ring groove. To the right is the missing chip.

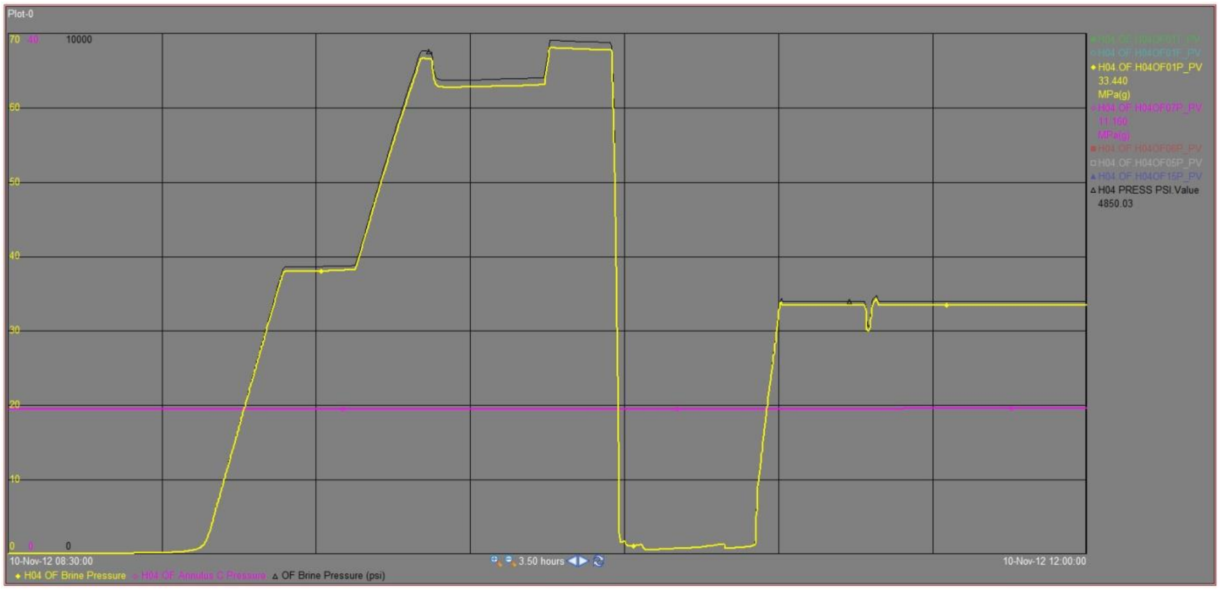
HABANERO 4

OBJECTIVE:

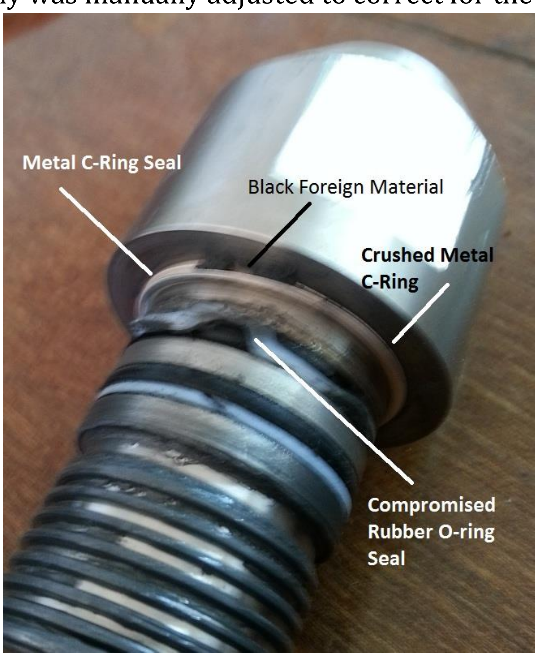
To log pressure and temperature at the production zone to support well flow testing before and after well stimulation activities. The expected temperature was 250°C and 1375 Bar (~20,000 psi). A flow test could last as long as 2 days. The tool would need to run at temperature and pressure for that period of time for each test.

RESULTS AT HABANERO 4:

The first tool was placed in the lubricator as the lubricator was pressure tested to 10,000 psi. The tool data was compared to surface data, see below. While in the lubricator, the tool was working over the 16,000 ft of HT logging cable. In short, the complete system was tested to 10,000 psi but only at low temperature. Following this success, the tool was lowered in the well to support the first production flow test at Habanero 4.



While moving down to the production zone, the tool was logging the well. Logging inside the well, the tool and cable started to see increasing well temperature and pressure. There is an increasing voltage drop between the tool's supply voltage and the voltage at the tool as a function of cable coming off the logging drum, cable resistance increasing due to elevated temperatures and tool supply current. During this first log, the increased voltage drop caused the tool to lose power. At this point the log was stopped and the surface power supply was manually adjusted to correct for the voltage drop. However, this process is slow because care must be taken to avoid an over voltage situation which could damage the tool. [In Perma Works' standard 150°C tool, we have electronics to protect the tool from over voltage. Unfortunately, those types of electronic devices don't exist for geothermal temperatures.]

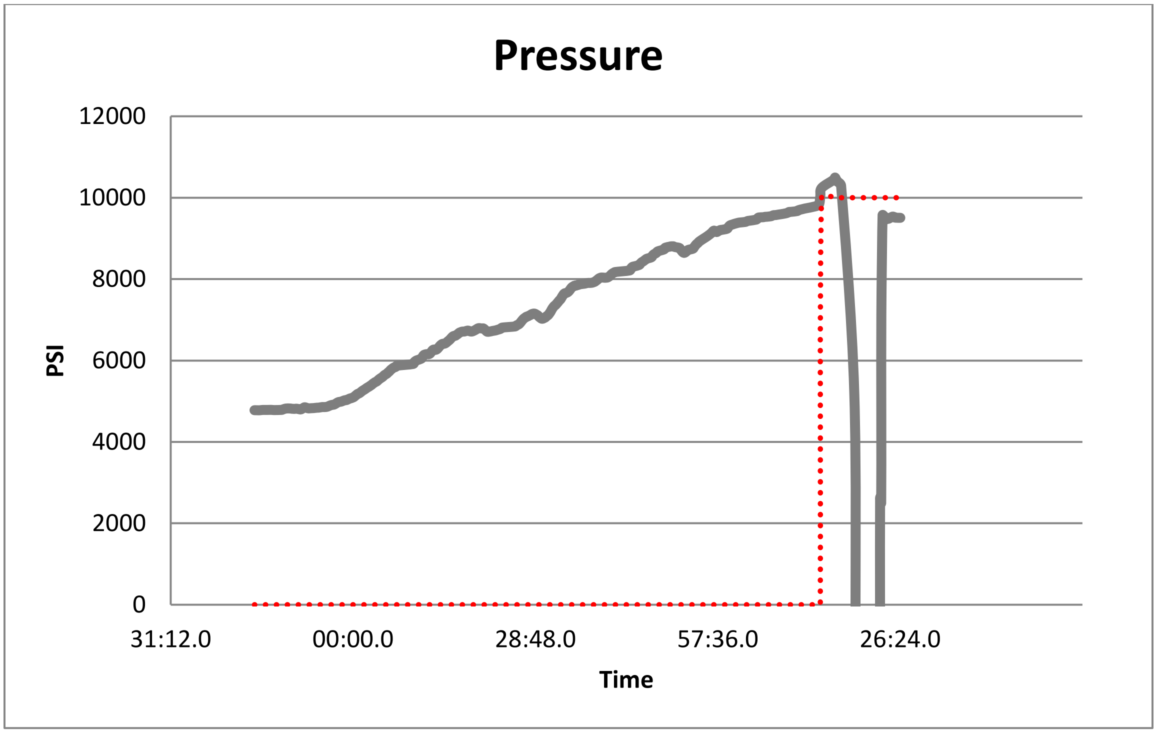


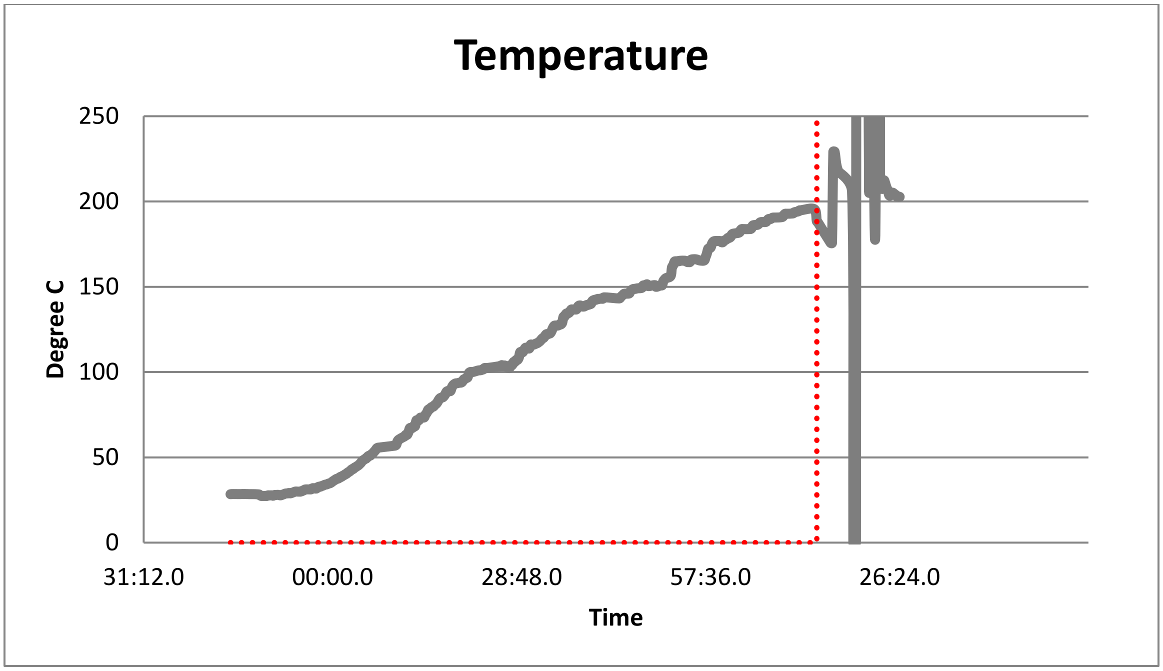
After an hour or so, the tool was back and running and continued to log until it was parked at the production zone. However, the measurements were surprisingly noisy. Much higher than had been seen in the NZ well. There seemed to be no reason. The data was unusable and the noise level was increasing as a function of time at station until the signal was clearly unrecognizable.

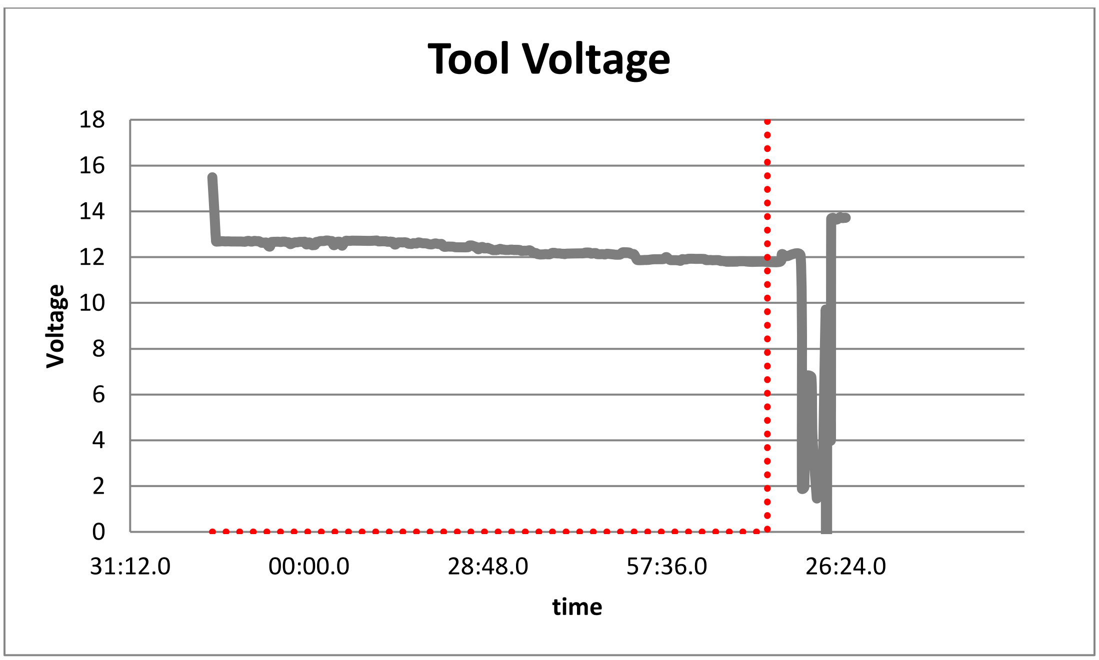
After retrieving the tool, it was disassembled where a small amount of water (several tablespoons) poured out. Inspection of the seals discovered the damaged seals in the image below. It appears that the seal was compromised by a black foreign material which was lodged on the pressure housing side of the seal. The tool is dependent on the metal C-ring for high pressure/high temperature operation. The C-ring was crushed over a ½ inch section. It was of no value for sealing. In addition to the C-ring there are rubber O-rings which are used to center the mating of the metal C-ring and they do provide some secondary sealing. Of the two O-rings one was compromised by the Teflon backing ring. As it turns out, the wireline crews at Tiger have a simple procedure to prevent this from happening. A lack of judgment created this result. Perma Works should have used the Tiger personnel for the assembly of the tool.

FIRST WELL LOG (BEFORE TOOL SHORTED)

Below is the log data taken as the tool left the lubricator heading down the well. Note, for this report this data is by TIME, not depth, so pressure changes can be caused by the logging truck operator stopping, starting or changing logging speeds. The red dotted line is the point of which the surface box lost communication due in part to the increasing voltage drop on the cable.







The tool voltage shows the drop in tool voltage as the cable comes off the drum and is heated by the well. The tool voltage is interesting. First, why the large drop at the start of the log? The tool had been running in the lubricator prior to saving this data. There is a time gap between the lubricator test and the start of this log because we had stopped saving tool data between these two activities. This drop in tool voltage consumed much of our overhead voltage for operating the tool over the cable. One likely cause is water leaking into the tool while in the lubricator was starting to increase current draw.

The surface receiver can record more than tool data. It can record well head pressure-temperature along with tool supply voltage-current at the logging truck. For some reason, the tool supply voltage-current measurements were not saved during these tests.

In short, operator error in tool assembly and then a lack of experience running the tool allowed the tool to take on brine and for the effects of the brine to be missed during the log. With more experience operating the tool, the operator may have detected the increased current draw before the tool had left the lubricator allowing the log to stop and to repair the bad seal.

Once the tool was returned to the surface and the water removed, the tool failed to run. The tool's power supply had been burned out and wiring to the tool's power supply had obvious signs of overheating. Over heating this wire occurs above 400°C.

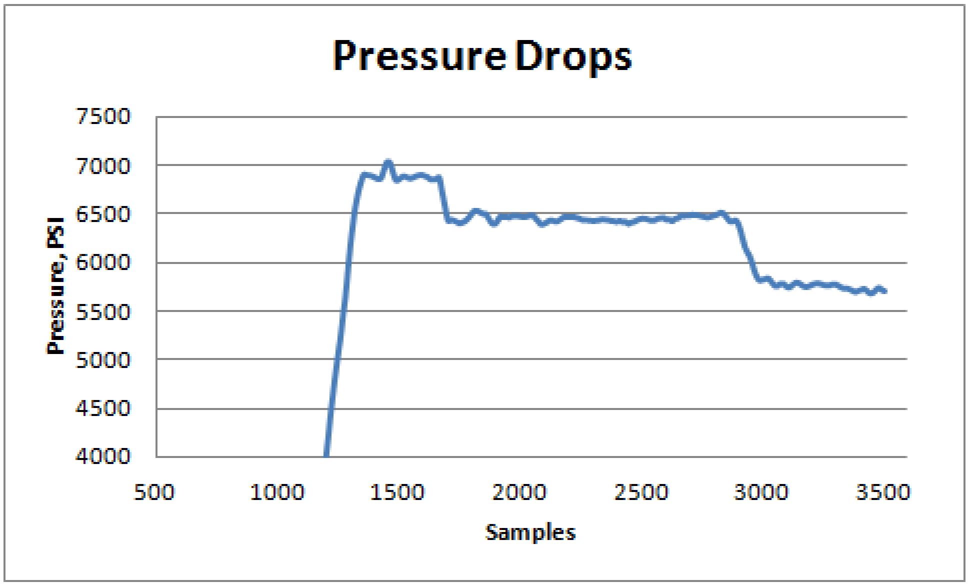
Using data from the cable manufacturer, Rochester Wire and Cable Company, we had modeled the cable versus our power needs and designed the surface equipment to be able to operate over the cable. However, the dynamic changes in cable resistance while the tool is being deployed in the well are too fast for manual control. Even without water inside the tool, there is a danger of damaging the tool.

At the time, the damaged power circuits were a bit of a mystery because at Perma Works, we have demonstrated that placing our HT electronics in brine does not damage the circuits. They stop working but once they are dried off, they start working again. So why were these damaged?

Cable voltage drop increases as the cable moves off the drum. The cable voltage drop increases as the cable is heated by the well. As such, tool supply voltage was manually <u>increased</u>. Even with excessive current draw, the tool continued to operate even at the bottom of the well but with huge noise on the signal line. However, when returning to the surface, the cable voltage drops were reversed but the manually operated supply voltage was <u>not reduced</u> accordingly. This neglect is easy to understand, the data on pull out was not important and no one was monitoring the tool. At some point, the supply voltage and current was no longer limited by the cable resistance and the tool's power circuits were damaged by excess voltage not well brine.

SECOND TOOL, SECOND RUN

After discussion with Geodynamics about the risk, cost and effort to run the second tool, it was decided to give it one more chance. Again the tool was placed in the lubricator for a surface test. In this case the test was more interesting because an actual injection test of the well was the stimulus. Here, the injection rate was decreased in order to monitor the change in well head pressure. The amount of change in well head pressure is a valuable reservoir response. The tool worked reasonably well as can be seen by the two step changes in pressure in the data plot below.



Following the lubricator flow test, the tool was lowered into the well to the production zone. As the tool was deployed in the well, pressure readings were lost. A resistor for balancing the pressure transducer bridge was lost. Paine Electronics is currently the only manufacturer of pressure transducers for these temperatures. Paine produces about 70% of the pressure transducers used in the oil industry. In heat-shielded tools, the pressure transducer is connected to the well bore by a small coil of oil filled tubing to prevent the well fluids ambient temperature from reaching the pressure transducer. That is not possible in our case because the entire tool is at well ambient temperature.

Paine's engineers understand this and developed a transducer able to handle 300°C at the sensor. However, they did not have a 300°C qualified balancing resistor so the 300°C pressure transducer is sold unbalanced. As such, each of their 300°C pressure transducer has a large offset voltage at zero pressure. In fact, at Perma Works we have an inventory of five, 30,000 psi transducers, some of which have offsets 30% negative, or -9000 psi. In the original Perma Works tools, the electronics were adjusted to compensate for pressure transducer offset. This creates an obvious issue, each set of electronics are now married to only one pressure transducer.

So that electronics and pressure transducer could be more easily exchanged, and because of the lack of room on the face of the transducer, the decision was to place the balancing resistor between the pressure transducer and the circuit board. It was this resistor which was lost during the vibration down the well.

The new high-temperature circuit boards have been designed with the resistor located on the circuit to resolve this issue.

LESSONS LEARNED AT HABANERO 4:

NEED FOR AUTOMATIC POWER SUPPLY CONTROL

The surface receiver has a manually programmable power supply to adjust for the changing voltage drop on the cable. However, manual control it is NOT sufficient for logging deep and hot geothermal wells. Only an automated system can monitor the tool voltage readings and adjust the voltage as needed as the tool moves up and down the well.

In fact, this need was identified following the work in New Zealand. A new surface receiver has already been designed with a second microprocessor added to handle control of the tool's supply voltage.

NEED FOR MONITORING TOOL'S SUPPLY CURRENT

Along with automated control of the tool voltage, the surface receiver needs to record surface tool supply current. As tool current always remains within known engineering limits (in this case <0.02mA), the receiver can report to the operator information about a possible tool short in the line or as water is filling the tool.

TOOL ASSEMBLY PRIOR TO SHIPMENT

We normally build and test the tools before shipping. In this case, the tool's hardware required repair in New Zealand while improvements in the electronics were done back in the US. To save costs, parts were shipped from New Zealand and the US to Australia meaning the tools had to be assembled on site. In hindsight, it was in everybody's interest to have spent the funds on shipping the tool's pressure housing back to the US for final assembly and shipment to Australia.

IMPROVED SIGNAL QUALITY FOR PRESSURE TRANSIENTS

The basic tool design uses HT SOI electronics with extreme operating temperatures and operating life times. The life limiting component in all HT designs is the simple ceramic capacitor. Ceramic capacitors fail as a hard short circuit, normally catastrophic to the tool. As such, the existing design uses a minimum number of capacitors. One of the functions of the capacitor is to reduce circuit noise. For permanent deployment, measurements are only made once an hour or day making electronic noise easy to deal with by simply oversampling. For tracking pressure changes during stimulation, production or logging, oversampling is not an option. For these applications, more signal filtering is needed inside the tool, meaning more ceramic capacitors. To improve future tools, a new design is needed where the technician can install or omit ceramic capacitors depending on the future application of the tool.

SINKER BARS (LOTS OF THEM)

The existing PW-PT535A tool design has a sinker bar mount below the tool rated to 80lbs. However, for Habanero 4 (and most future well stimulation activities), an additional 400lbs of sinker bars were required. The additional weight is required for the tool to pull the logging cable through the surface packoff used to seal between the logging cable and the high pressure injection fluid above the lubricator. For Habanero 4, the PW-PT535A tool was modified with a standard GO cable head connector so that the tool could be mounted below the sinker bars. However, a standard GO cable head uses rubber O-rings while the tool uses metal C-rings. The O-rings have a limited life at 250°C and above. A new cable head with metal to metal seals will improve the operating life in the well when using braided cables.

SUGGESTED FUTURE ACTIONS

Based on the lessons learned here are our actions.

1. A second microprocessor has already been designed in the next surface receiver. The next step is to build the circuit and program the new microprocessor. Programming will take 6 to 8 weeks.
2. With the new surface receiver design, the program will automatically monitor surface voltage and current going to the tool.
3. Schlumberger builds and pressure tests every MWD tool prior to shipping to the site; Perma Works should do the same.
4. A new HT tool design incorporating better signal filtering options and wider operating voltage range (learned in New Zealand) has already be completed.
5. A new cable head mating with 7/32” 300°C braided cable design was undertaken in 2011 but never built. This design uses double sealing around the braided cable and metal to metal seals to increase the operating time. At this point, we need to reevaluate this design for increased weight and build it.

CONCLUSIONS OF FIELD DEMONSTRATION

The value of Geodynamics and their work in the Cooper Basin, Australia, is critical to the world geothermal industry. In hindsight, more effort should have been taken to coordinate with Geodynamics on shipping hardware back to the US for assembly and testing. The cost of such an effort is minor compared to the cost of running a surface readout logging truck in the middle of the Australian outback. Also, the Tiger wireline crew should have been more involved in assembly of the tool to at least double check the seals.

Otherwise this experience has provided invaluable insight to the reservoir engineering needs in HT and geothermal wells and highlighted a number of operational issues of field testing new HT tools to support future EGS projects.

APPENDIXES

A: Building Ceramic Circuit Boards Working With Life BioScience

B: Ceramic Bread Boards

C: Hydrogen Oven Test of ¼ Watt Resistors

D: Pressure Capabilities of the 1.75 inch PT Tool Pressure Barrel

E: New Rechargeable Battery for Application in a Wide Temperature Range

F: Fiber Optic Communication with Distributed Temperature Sensing

G: Project Report 300°C Clock

H: Design Considerations for a Downhole Magnetic Flowmeter

I: Designing Logging Tools for Future High Entropy Geothermal Wells

J: Feasibility of EGS Well Control Systems

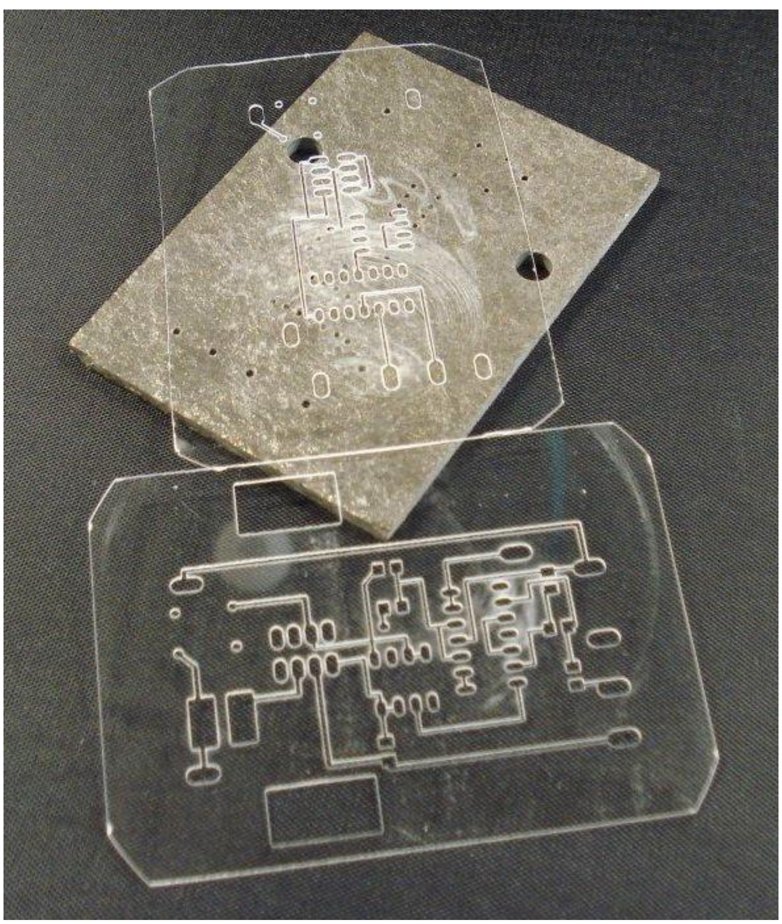
Appendix A

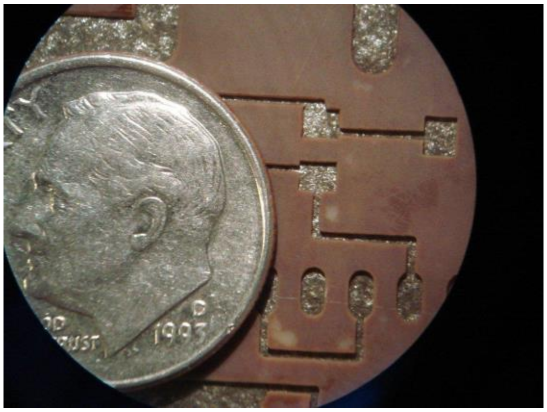
BUILDING CERAMIC CIRCUIT BOARDS WORKING WITH LIFE BIOSCIENCE

By Randy Normann

Life BioScience was a small company operating in Albuquerque, NM at the time of this grant. They have a very unique photo-chemical process for cutting through a glass like material. Once the glass lime material had been modified, a heating process would convert it to a solid ceramic. Under contract with Perma Works, they tried to build a simple two sided circuit board using their material and their cutting process and mounting the result on to our machinable ceramic.

In this case, the machinable ceramic would not be machined. It was used only to support their glass like material and it would be used to mask the metallization layer. Metal would not bond to their glass like ceramic material. To the left are the three sections needed to build a 2-sided circuit board using this unique process. The glass like ceramic material has already been cut with a practice circuit.





The photo with a dime for proving the user with an idea of size is a finished product. Their glass like ceramic turns brown with converted. It is easy to see in the photo that the machinable ceramic is exposed to make electrical traces.

Unfortunately, this process failed to yield a usable circuit boards. The issue is some type of mismatch between the Life BioScience ceramic and the machinable ceramic created while joining the two surfaces. At first it seemed like the machinable ceramic was truly flat so small bending in the thin Life BioScience ceramic would cause cracks. So, the machinable ceramic was trued flat with lapping. This this not help. This cracking can be seen in the image below.

Also another problem was even harder to deal. A normal (more complex than the test circuit here) would create a number of islands where sections of the glass ceramic would become detached as traces enclosed a small section. Placing these back in to place and then bonding them to the machinable ceramic would be difficult.

This effort was dropped.

Appendix B

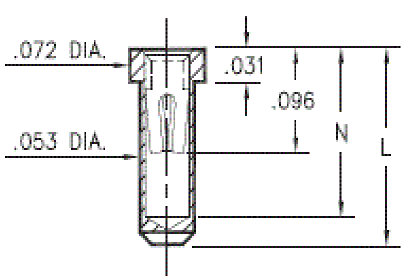
CERAMIC BREAD BOARDS

James Parker, Perma Works LLC

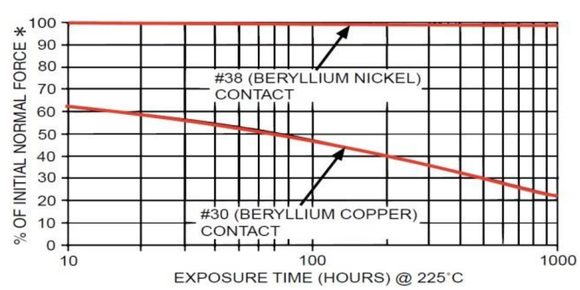
<u>Ceramic Material</u>: A glass-mica composite, rated for continuous use at a maximum temperature of 600°C. Thickness is 0.125 in. thick.

Thermal Conductivity (W/m.K):	1.32
Tensile Strength (psi):	5000
Compressive Strength (psi):	32,000
Dielectric Strength (V/mil):	420

<u>Socket Pin</u>: Mill-Max® Brass Alloy Receptacle 1401; is a brass alloy receptacle, with no tail. It is a gold plating over nickel, and will accept wires or leads ranging from 0.015 - 0.025 in. in diameter. Standard contact material is beryllium copper but will loose tension with extended use over 150°C. For an extra cost of $2 per socket, a high temperature version is available made with beryllium nickel that offers no loss of tension when tested for 1000



Depth N	Length L
.145	.165



hours at 225°C.

<u>Conductivity</u>: Pins are soldered in place with a 300°C solder. There is typically less than 1Ω between any two pins, and a current rating of 1 A. For continuous use, there is a temperature rating of 225°C, or reduced lifespan at 300°C for short durations.

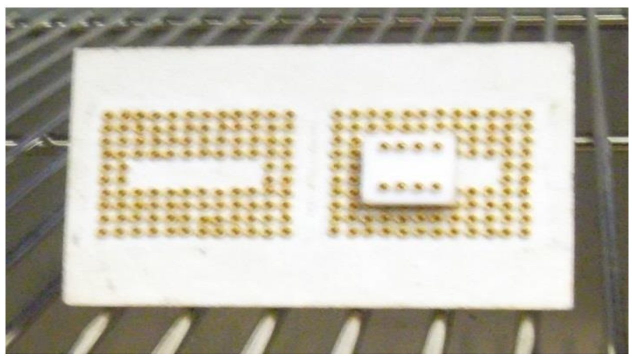
Wires: Ceramawire is used for all wired connections, and is a nickel clad copper, high temperature wire insulated with a fully cured vitreous enamel film.

Temperature range: -260°C to +530°C continuous; Up to 810°C for a reduced lifespan.

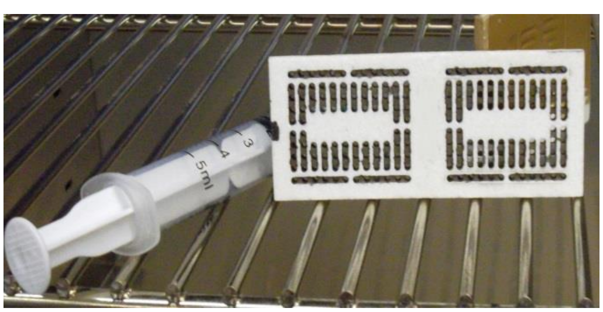
Dielectric Rating: 200V

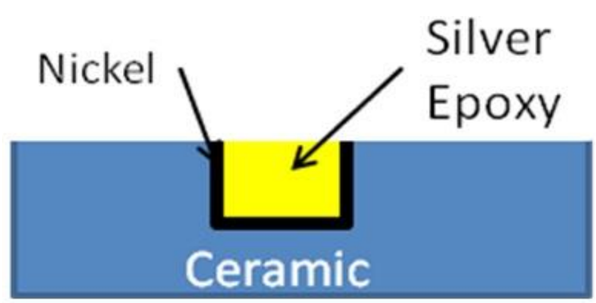
Electrical Resistance: 26.9Ω/circ mil at 260°C; 42.3Ω/circ mil at 530°C

Bread Board Design: The purpose of the bread board is to allow prototyping and testing of high temperature circuits, using high temperature rated components, AT high temperatures, without having to solder until you are ready to construct the final circuit.



Build-Your-Own: In addition to building custom order circuits, we also provide a metalized ceramic "blank" along with a syringe of solder material, allowing you to build your own circuits. Components are populated on a metalized ceramic circuit board, and traces are filled with silver epoxy (provided in the syringe), bonding components in place as with the design of your circuit.





Appendix C

HYDROGEN OVEN TEST OF ¼ WATT RESISTORS

James Parker, Perma Works LLC

First, a synopsis of what was done:

Upon receiving three (3) "new" resistors, ordered from Digi-Key, measurements were taken of each, as well as two (2) variations of the cheap, "china" resistors, and one (1) "witness" resistor. Using the 4-wire test leads to obtain an as accurate a reading as possible, the resistors were measured at, and subsequently labeled the following:

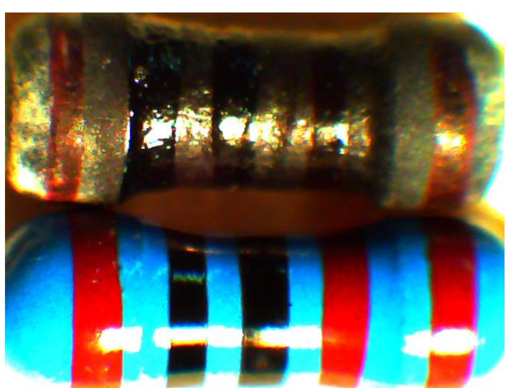
Resistor #	Part #	Measured Value
R1	"china" 1k ohm	1.022k ohm
R2	"china" 2.2k // 2.2k	1.097k ohm
R3	"witness"	2.995k ohm
R4	RS01A1K00FE	1.003k ohm
R5	PAC10000100FA	0.992k ohm
R6	IC 694-3-R1KBLF	0.998k ohm

The resistors were first connected to 200 deg C wire, placed in a seal oven, and exposed to both 200 deg C heat and Hydrogen over the course of around 3 days. The resistors were first brought to a temperature of 200 deg C, and allowed to "settle" for about 4-5 hours before hydrogen forming gas was introduced into the system. Hydrogen forming gas was bubbled through for about a day and half, all the while tracking and consistently measuring the resistor values throughout the testing period. The results of this 200 deg C test were that only the "china" resistors had significant reactions to the heat exposure, and none of the resistors, except the "witness" reacted really at all to the hydrogen exposure.

Following the test at 200 deg C, the resistors were removed from the oven, wires were cut, and measurements were taken again of just the resistors (without wire). The resistors were then placed on top of a brick, and placed back into the oven, where it was sealed and brought to a temperature of 300 deg C. The purpose this time to expose the resistors to a hotter temperature (before we were limited by the temperature rating of the wire used to monitor the resistors during the initial test), and see what kind of long term, if any, reaction was obtained by hydrogen exposure at that higher temperature. As we were not monitoring resistor reading during the test, the sealed oven was capped off (rather than through a tube into a water bucket) and once at temperature, the cap was removed and hydrogen forming gas turned on to allow the system to expunge any remaining "air". The oven was capped once again and the resistors now "soaked" in hydrogen for about a day. Readings were as follows; Notice how R3, the "witness", again has a high-reaction to hydrogen exposure, so we know hydrogen was present during this test, as designed and intended:

Resistor #	Post 200c	Post 300c/hydrogen.
R1	1.021k ohm	1.017k ohm
R2	1.095k ohm	1.095k ohm
R3	3.580k ohm	5.136k ohm
R4	1.004k ohm	1.003k ohm
R5	0.992k ohm	0.994k ohm
R6	1.000k ohm	1.013k ohm

Based on this test, the resistor with the highest potential is R4, as given the data, it had the least reaction through out the entire testing to both heat AND hydrogen. However R5 and R6 come in a close second/third and would most likely also be a wise selection as their reactions may be deemed negligible.



R1: Cheap, "China" 1kΩ. Notice the discoloration and "blackening" of the resisotr shell.

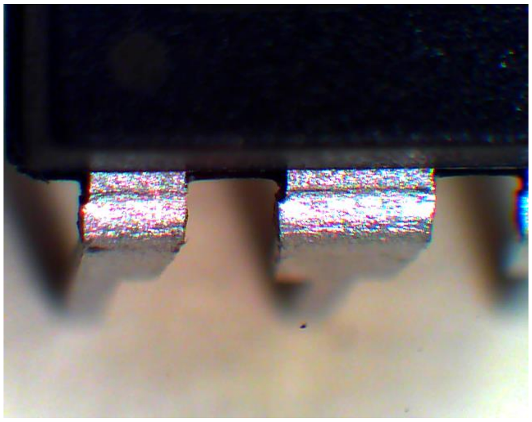
R2: Cheap “China” 2.2kΩ // 2.2kΩ (parallel). Again, notice the discoloration.

R4: RS01A1K00FE.

The discoloration of the letters (from blue to white) is the only physical changes clearly visible evident of the heat/hydrogen exposure.

R5: PAC10000100FA

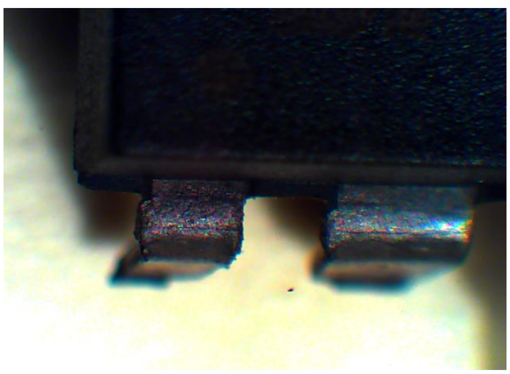
Visible evidence is the slight discoloration of the blue shell, and other than that there is very little change in appearance.



Pins

Top

R6: 694-3-R1KBLF BEFORE



R6: AFTER. Notice the slight discoloration of the letters on top, as well as the blackening of the pins.

Appendix D

PRESSURE CAPABILITIES OF THE 1.75-INCH PT TOOL PRESSURE BARREL

By
David A. Glowka
Red Rock Research, Inc.

March 26, 2009

EXECUTIVE SUMMARY

The pressure capabilities of the pressure barrel used in the 1.75-inch Sandia/USGS PT tool are estimated using an analytical solution for stresses in a thick-walled cylinder. The analysis focuses solely on the relationship between borehole pressure and stresses within the pressure barrel. It does not include temperature effects nor examine the pressure capabilities of the seals used with the pressure barrel. Those issues will be addressed separately.

The results indicate that the present 1.75-inch pressure barrel will become permanently deformed at a borehole pressure of about 23,000 psi. In order to operate at 40,000 psi, it would be necessary to increase the outer diameter of the pressure barrel to at least 2.375 inches, assuming the same inner diameter and material as currently specified.

STRESS AND FAILURE MODELS

The tangential stresses in a thick-walled cylinder (i.e., a cylinder in which the stresses are not assumed to be constant across the cross-section) are given by the equation [1]:

$$\sigma_t = [p_i\, a^2 - p_o\, b^2 - a^2\, b^2\, (p_o - p_i) / r^2] / (b^2 - a^2) \quad , \quad \text{..................(1)}$$

where

σ_t = tangential stress
p_i = internal pressure = 15 psi
p_o = external (borehole) pressure = variable
a = one-half cylinder ID = 1.377/2 = 0.6885 inch
b = one-half cylinder OD = 1.75/2 = 0.875 inch
r = radial position between a and b where stress is to be calculated.

The radial stresses, σ_r, in the cylinder wall are [1]

$$\sigma_r = [p_i\, a^2 - p_o\, b^2 + a^2\, b^2\, (p_o - p_i) / r^2] / (b^2 - a^2) \quad , \quad \text{..................(2)}$$

and the axial stress, σ_a, is

$$\sigma_a = [\text{axial pressure force}] / [\text{c.s. area}] = [-(\pi\, b^2\, p_o - \pi\, a^2\, p_i)] / [\pi\, (b^2 - a^2)]$$

$$\sigma_a = (a^2\, p_i - b^2\, p_o) / (b^2 - a^2) \quad . \quad \text{....................................(3)}$$

These three stresses represent the tri-axial stress state at any radial location in the pressure barrel at its thinnest cross-section along the o-ring sealing area. There are many ways to determine failure in a material under triaxial load, but one of the most popular and time-honored techniques uses the distortion-energy theory. Under this theory, it is the differences between the triaxial stresses that cause distortion of a metal and subsequent failure. A combined quantity known as the Von Mises stress, σ', is derived that is dependent on these differences in the triaxial stresses:

$$\sigma' = [(\sigma_t - \sigma_r)^2 - (\sigma_r - \sigma_a)^2 - (\sigma_a - \sigma_t)^2]^{1/2} \quad . \quad \text{...........................(4)}$$

This quantity is then compared with the yield strength to determine when failure of the material is likely [2]. Thus a cube of solid metal surrounded on all six sides by the same pressure will not fail because $\sigma_1 = \sigma_2 = \sigma_3 = p$, and the Von Mises stress is zero. The tensile yield strength of the 17-4 PH precipitation hardening stainless steel (Condition H 1150) specified for the pressure barrel is 150 kpsi according to one source (AK Steel [3]) and 126 kpsi according to another source (Carpenter [4]). No compressive yield strength data has been found, but the compressive yield strength is similar to the tensile yield strength in most ductile materials.

The change in pressure barrel diameter due to borehole pressure at any radial position in the cross-section can be calculated by noting the relationship between stress and strain in a triaxial stress state [5]. In the tangential direction,

$$\varepsilon_t = \sigma_t / E - \mu\, \sigma_r / E - \mu\, \sigma_a / E \quad , \quad \text{....................................(5)}$$

where

ε_t = strain in tangential direction
E = elastic modulus = 28,600,000 psi for 17-4 PH [4]
μ = Poisson's ratio = 0.272 for 17-4 PH [4].

By definition, the tangential strain is simply the fractional change in circumference at a given radial position due to the borehole pressure:

$$\varepsilon_t = [2\pi (r + \delta) - 2\pi r] / [2\pi r] = \delta/r = \Delta d/2r \;, \quad \text{......................(6)}$$

where

δ = change in radius = ½ Δd
Δd = change in diameter at a given radial position in the pressure barrel c.s.

Combining Eqs. 5 and 6 produces the result

$$\Delta d = (2\, r / E)[\, \sigma_t - \mu\, \sigma_r - \mu\, \sigma_a] \;. \quad \text{..................................(7)}$$

This allows us to estimate the inward deflection of the pressure barrel at a given borehole pressure.

Results

The above equations were programmed into a spreadsheet, and the results are shown in Figure 1 for a wellbore pressure of 10,000 psi. Shown here are compressive stresses (plotted as positive values rather than the negative values predicted by the equations). Note that the tangential stresses are highest near the ID of the pressure barrel, radial stresses are highest near the OD, and axial stresses are constant over the cross-section. The resulting Von Mises stresses are highest at the ID, where the differences between the various triaxial stresses are at their greatest (see Eq. 4).

The maximum Von Mises stresses reach about 64,000 psi under a borehole pressure of 10,000 psi. Compared with a yield strength of 150,000 psi, the pressure barrel thereby operates with a safety factor of about 150/64 = 2.3 at 10,000 psi. This means that the pressure barrel as designed should fail at about 23,000 psi borehole pressure.

The effects of increasing the outer diameter of the pressure barrel while maintaining the same inner diameter are shown in Figure 2. Shown here are the maximum Von Mises stresses, which occur at the inner diameter of the pressure barrel, as a function of borehole pressure and pressure barrel OD. The 150 kpsi yield strength of the material is shown for comparison. Based on these results, the various pressure barrel OD's can operate to the following borehole pressures:

Pressure Barrel OD, inches	*Maximum Borehole Pressure, psi*
1.750	23,350
1.875	28,200
2.000	32,200

2.250	38,300
2.375	40,650

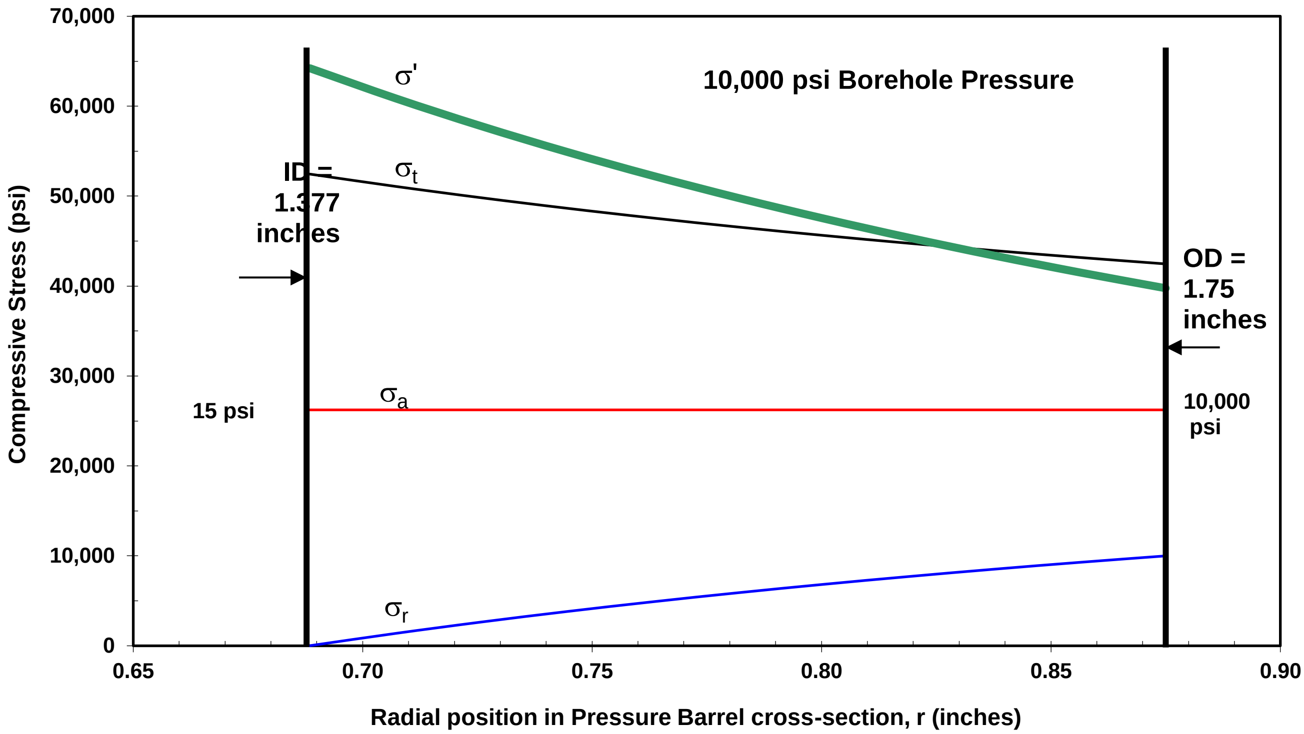


Figure 1 – Tangential, radial, axial, and Von Mises stresses in pressure barrel cross-section at 10,000 psi borehole pressure.

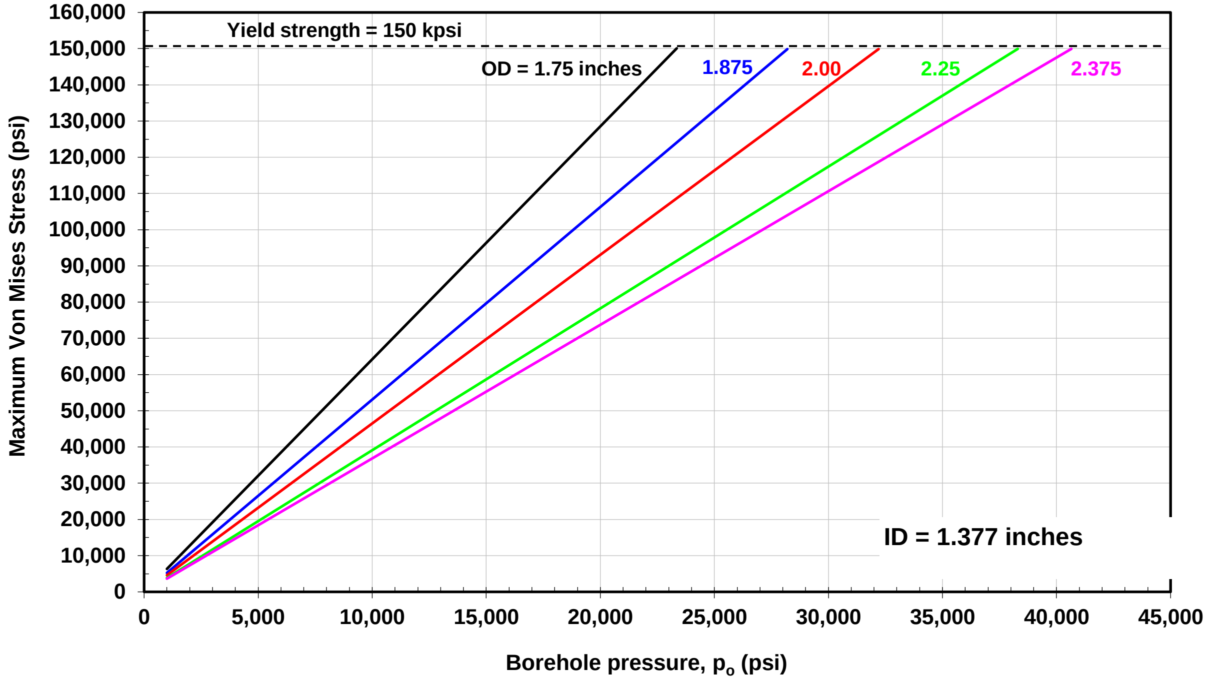


Figure 2 – Maximum Von Mises stress at pressure barrel ID for various outer diameters.

These calculations do not rely on any support for the pressure barrel from the bulkheads that fit inside the barrel in the o-ring seal area. This is because the reduction in ID at the maximum borehole pressure is calculated from Eq. 7 to be about 0.005 inches, which is on the order of the diameteral clearance between the bulkhead and the pressure barrel that is specified by the o-ring design. Thus, by the time the pressure barrel shrinks tightly around the bulkhead, where it could get support from it, the pressure barrel has already become permanently deformed. The support obtained from the o-ring is substantial but fairly localized, and the point loading may concentrate stresses there as much as the support reduces them.

References

1. Shigley, J.E., Mechanical Engineering Design, p. 75, 2nd Edition, McGraw-Hill Book Co., 1972.

2. Shigley, J.E., Mechanical Engineering Design, p. 235, 2nd Edition, McGraw-Hill Book Co., 1972.

3. Matweb.com data sheet provided by AK Steel for 17-4 PH Precipitation Hardening Stainless Steel, Condition H 1150.

4. Matweb.com data sheet provided by Carpenter Technology Corp. for Custom 630 (17-Cr-4Ni) Precipitation Hardening Stainless Steel, Condition H 1150 (Heated 621°C).

5. Shigley, J.E., Mechanical Engineering Design, p. 77, 2nd Edition, McGraw-Hill Book Co., 1972.

Appendix E

NEW RECHARGEABLE BATTERY FOR APPLICATION IN A WIDE TEMPERATURE RANGE

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Abstract

At this time there is no rechargeable battery available which can deliver required currents in a wide operating temperature range, such as from ambient or low temperature to higher temperatures (e.g. 150^{o}C). In this paper a CC size rechargeable Li-ion molten salt battery which can operate in the temperature range from room temperature to 130^{o}C is presented. The cell has open circuit voltage of 2.3V for fully charged cell. It exhibits high coulombic efficiency. The cell can operate at low currents as well as at high currents; however, at very high currents coulombic efficiency decreases. It can operate at temperatures greater than 130^{o}C but its cycle life is shorter. The battery demonstrates very good safety features. Short-circuiting, overcharge, deep discharge, or reverse charge does not result in violent reaction. These properties make this cell a very good candidate for application in drilling and logging industry. In addition, these cells could help in extending the drilling capabilities of tools.

Introduction

The measurement equipment used in down-hole drilling application is powered by wireline (electric line connected to the surface). However, new drilling methods employing Measuring While Drilling (MWD) and Logging While Drilling (LWD) technologies can not be powered from the surface; instead power is provided by an autonomous power source, for example, battery.

Most electronics in down-hole equipment (MWD, LWD) are used at moderate temperature powered mainly by primary lithium batteries [1,2]. These batteries have high voltage, high energy density, and good shelf life. However, safety is an important consideration. If the cells are operated at high rates of discharge or if short-circuited they can develop high internal temperature which can cause venting or thermal runaway reactions. Therefore these cells are equipped with an internal fuse to prevent overheating. Deep discharge can force the cell into voltage reversal which in some lithium cells can result in venting or even in cell rupture.

There are no rechargeable batteries which can be operated in down-hole drilling applications in a wide temperature range for extended period of time. Most of the present rechargeable batteries, for example, lithium-ion rechargeable batteries will not operate in a wide temperature range; they operate at temperatures less than 60^{o}C. If they operate at higher temperatures there are safety considerations such as possible fire and burn hazards. Further, they should not be short circuited, crushed or heated above 125^{o}C. At higher temperatures these cells are unstable and operation at high temperature eventually would lead to thermal runaway reactions which will incapacitate or even rupture the cell.

This paper presents a rechargeable cell that would meet most of requirements for operation in down hole environment at higher temperatures. It is a molten salt battery where the electrolyte is made from a low temperature molten salt. It can operate at low temperature (room temperature) and at high temperature (130°C). Further, this battery is much safer than any presently used battery operating in the mentioned temperature range. The improved safety of the molten salt battery is partially due to the better safety that is intrinsic to a low temperature molten salt electrolyte. The molten salt is a liquid in a wide temperature range; it has negligible vapor pressure, high conductivity, and does not sustain fire. Therefore for these batteries, high temperature or overheating (up to 200°C) is not a concern because the heat will not significantly increase the internal pressure, and, consequently, will not cause the cell to burst. In addition, high currents (including short circuiting) will not increase internal pressure; thus it will not cause the cell to vent or burst.

Main features of battery:

CC size

Dimensions: 2.5cm(1.0inch) diameter 10.2cm(4.0inch) length

Cell voltage(OCV); 2.3V

Cell capacity : 2Ah

Operating temperature: RT to 130°C

CC cells exhibited energy density of 103Wh/L. The cells had been successfully tested for down hole drilling application [3].

EXPERIMENTAL

Cell construction

Figure 1 shows an image of a CC molten salt cell. The cell consists of a stainless steel case containing an anode separated from the cathode by a separator. The electrodes are in the form of a foil rolled together with the separator into a coil impregnated by the molten salt electrolyte. The cell is hermetically closed by a seal consisting of a metal cap welded to the case. The cap has centrally located metal button which serves as a positive terminal of the cell. Cell case is negative terminal. Metal button and the cap are sealed with a glass, forming hermetical glass to metal seal. Cells were assembled in an inert atmosphere.

Figure 1 Image of CC size molten salt cell

The cell is a lithium-ion system where both electrodes are made of lithiated materials [4]. The electrodes were made by coating a slurry of electrode materials on metal foil using standard coating technology employed for lithium ion battery production. Electrolyte consisted of the low temperature molten salt. The molten salt is made of ions and serves both as a solvent and an electrolyte.

All charging/discharging measurements were performed using multichannel MACCOR automatic battery test system.

Results

Charge/discharge performance

Figure 2 represents typical charge/ discharge curves at 125°C for CC cell at 150mA. Cut off voltage was set at 2.5V for charging and 2.0V for discharging.

Figure 3 gives several charge/discharge cycles for 2Ah CC cell at 140 °C.

Figure 2 indicates flat charge/discharge curves as well as high coulombic efficiency.

Figure 3 demonstrates that the cell can be cycled at high current (500mA) and that cell resistances for charging and discharging are very close in value.

Figures 4 and 5 give discharge curves at 100°C and 125°C respectively, for currents 220mA, 440mA, 733mA and 1100mA. Both figures demonstrate that discharged capacity decreases with an increase in current. However, discharged capacity at 125°C is much higher for the same current than at 100°C. Further, cell capacity at 125°C is equal for currents of 220mA and 440mA. It also shows that even at ~C/3 rate the cell delivers >95% of the capacity.

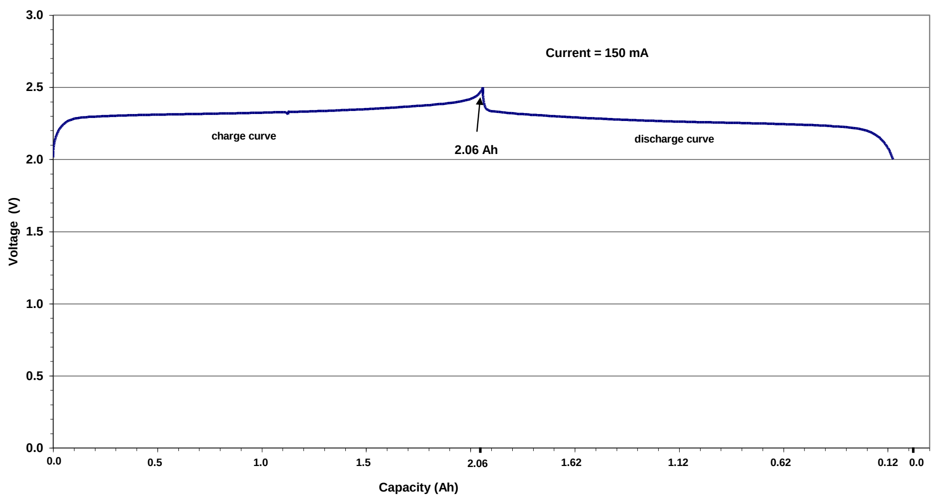

Figure 2 Charge/discharge curves for CC cell at 125°C

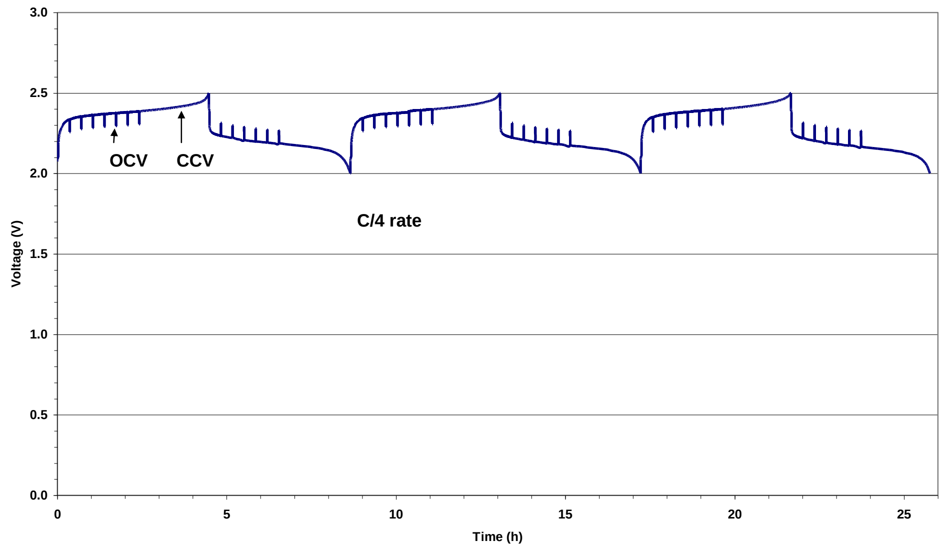

Figure 3 Cycling of CC cell at 140 °C

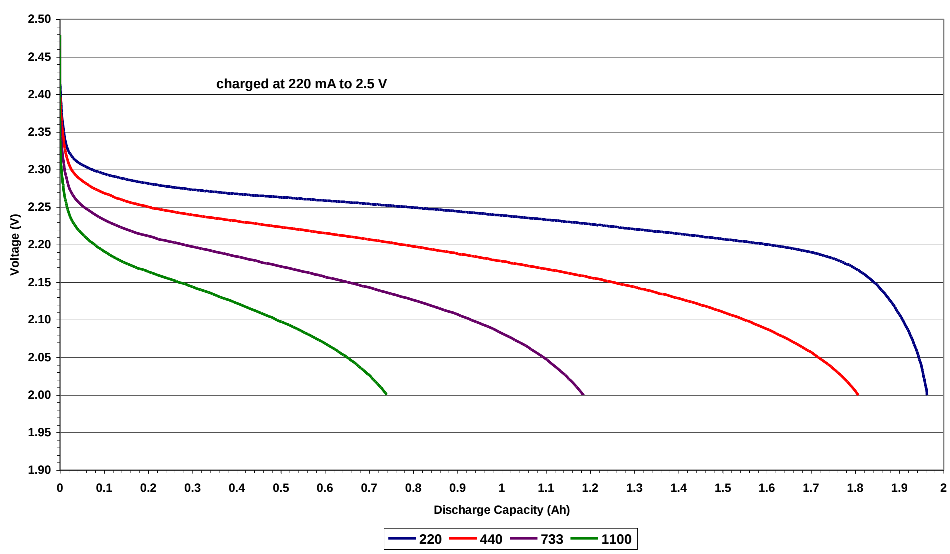

Figure 4 Discharge curves for CC cell at 100°C at four different currents. Current in mA.

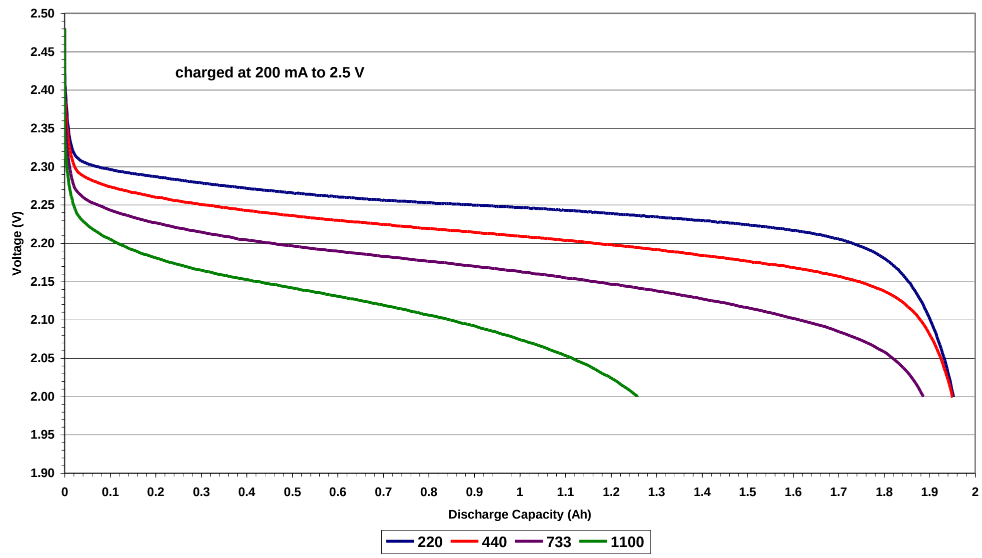

Figure 5 Discharge curves for CC cell at 125°C for four different currents. Current in mA.

Figure 6 shows charge/discharge capacity and coulombic efficiency depending on cycle number at 95 °C and current of 250mA. From this figure it is obvious that capacity is very stable and does not change much with cycling and that coulombic efficiency is very high.

Table 1

Coulombic efficiency depending on temperature

at different currents

Temperature [°C]	Current [mA]	Coulombic efficiency [Ah_{dc}/Ah_{ch}]
25	130	>0.99
70	250	>0.99
100	250	0.99
120	250	0.97
130	250	0.94
140	250	0.92
150	500	0.91
160	500	0.90

Results in Table 1 demonstrate that coulombic efficiency is greater than 97% for the temperature range from 25°C to 120°C. However, at higher temperatures (above 120°C) coulombic efficiency decreases due to self-discharge as well as to other effects, for example, instability of electrolyte and electrodes.

Figure 7 presents dependence of discharge capacity on temperature.

From Figure 7 it is clear that discharged cell capacity increases with an increase in temperature, however, in the range of temperatures from 90°C to 120°C it is stable and unchanged at around 2.1Ah. Then at temperatures greater than 120°C the capacity decreases very fast; thus at 160°C it drops to 1.25Ah. These results indicate that the molten salt cell can operate even at very high temperatures but with a loss in capacity and at lower coulombic efficiency.

Self-discharge

Preliminary self-discharge testing showed that 50% capacity loss of the CC cell took 12 months at 70°C, 37 days at 90°C , and 24 days at 120°C.

Cycle lifetime

Cell delivered 120 full charge/discharge cycles retaining 80% capacity at 120°C.

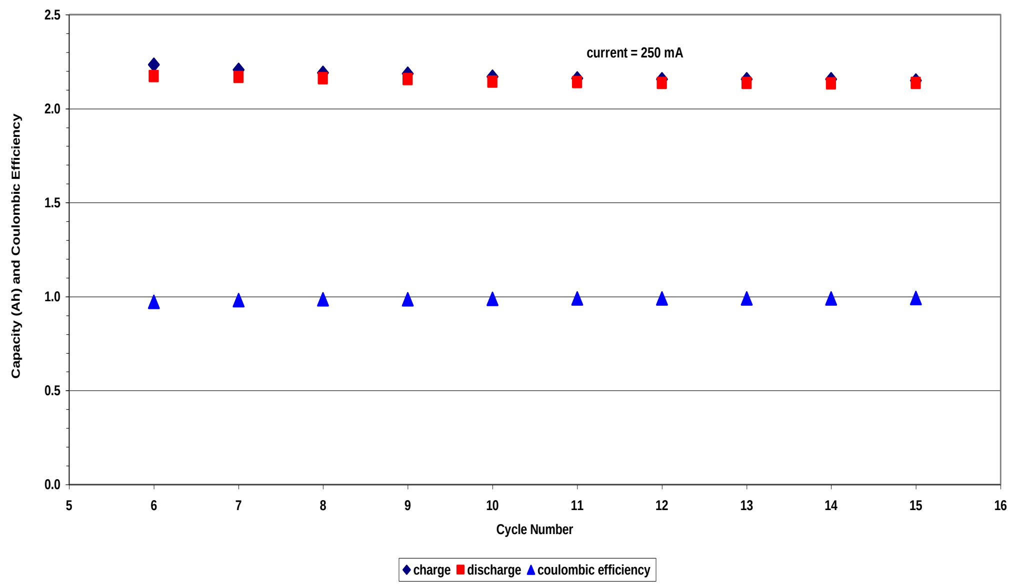

Figure 6 Dependence of charge/discharge capacity and coulombic efficiency on number of cycles at 95°C at 250 mA

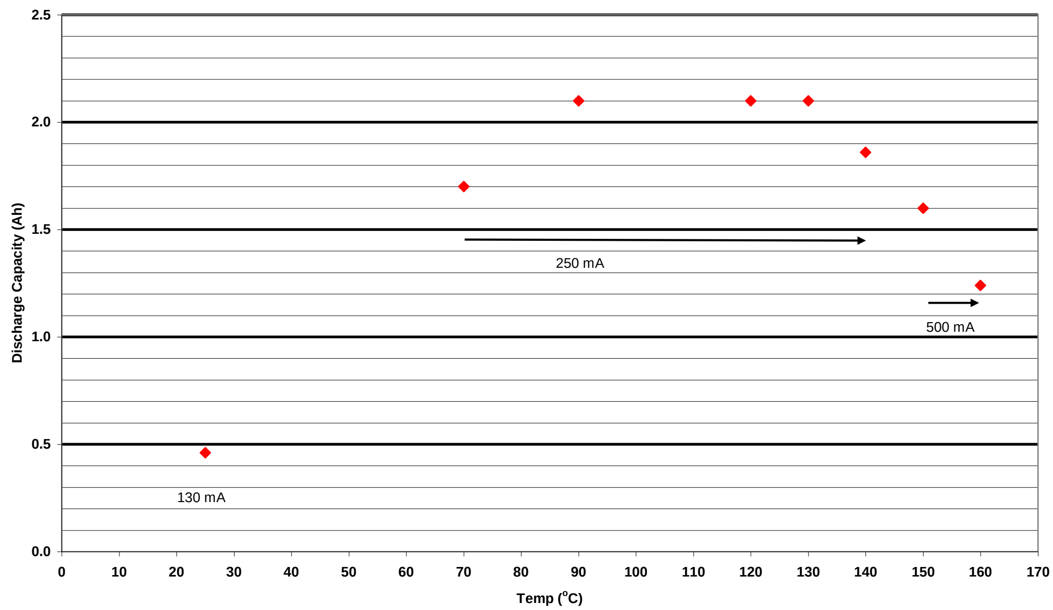

Figure 7 Dependence of average discharge capacity on temperature for three different currents. Average of first 5 cycles; charge/discharge cut off limits 2.5V/2.0V.

OTHER FEATURES

One of the big advantages of the molten salt rechargeable cell is safety which was mentioned earlier. In addition, it should be added that short-circuiting the cell did not cause any danger either to the battery or to the environment. Overcharging, reverse charging, heating to very high temperature did not cause venting, bursting or any other dangerous or hazardous behavior.

The batteries do not require special storage or special handling during transportation.

Vibrations and shocks did not affect the operation of the molten salt cells.

Molten salt batteries can be charged at constant current, or at constant voltage or by combining both methods.

Rechargeable molten salt cell can be a very good replacement for primary lithium batteries. This cell can deliver high current as well as a primary battery; however, their capacity is lower than for primary lithium cells. This is their disadvantage when compared to the lithium primary batteries.

CONCLUSION

Rechargeable molten salt batteries possess several advantages for application in down-hole drilling. These cells can operate safely in a wide temperature range from room temperature to 130°C and can deliver low and high currents in this entire temperature range. Their high coulombic efficiency and good cycle life except for very high temperatures (>130°C) are very important properties which increase operational capabilities for drilling applications. Having an option to recharge batteries down-hole could bring new flexibility and allow new methods of drilling. Vibrations and shocks do not affect battery operation and do not cause dangereous behavior such as venting, bursting, explosions. Storage and transportation of batteries do not need special procedure. Application of rechargeable batteries may turn out to be more economical than the use of primary batteries once the initial psychological barrier of changing the way of using batteries and deciding to develop new equipment and methods of employing the batteries. However, it may not be possible to use them in every single intended application. Further, improvement of properties such as stability at high temperature and self-discharge can open up a wide field for application of molten salt batteries in down-hole drilling.

References

[1] Jean-Paul Gabano, "Lithium Batteries", Academic Press, London, Chapter 12-14, pp.281-403, 1983.

[2] David Linden, Thomas B. Reddy, "Handbook of Batteries", McGraw-Hill Publishers, third edition, New York, Chapter 14, pp.14.9-14.53, 2002.

[3] M.Fripp, D. Kyle, S. Hamid, D. Moore, J.Caja and T.D. Dunstan,"Development of a High Temperature Rechargeable Battery for Downhole Use in the Petroleum Industry", Proceedings of the 2008 Offshore Technology Conference (OTC), Houston, Texas,Paper No.OTC 19621, May 5-8, 2008.

[4] T.D.J. Dunstan and J. Caja,"Lithium-ion cell with a wide operating temperature range", U.S.Patent 7,582,380, September 1, 2009.

Appendix F

PROJECT REPORT 300°C CLOCK

GRANT: DE-FG36-08GO18185

PROJECT TITLE: WELL MONITORING SYSTEMS FOR EGS
AWARDEE: PERMA WORKS, LLC

SUB-AWARDEE: FREQUENCY MANAGEMENT INTERNATIONAL

KOUROS SARIRI

"A Rugged, Durable, Stable, High Temperature, Compact, Low-Power Crystal Clock Oscillator for Geothermal, Down-hole & other High Temperature/Hi-Rel Applications"

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HTXO FABRICATION DEVELOPMENT ROADMAP

The generalized development process of the HTXO took the following steps from the project onset to the completion

a- Evaluation of the initial design configuration details
b- Fabrication of the initial model followed by electrical testing
c- Incremental thermal stress testing steps to reach and identify new failure mode
d- Identification of the new root cause of failure mechanism
e- Design modification to resolve and mitigate the identified failure mode
f- Fabricate new and improved design configuration and go to step b
g- Continue until the life test objectives have been met
h- Extend the evaluation process to identify new performance milestone or new sources of failure even though outside the scope of the project (if project schedule permits)

DESIGN ELEMENTS

PACKAGE

As originally proposed, FMI focused its effort in developing the HTXO solution in the standard 8 pin DIP package with the dimensions of 0.505x0.505 inch and 4 corner pins as shown in the figure below.

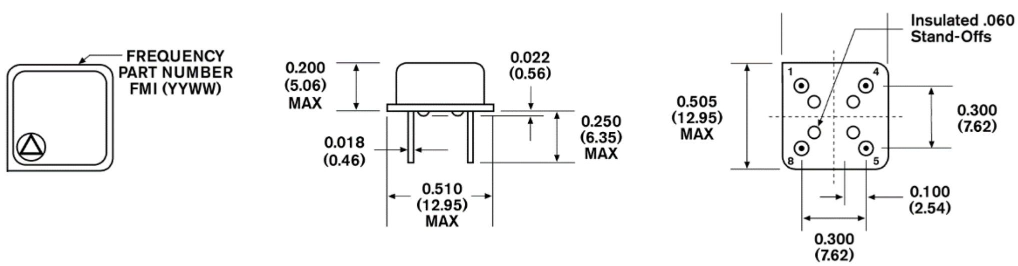


FIG 1A - 8 pin DIP for HTXO [mm /inch]

The internal configuration of the package would provide degrees of freedom to accept and adapt to the variation of substrates, circuit diagrams and resonator mounting schemes while and at the same time it facilitates the external I/O connections. The common elements of the clock oscillator circuit is shown in the FIG1B.

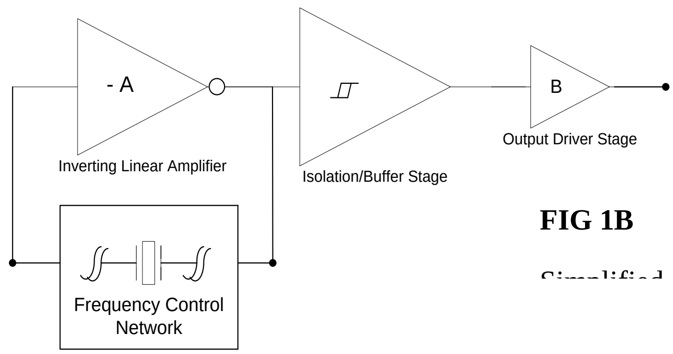


FIG 1B

Simplified oscillator Diagram

MICROCIRCUIT AND CRYSTAL DRIVER

The initial (starting) configuration was established based on a complete evaluation of the oscillator design families that had been developed by FMI prior to the start of this project. The candidate configurations all have three main elements such as a piezoelectric crystal resonator, electronic circuit and the interconnect system based on a substrate.

Incremental reporting was done throughout the effort on the project and all such reports are summarized as follows:

STATUS REPORT 1

Completed tasks

1- Two types of substrates have designed and fabricated for 300°C operation. Each substrate type is configured for a particular assembly process (both for crystal only devices and for crystal oscillators) when integrated with the rest of the components. Substrates were made to result in packaged devices that could be only a crystal resonator or complete clock oscillator.

2- Crystal support

Crystal support (mounts) were designed and fabricated to be used in the assembly of devices and for the substrates described above in the proposed DIP-8 hermetically sealed package.

3- Packaged crystals (in DIP-8) were made for the purpose of environmental stress. The assembly configurations were optimized progressively with newer versions of the crystal assemblies.

4- Initial Experimental Life Test & Comparison

Life test was conducted on packaged clock oscillators and packaged crystals using the substrates (above) to establish a reference point for both 250°C and 300°C operation over the long term.

In this case the same package configuration and crystal support scheme was used for both types of assemblies. Also in both cases the same assembly processes, epoxy material and curing schedule and was used to integrate the crystal resonator with the rest of the circuit.

The piezoelectric crystal configuration was the same used in the packaged clock oscillator assembly and the packaged crystal assembly. In both cases 8 pin DIP style package was used.

The various elements of the material and the differences between the two types are shown in the table below.

Item	**Packaged Crystal**	**Packaged Clock Oscillator**
Header, Half DIP	YES, Same	YES, Same
Cover, Half DIP	YES, Same	YES, Same
Substrate	YES, Same	YES, Same
Crystal Mount Supports	YES, Same	YES, Same
Piezoelectric Resonator	YES, Same	YES, Same
IC	NO	YES
Capacitor	NO	YES

Tests were conducted over a few weeks while packaged crystal functionality and packaged clock oscillator functionality was monitored frequently during the parts temperature exposure. Test setup was modified to allow conducting such tests up to the upper limit of the oven temperature and its controller. This test was conducted despite the fact that the IC wire bond pad surface and the interconnect configuration need to be further optimized for the 300C operation. Detailed performance measurements were conducted

Based on the observations, packaged clock oscillators would be modified and fabricated and the tests will be repeated. At the same time, collaborative effort is in process to determine the possibility to modify the bonding pad metallization of the active device in order to increase the interconnect reliability for long operating life at +300°C.

STATUS REPORT 2

This report focuses on the status of high temperature oscillator configuration development, testing and evaluation of the results using high temperature active circuit configuration.

Oscillators were manufactured using two separate types of packages. In one case, a half DIP package (as originally proposed) was used. In the other case, a ceramic surface mount package was used. In all cases the resonator driver circuit was the same. The half DIP package used a ceramic substrate while the ceramic package includes its own conductor layer.

The first round attempt at +250ºC pointed to premature device failure after multiple attempts. This was not expected based on the understanding that the high temperature resonator driver performance specifications indicated operational confidence at temperature close to what we had tried. Repeat of the test on separate parts at +240ºC in the ceramic package resulted in much operating life than the half DIP version equivalent. To make sure that there was no other contributing factors uncounted, the same test was repeated one more time on new half DIP oscillators and the same observation was made.

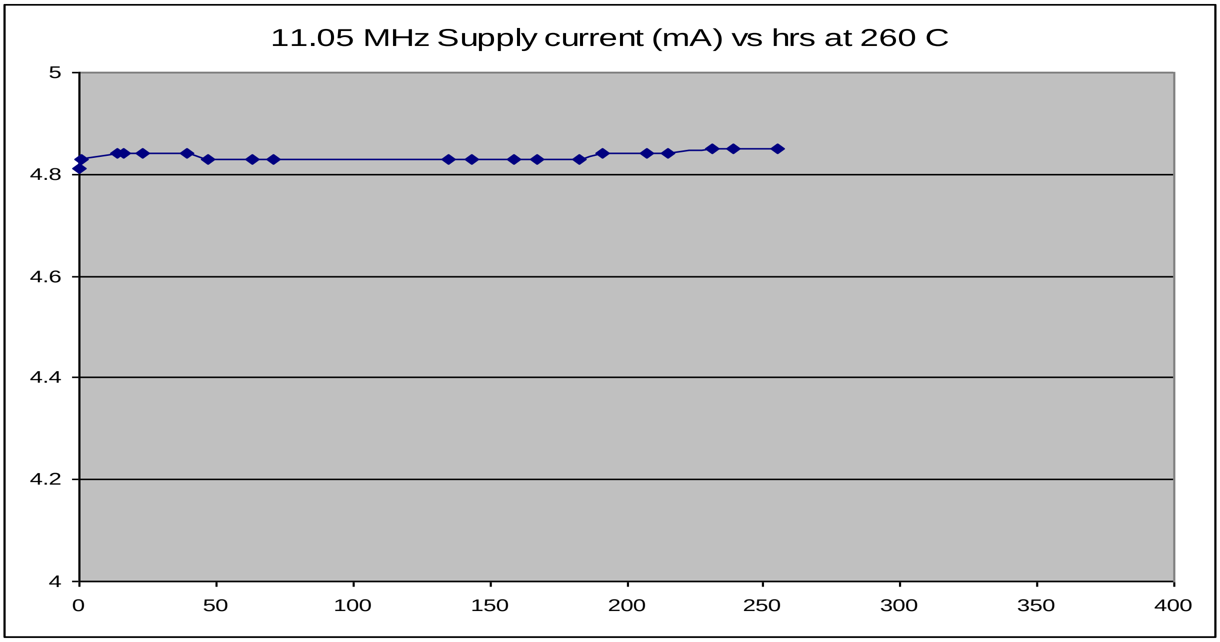
It should be noted that prior (FMI internal) developments for oscillator configuration at +210ºC indicated no performance degradation with life test extending beyond 2000 hours. The conclusions point to a combination of circuit layout considerations and the distributed and/or parasitic capacitance influencing the long term performance of the resonator driver circuit.

At this point we have the following performance milestones established:

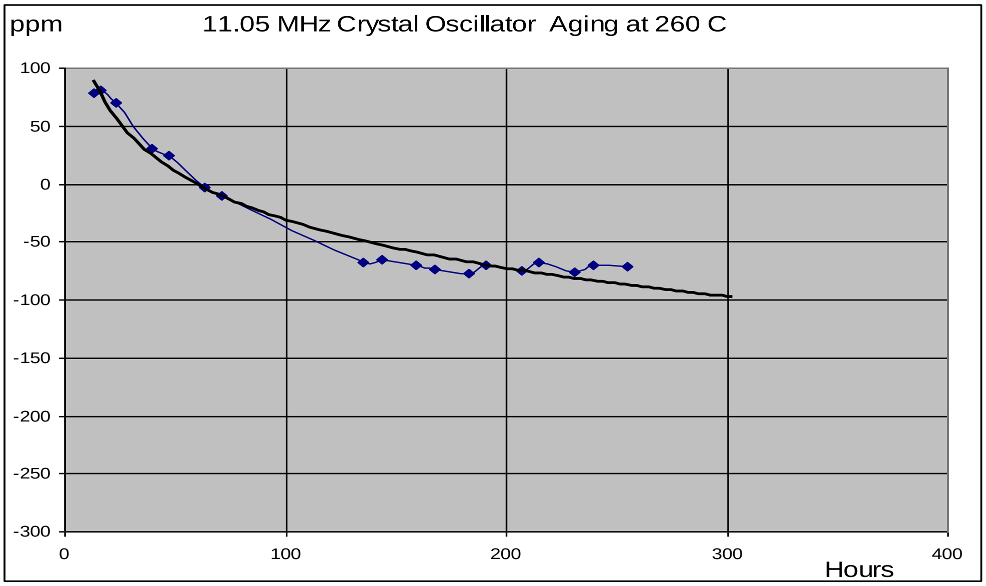
1- Reliability of the component attachment scheme using the appropriate epoxies for temperatures exceeding +275ºC
2- Reliability of the wire-bond connections between the various parts of the circuit and substrate for steady operation at temperatures > +275ºC
3- Fully compliant and robust electromechanical support of the crystal resonator unit used in the oscillator circuit configuration

The next step was to produce a new circuit layout and configuration that used modified circuit to drive the resonator and to specifically address the failure we had observed during the previous tests. One such part was manufactured and tested at +260ºC.

The test was continued to make more observations while it already has successfully surpassed any configuration of the half Dip that has been tried so far. The graphs below exhibit the supply current performance over hours of operation at +260ºC



With the hybrid crystal oscillator configuration established, it is also necessary to investigate the long term effects of high temperature exposure with respect to frequency drift or aging. The graph below is a first attempt to establish a pattern for aging over the same period of test.



Note that the aging pattern of the oscillator follows the expected logarithmic behavior over the operating life period and points to settling of the frequency within approximately 400 hours of operation. This has been the first such measurement and based on the specifics of the crystal metallization configuration. Our objective is to improve the performance and thus reduce the long term drift by a factor of 2 at the same temperature.

STATUS REPORT 3 & 4

As a quick update to the last status report where we had submitted the successful test results of our working crystal oscillator unit at +275ºC. The same test was continued for further data collection and accumulation of more operating hours at the high temperature as shown in the figure-1 below.

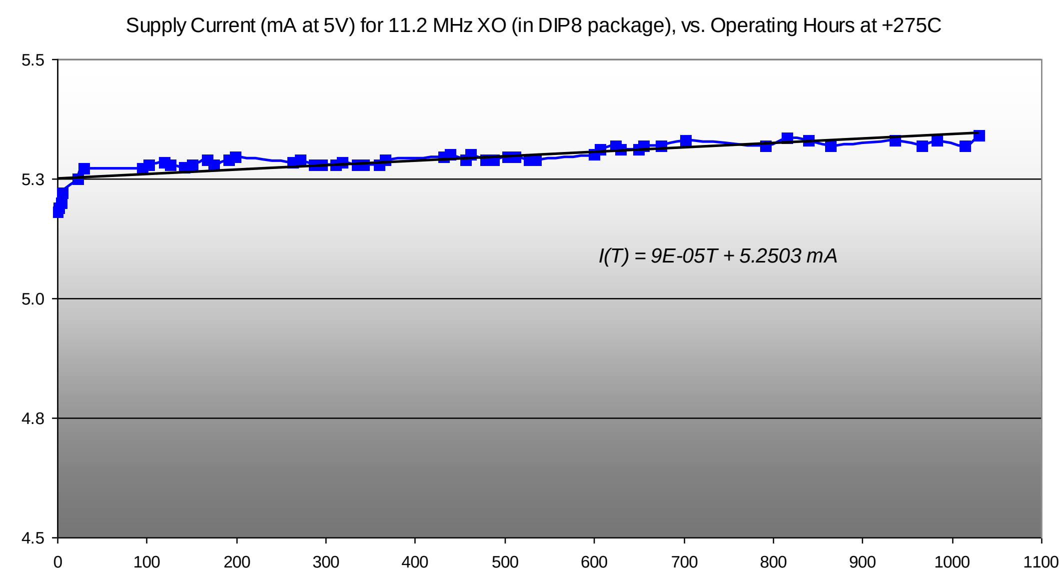


Figure-1

The described test was terminated upon completing more than 1000 hours at +275ºC. This was the best record achieved for the specific configuration. It is noteworthy to mention that the slight positive slope of the supply current vs. time could be a due to a combination of factors that impact the device performance. The high temperature migration effects on the crystal driver circuit could also contribute to the positive. We further observed the behavior of other electrical parameters such as the minimum starting voltage and change of frequency vs. power supply variation to additionally confirm the robustness of the circuit and assembly (see Figure-2)

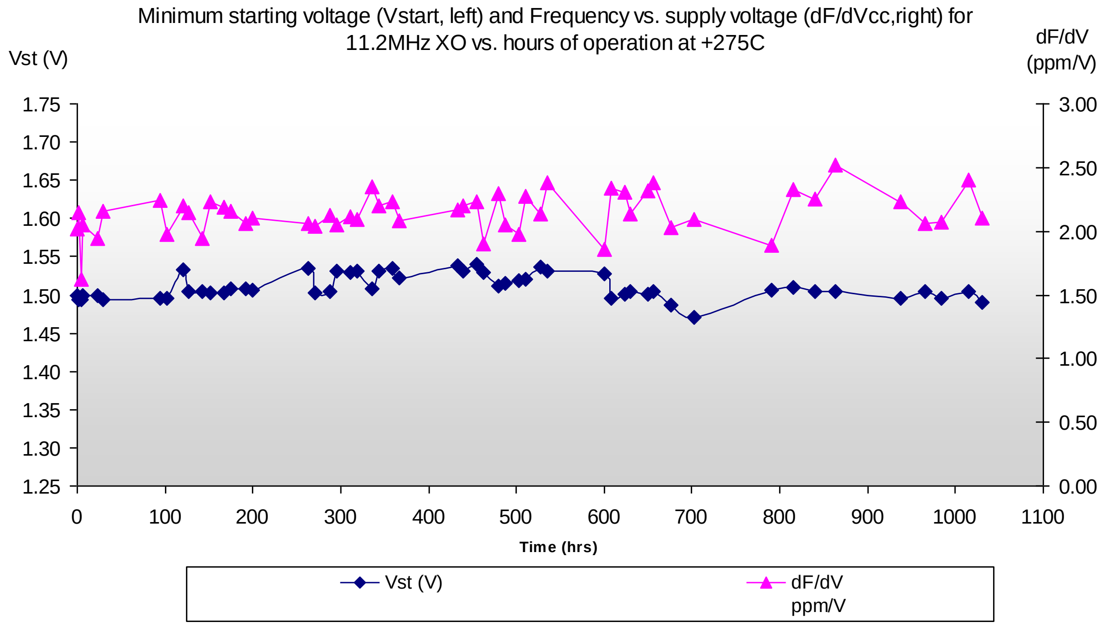


Figure-2 Minimum starting voltage variation & frequency vs. power supply variation during the +275ºC life test

The performance results guided us to review all aspects of the manufacturing process, component selection as well as the interconnect system one more time. This process helped to establish the desired configuration that would target the final goal of the project and to meet the performance expectations at the temperature of +300ºC. Although there is no specific frequency drift target limit in this effort, it is still a valuable piece of performance information that could point to further circuit and material selection and optimization.

We modified the components and configurations upon completion of the review process and other related tests with the focused goal of achieving the target performance of at least 100 hours at +300ºC. The new circuit configuration and layout was prepared and the required material was planned in order to fabricate the new crystal oscillator assemblies. We produced a few of such assemblies.

In the course of performing the life test at +275 ºC, we also observed certain wear and tear in the utilized test apparatus. We took measures to modify the various fixtures and adaptors in order to prevent premature test apparatus failure while performing life test at +300ºC. Additional thermal fail/safe has been added to the oven in order to prevent any uncontrolled (runaway) thermal transition and other possible related safety concerns. All said provisions were implemented in order to start the +300ºC life test.

POWER-UP AND INITIAL TEST OF CRYSTAL CONTROLLED OSCILLATOR AT +300ºC

The test preparation for +300ºC part started from the careful layout of the test apparatus to the selection of instruments to be available for the duration of the test while having the necessary safety related precautionary measures.

Device under test was carefully and incrementally tested from room temperature to +300ºC to make sure the main performance parameters over the thermal gradient are recorded and to identify if the behavior of the unit would be outside the expected pattern. The graph shown in Figure-3 depicts both 3.3V and 5V supply current over the temperature range although the target operating voltage is 5V.

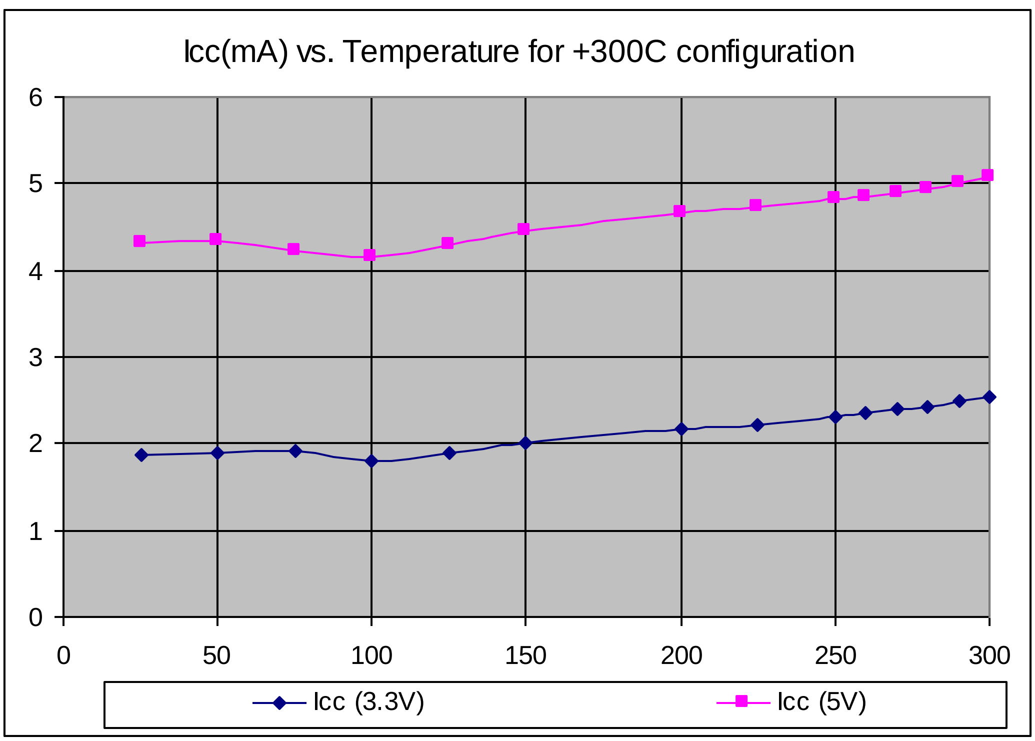


Figure-3 Supply current vs. operating temperature for +300ºC configuration

LIFE TEST FOR CRYSTAL CONTROLLED OSCILLATOR TEST AT +300ºC

Once the operating temperature reached +300ºC, the temperature chamber was stabilized and the soak time initiated. Test data was taken more frequently at the starting phase of the test. Data collection periodic increments increased as the device operation reflected the expected stability in its performance with accumulated high temperature exposure time.

A number of parameters were measured with the intent of fully characterizing the behavioral performance of the new design configuration at the extreme high temperature. Each parameter reflect a certain aspect of the device performance that range from functional performance to interfacing hypothetical external load. In the sections that follow we cover the test results on the relevant parameters throughout the life test.

OUTPUT WAVEFORM

One particular parameter that is specific to the output characteristics of the crystal controlled clock oscillator is the duty cycle that indicates the percentage ratio of output logic "1" portion of the output waveform as compared to the full one cycle period. The acceptable range of output duty cycle would be anywhere from 40 to 60 %. Figure-5 illustrates the stability of the output waveform duty cycle (at 5V) over the span of the life test at +300ºC with the vertical scale also showing the acceptable limits of 40 to 60%.

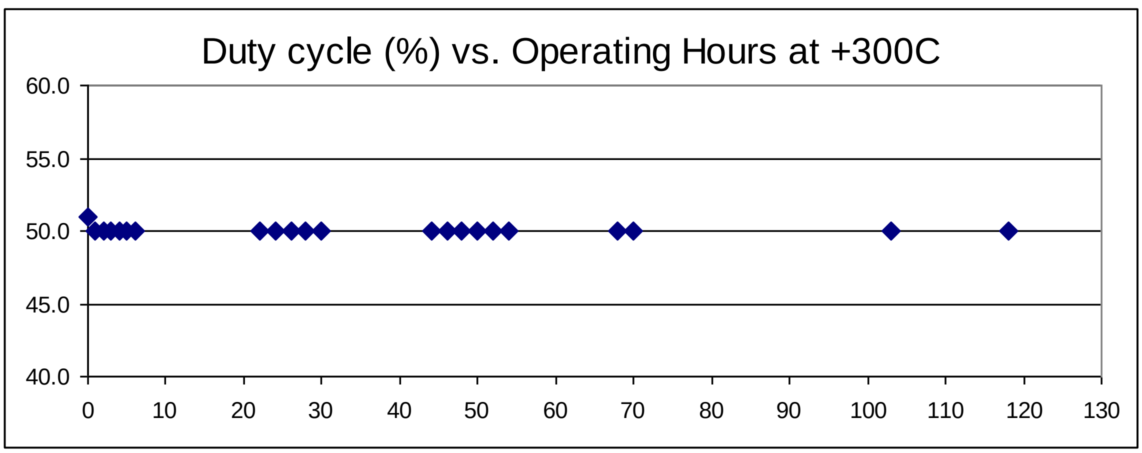


Figure-5 Output Duty Cycle (5V operation)

CRYSTAL OSCILLATOR DYNAMIC PERFORMANCE TEST

Our objective from the inception of this project has been to develop the crystal oscillator to be a real viable component for demanding and commercially viable applications. Standard operating voltages and output logic levels are major performance attributes of a compelling product. Although +5V performance is the main project objective, we have at the same time addressed operation of the device at 3.3V. Note that nominally the highest operating frequencies at 3.3V would be lower than that at 5V.

In order to check the dynamic range of the device operation, we have tested and monitored the minimum operating voltage of the device throughout the life test as shown in Figure-6. to see if the design will maintain a healthy operating voltage margin with respect to either standard operating voltages (5V and 3.3V). A linear approximation is added to further indicate the long term small but positive slope.

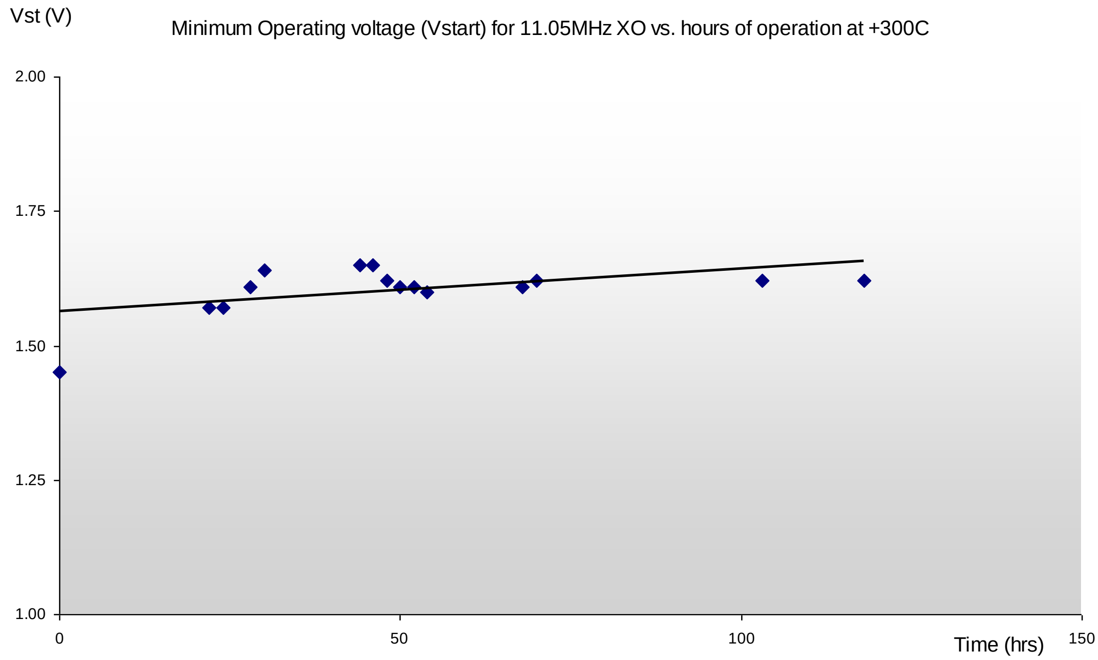


Figure- 6 Minimum Operating voltage as a function of operating hours at +300ºC

LONG TERM FREQUENCY DRIFT:

As a general aging pattern for crystal oscillators and based on empirical examples at lower temperatures, we would expect the frequency drift to eventually diminish over some time as all the elements of the circuit will reach equilibrium at the operating temperature. Although not part of the technical objectives, long term drift for the designed configuration was measured along with other parameters as explained before at +300ºC. Typical drift measurement is done at the zero slope temperature (of the frequency vs. temperature curve). However, in measuring the drift we just did it at the same time as the life test and at the same temperature of +300ºC (instead of running separate tests). The drawback of this decision would be the introduction of frequency vs. temperature error since the frequency vs. temperature slope would be in the +40ppm/ºC range at the extreme end and slight error in the accuracy of the temperature could make a large difference in frequency. In any case the long term drift test data should reflect the diminishing nature of the change over the longer term exposure. Figure-7 illustrates the long term frequency drift that we have measured plus the logarithmic best fit curve. It shows that the frequency drift has approached the much smaller slope zone within 20 to 30 hours of the start of the life test at +300ºC compared to about 100 hours that it took on the previous test at +275ºC to reach the same relative point. Note that the crystal electrode material can be reconfigured to significantly improve the net magnitude of the long term frequency drift at the high temperatures. This has already been established based on our prior development of packaged piezoelectric crystals for +500ºC operation.

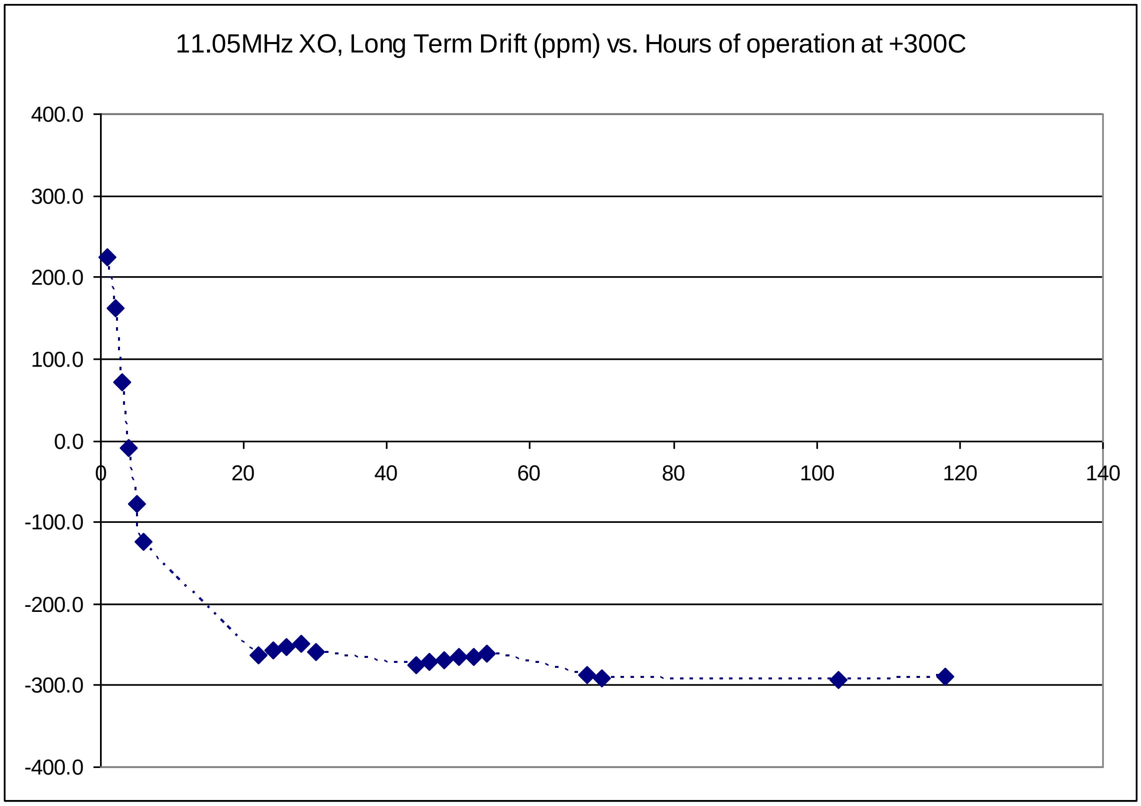


Figure- 7 Long term frequency drift due to exposure to +300ºC

SUPPLY CURRENT PERFORMANCE AT +300ºC

The supply current has been used as the main indicator for device reliability and performance as well as a leading indicator for possible failure. Supply current is measured at the defined operating voltage and without external load (although test fixture presents a load while under test). From the project start a nominal tolerance limit of ±10% (of the initial value) has been observed with respect to the supply current measurements to define the acceptance range. For example, at 5V operation and with the initial reading of 5mA, the acceptable range of supply current would be from 4.5mA to 5.5mA as measured on the unit under test is depicted in Figure-8.

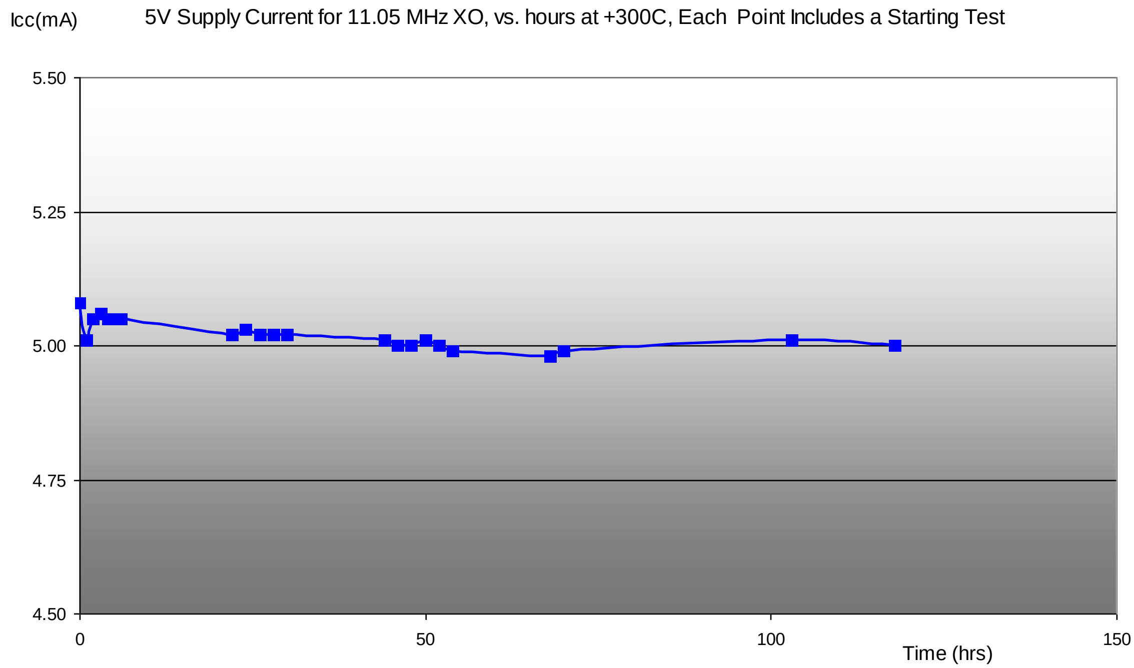


Figure-8 Supply current (at 5V) vs. operating hours at +300ºC

The supply current behavior at 3.3V is shown in Figure-9 with a linear approximation added to the graph.

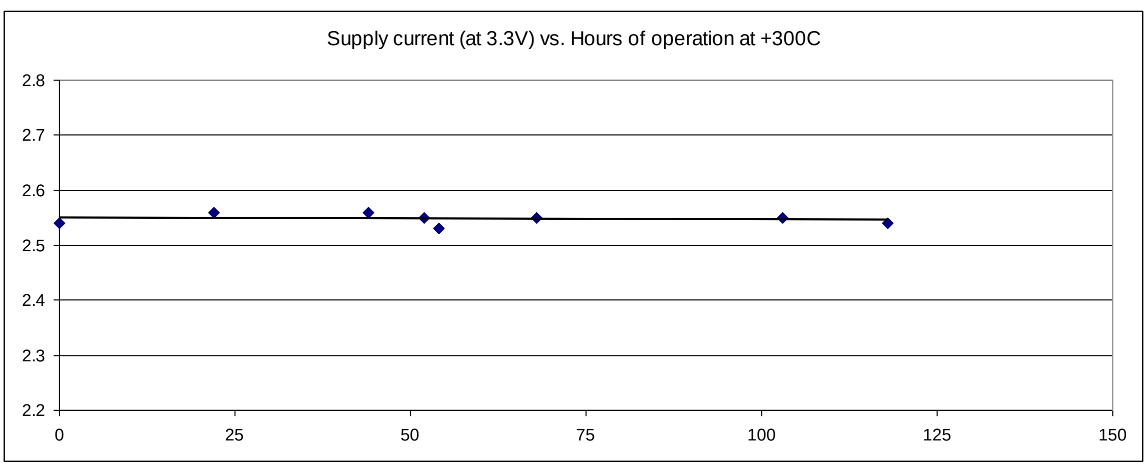


Figure-9 Supply current (at 5V) vs. operating hours at +300ºC

Note: the monotonic behavior of the current vs. high temperature exposure time (at both voltages) indicate that our design for +300ºC operation is quite stable and is expected to continue to operate for much longer time. We will continue to extend the test beyond the project commitments if the test setup utilization schedule for other activities would allow it.

CONCLUSIONS:

In the course of the project we have made definitive progress to achieve the following

4- Selection of the material and components that would make up the design configuration for successful +300ºC static operation
5- Finalized component attachment scheme for +300ºC
6- Established reliability of the wire-bond connections between the various parts of the circuit components to substrate and to package pins for +300ºC operation
7- Fully compliant and robust electromechanical support of the piezoelectric crystal resonator used in the oscillator circuit configuration
8- Fabrication of complete crystal controlled clock oscillator samples that can operate at both 3.3V and 5V systems for life test at +300ºC and in the intended hermetically sealed package
9- Successful electrical testing of the design from room temperature to +300ºC
10- Successful device performance during the life test of the design at +300ºC going beyond the 118 hours (100 hours was the target) and accumulating

Our design has completely met the project objectives that range from electrical performance to device configuration, package size and type for operation at +300ºC.

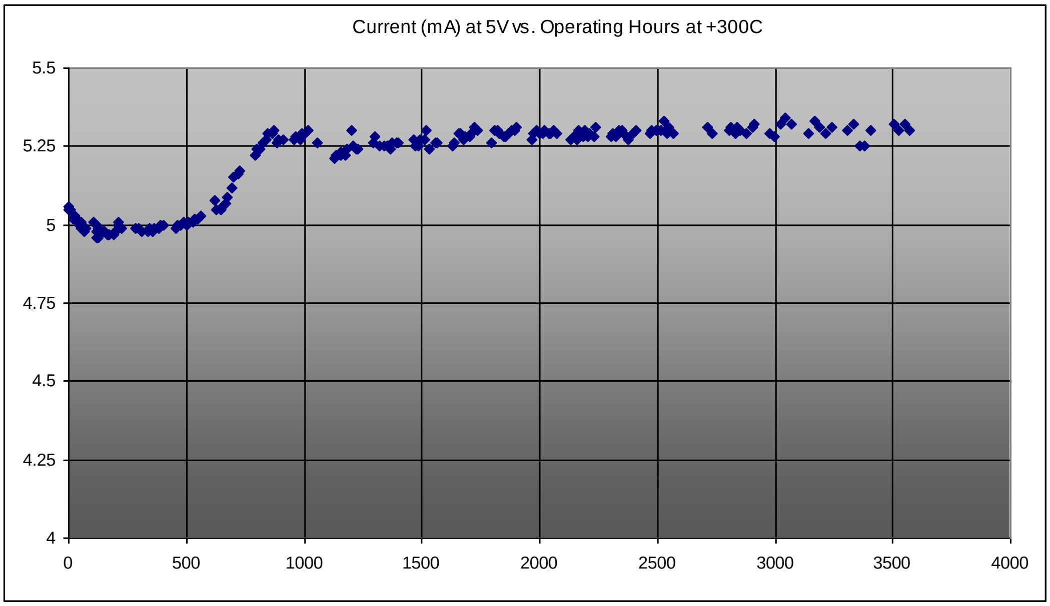
EXTENDED LIFE TEST

Once the performance objectives were clearly met, it became a worthwhile effort to extend the life test to establish a more realistic picture of the device operation at +300ºC. FMI performed this test by adjusting its other competing obligations. The following graphs are the compiled results of the various measurements we had done on the unit under test at the high temperature. We extended the test to the point where either the company priorities for the test setup would change or a failure is observed. We consider a failure in the test setup as also an end tot he test. All the indications is that the final design configuration has surpassed the objectives by a significant margin. It is our belief that opportunities to further improve the design includes

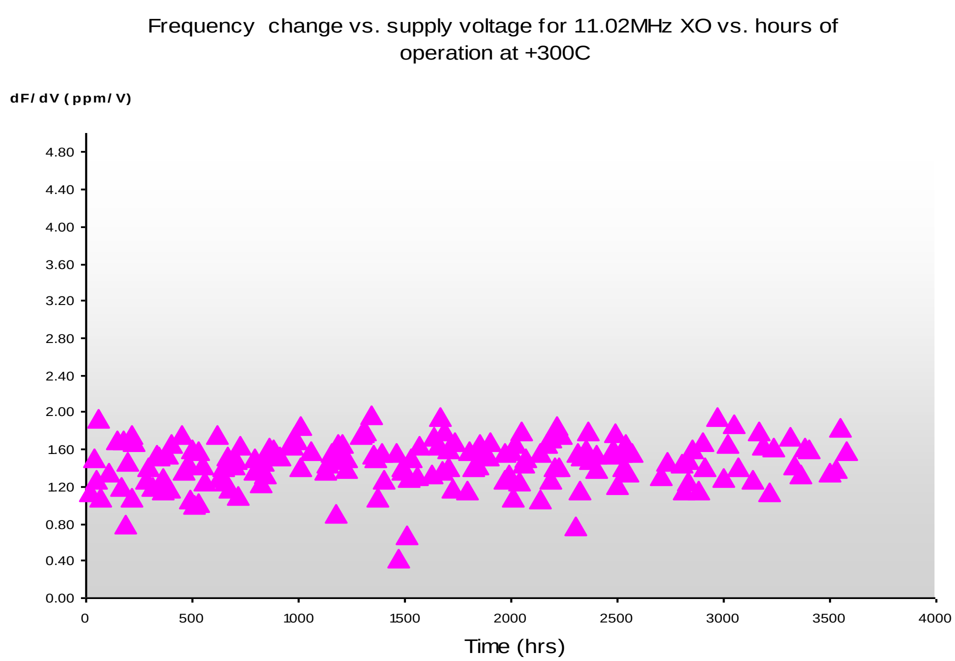
- A more applicable and optimized active device to drive the crystal
- address the device performance and improve its reliability under dynamic thermal profiles from low temperatures to +300ºC or as required in such wide temperature range operating and environmental conditions.

In conducting the continued static life at +300ºC, we included the same power cycle at every increment of the measurement. All the data points on the various graphs include a reliable starting test of the oscillator at the high temperature.

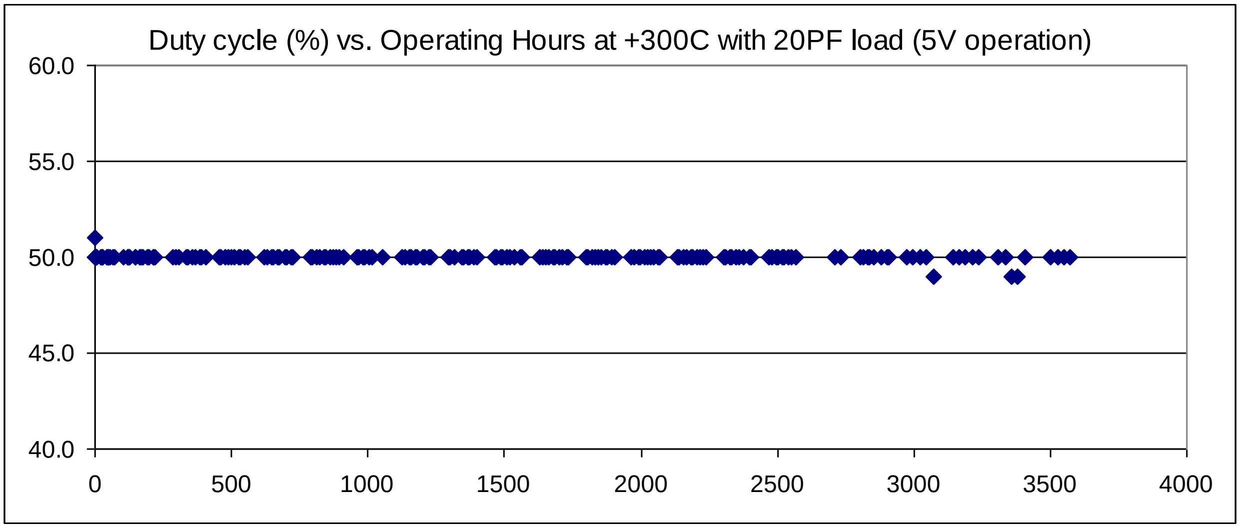
Supply current at 5V over the course of the life test behavior which extended more than 3500 hours exhibit the initial settlement over the approximately 800 hours at the start of the test as shown in the figure below



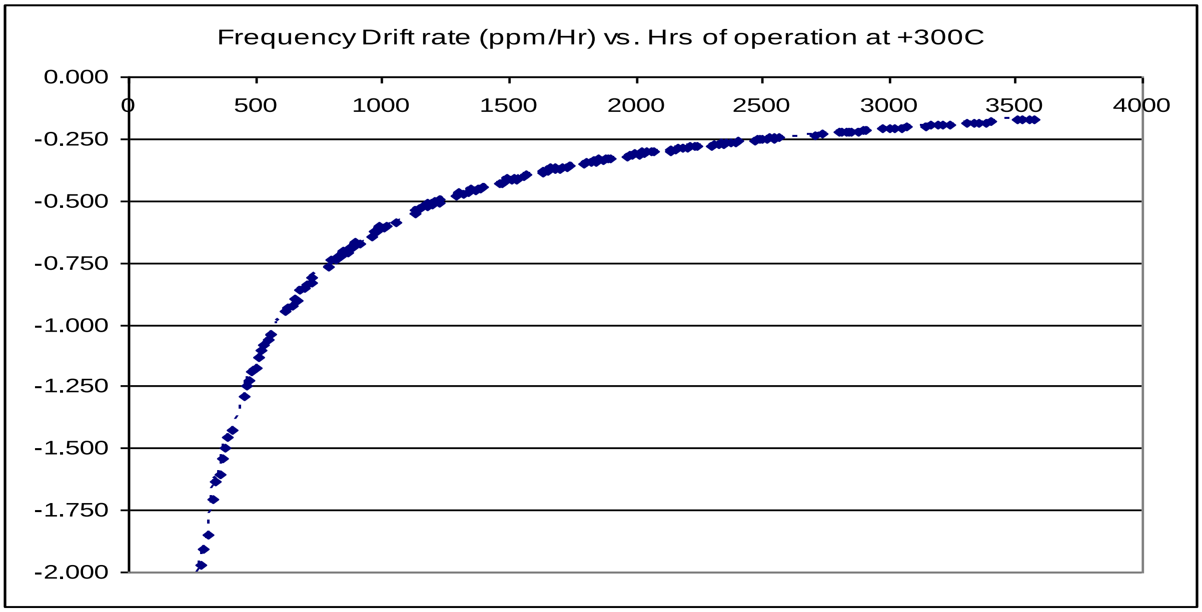
Frequency sensitivity to power supply change. Our design performs much better than the target of 4ppm per volt.



Output duty cycle was another parameter that was monitored. It was measured at the 50% of the power supply as required for a CMOS type logic output. The total capacitive load of 20PF included the test socket and scope probe capacitance. The device output showed very stable waveform parameters as reflected by a solid duty cycle



Although not one of the design targets we continued to monitor the frequency drift (aging) rate as shown in the graph below. Note that this parameter could be significantly improved (reduced) by using other crystal design configurations. This data include systematic error due to the measurement shortcomings relative to the precision of the measurement temperature. The actual figures are smaller than what is shown.



This work has been supported by DOE project DE-FG36-08GO18185 and in cooperation with Mr. Randy Normann at PermaWorks http://www.permaworks.com/. We appreciate the support for this effort.

Appendix G

FIBER OPTIC COMMUNICATION WITH DISTRIBUTED TEMPERATURE SENSING

[Below was taken from a 2013 MagiQ Technologies report to Perma Works by Craig Beal on using DTS fiber for both DTS and communication to the surface for well monitoring electronic data. Their actual report considered options where were outside of grant funded effort.]

FIBER SELECTION

Fiber selection is a critical element in the optical telemetry system design and proper selection is even more important for downhole operation. Only a few manufacturers produce fibers capable of surviving temperatures greater than 250°C.

High temperature fiber is coated with a polyimide coating rated for continuous operation at 300°C. There are also “high temperature” fibers that have a silicone coating which performs well up to 200°C but these are not suitable for all geothermal applications. In addition to the polyimide coating some fibers have a carbon layer applied directly to the glass which provides hermetic protection.

At high temperatures and pressures fiber loss tends to increase due to hydrogen darkening which occurs when free hydrogen from the environment is able to bond with oxygen in the SiO_2 silica glass in the fiber to form hydroxyl (OH) groups. These compounds absorb light in the IR region of the spectrum. A few specialty fiber vendors have developed fibers with modified glass chemistry which greatly reduces the effects of hydrogen darkening. MagiQ has primarily worked with three such vendors: Draka, AFL/Verrillon, and Fibertronix.

Figure 1 below compares the loss coefficient (dB/km) of Verrillon multimode fiber with a Carbon /Polyimide coating to that of standard non-hermetic fiber. The test temperature is 140°C with 25 psi of hydrogen. It is clear that under these conditions the attenuation of the standard fiber (red) is significantly higher than the Verrillon specialty fiber. Figure 2 shows a similar comparison at a higher temperature and pressure, 200°C and 1500 psi of H_2. In both cases the loss at wavelegths of interest (1064 for DTS and 850 nm or 1300/1550 nm for telemetry) remain quite manageable in the Hermetic Verrillon fibers.

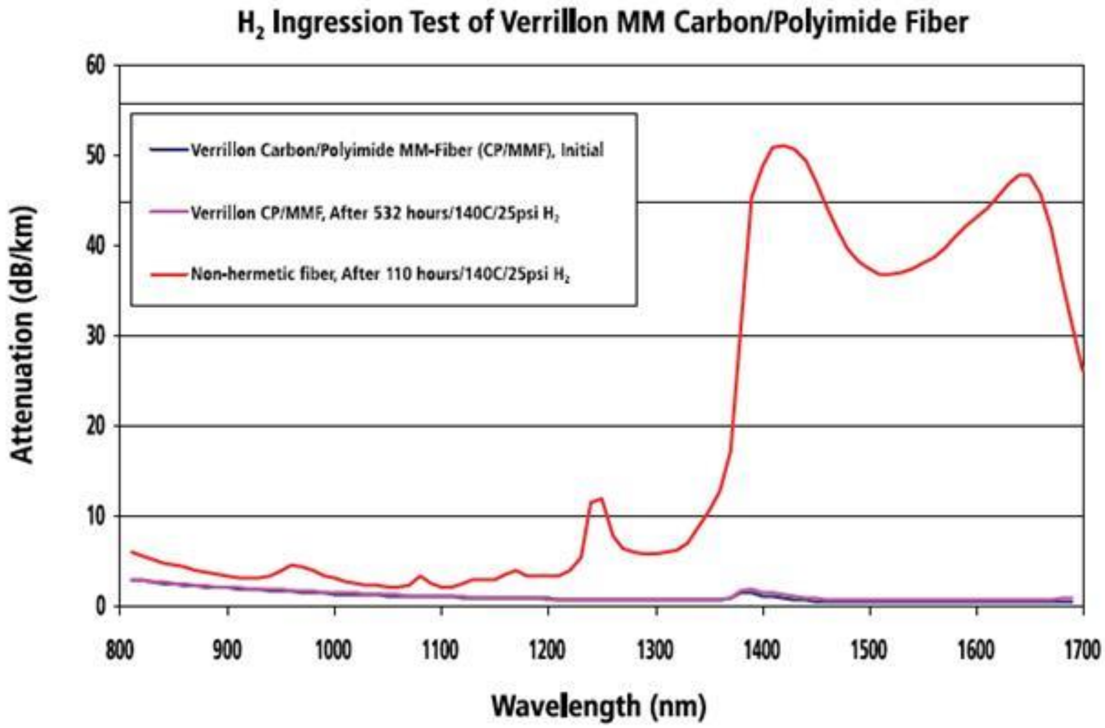


FIGURE 1. COMPARISON OF HYDROGEN INDUCED ATTENUATION AT 140°C/25 PSI H_2 FOR STANDARD FIBER (RED CURVE) AND VERILLON HYDROGEN RESISTANT FIBER (PURPLE CURVE) [1]

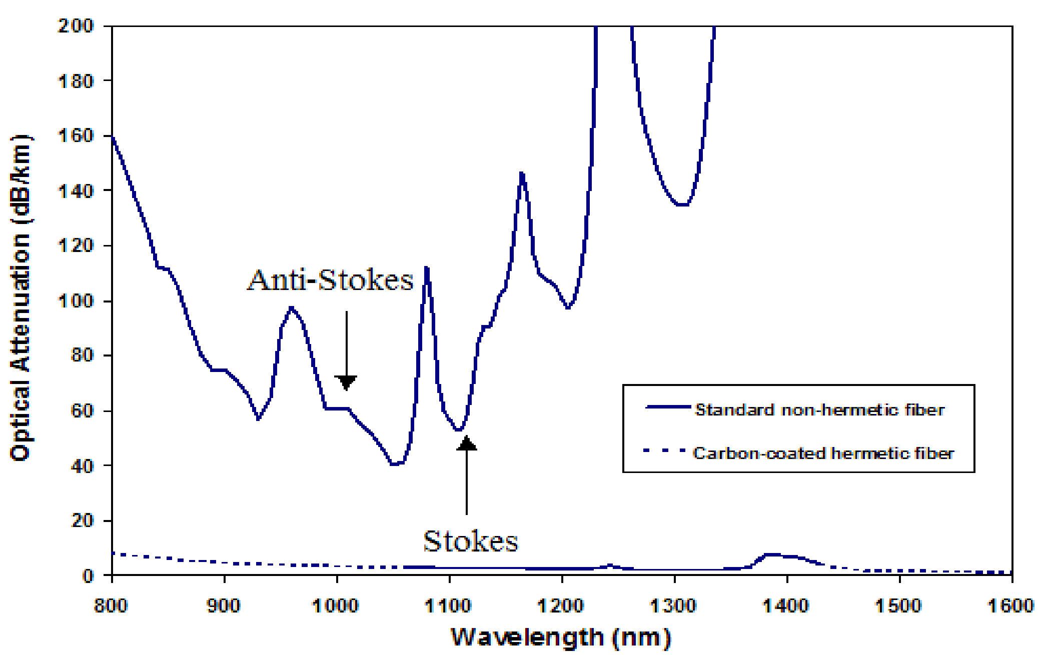


FIGURE 2. EFFECT OF HYDROGEN INGRESSION ON MULTI-MODE OPTICAL FIBERS AT 200C, 1500PSI OF H_2 FOR 17HRS, THE TYPICAL DTS LINES (STOKES AND ANTI-STOKES) OF INTEREST ~ 1064NM ARE INDICATED. [2]

Hydrogen resistant fiber is available in both single and multimode varieties. Due to the high per meter cost of these specialty fibers there is a significant advantage to multiplexing services onto a single fiber strand. For example sensor telemetry can be combined with distributed temperature sensing (DTS) using a wavelength division multiplexing (WDM) approach. DTS systems typically operate on multimode fiber because of its ability to handle high optical powers. They use a 1064 nm pump laser while detecting Stokes and Anti-Stokes spectral components between 1µm and 1.1µm. These operating parameters mean that this portion of the spectrum is not available for our telemetry scheme. However, two other low loss windows can be used. Of particular interest are wavelengths between 700 and 900 nm and between 1300 and 1550 nm.

It is conceivable that one could also operate within the visible part of the spectrum between 400 nm and 700 nm. The fibers we typically consider do not specify performance in the visible region, however we did find one source of fiber rated to 300°C which was specified down to 200 nm.

When considering visible wavelengths, it is important to note that optical transmission is predominately limited by Rayleigh scattering which is inversely proportional to the fourth power of wavelength. Because of this, shorter-wavelength light experiences high loss in optical fiber. The loss below 600 nm exceeds 10 dB/km and increases with decreasing wavelength, reaching approximately 30 dB/km for blue wavelengths. We were not able to obtain information from the manufacturers regarding hydrogen darkening at visible wavelengths.

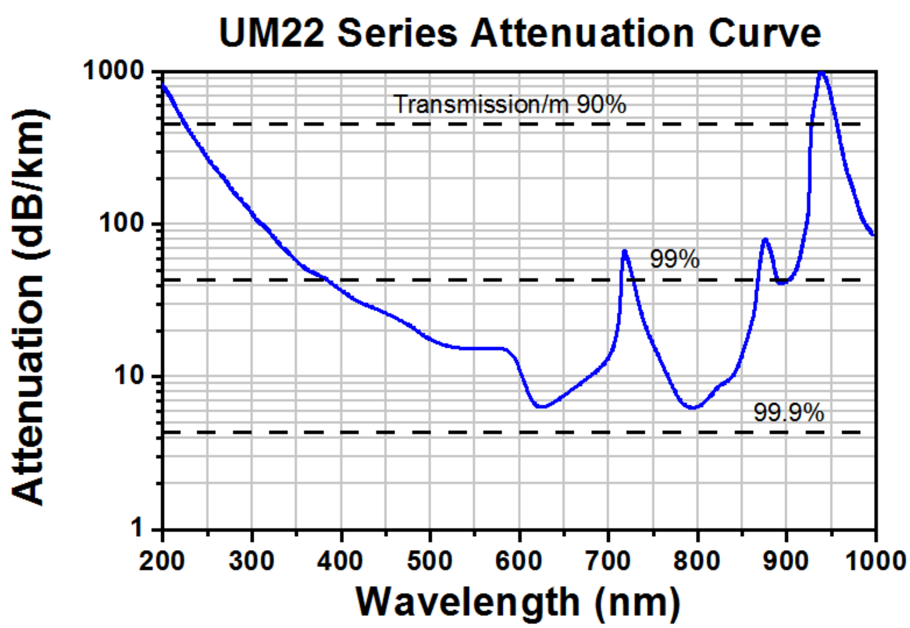


FIGURE 3. ATTENUATION CURVE FOR THORLABS UM22 SERIES 300°C RATED FIBER SHOWING LOSS AT VISIBLE WAVELENGTHS. [3]

We looked at fibers from several vendors including Draka, AFL/Verillon, Fibertronix, and Thorlabs. Our telemetry approaches are compatible with most (if not all) the applicable MM fibers intended for downhole use. Consequently the driving force for fiber selection will be the requirements of the DTS system. We focused our design on fibers with 50µm core diameters as these are one of the most common types. Based on comparison of hydrogen darkening data it appears that AFL/Verillon VHM5000 is a top performer with the following specs.

Specifications – VHM5000 Series

PART NUMBER	MMF-50-4-CP-125-4
Description	50/125 Carbon/Polyimidecoated Ultimate Performance Graded Index, Multimode Fiber
PARAMETER	
Material	
Core	Doped Synthetic SiO_2
Clad	Doped Synthetic SiO_2
Hermetic Coating	Carbon
Primary Coating	Polyimide
Secondary Coating	—
Geometry	
Core Diameter (μm)	50 ± 2.5
Clad Diameter (μm)	125 ± 2
Core Non-Circularity (%)	≤ 5
Clad Non-Circularity (%)	≤ 1
Core/Clad Offset (μm)	≤ 1.5
Coat Diameter (μm)	155 ± 5
Polyimide Coating Concentricity* (%)	> 80
Combined Coating Diameter (μm)	—
Optical	
NA (nominal)	0.20
Attenuation @ 850nm (dB/km) @ 1300nm (dB/km)	 ≤ 3.0** ≤ 1.2
Bandwidth @ 850nm (MHz-km) @ 1300nm (MHz-km)	 ≥ 300 ≥ 300
Mechanical	
Proof Test (kpsi)	≥ 100
Operating Temperature (°C)	$-65 \leq °C \leq 300$

* Measured as (Minimum Wall/Maximum Wall) x 100
** Measurement on Zero Tension Spool

FIGURE 4. SPECIFICATIONS FOR AFL/VERILLON VHM5000 SERIES FIBER. [1]

MEASURED FIBER COUPLING PERFORMANCE

In the lab we tested fiber coupling several LEDs to 50μm MM fiber using a variety of lenses. The best performance we observed was by opening the TO-18 package and placing the fiber as close as possible to the semiconductor die. Figure 5 below shows an opened Honeywell SE5470-004 mounted in the high temperature test fixture. Care must be taken not to damage the bondwire which can just be seen connecting the surface of the die to the off-center bondwire pad to the left.

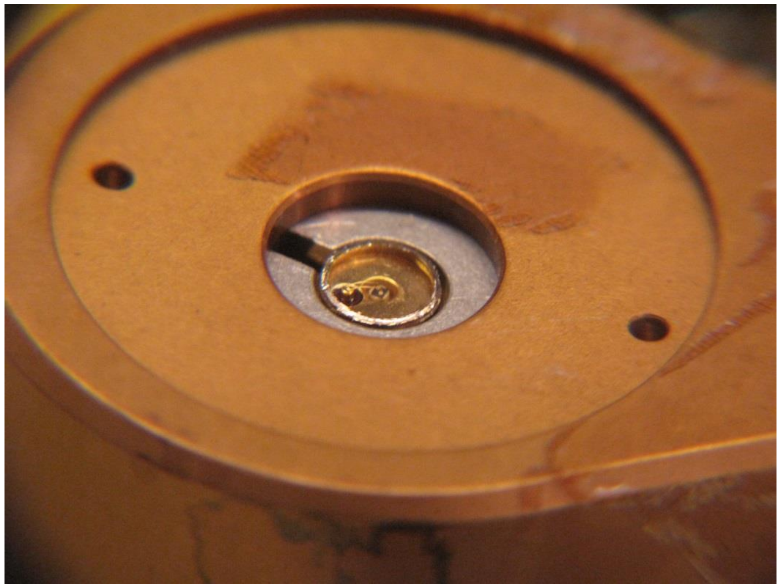


FIGURE 5. AN OPENED HONEYWELL SE5470-004 MOUNTED IN THE TEST FIXTURE

The Honeywell SE5470 was biased at 25 mA average current which should supply 1.75 mW (2.4 dBm) total optical power (at all angles). We were able to couple -33 dBm (0.5 µW) into the fiber for a net coupling loss of 35.4 dB (0.03%). This is a bit lower than the simulation suggested however actual dimensions of the active area are not listed in the manufacture's datasheet and the LED divergence angle was not accurately characterized – both these factors could explain the discrepancy between simulated and measured performance. We also tested butt coupling fiber to an unmodified TO-18 can – pushing the fiber right up to the glass lens on the package. In the case of the Honeywell SE5470, this resulted in about 4 dB lower coupling efficiency – yielding approximately -37 dBm coupled into the fiber.

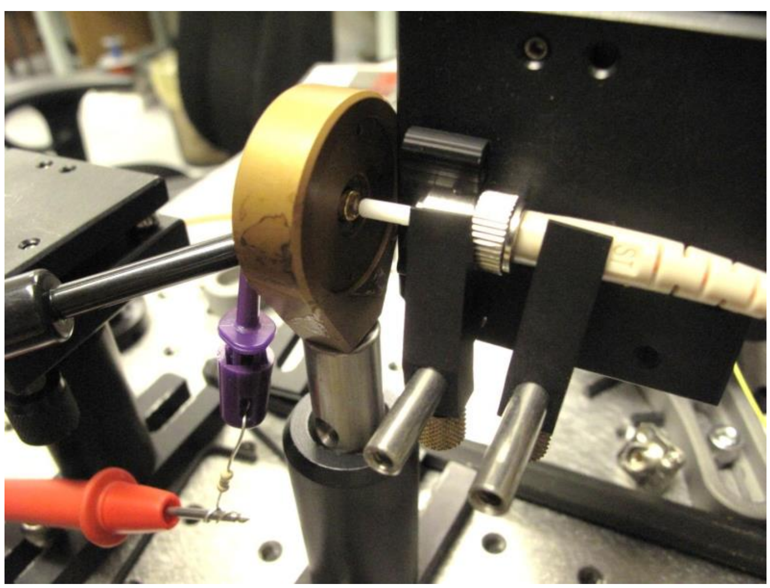


FIGURE 6. MEASURING FIBER COUPLING OF AN OPENED HONEYWELL SE5470-004 AT ROOM TEMPERATURE.

LINK BUDGET ANALYSIS

Finally we consider the optical link budget of a communications link using one of the candidate LEDs operated down hole at high temperature. Let's consider the Honeywell SE5470 selected because of it's overall high performance compared to the LEDs we tested and due to the absence of silicone potting compound in the optical path. The room temperature peak optical power at 25 mA is assumed to be 2.4 dBm based on datasheet values and integrated light emitted into all directions. We derate the optical output power by 10 dB based on our measured results of output power at 300°C. We also measured a fiber coupling loss of -35.4 dB. When we combine these factors we expect to see a peak power of -43 dBm coupled into the fiber at 300°C. This does not account for accelerated aging of the LED at high temperature which will lower the power even more.

The optical detector exists in the benign environment at the surface. A standard low noise silicon photodiode with transimpedance amplifier (TIA) can have a noise equivalent power (NEP) of around 1 $pW/\sqrt{Hz}$. Assuming a signal bandwidth of 12 kHz we'd expect around 110 pW RMS NEP or about -69.6 dBm. Said another way, the noise in the detector contributes a noise level equivalent to -69.6 dBm optical (noise) power incident on an ideal noiseless detector. This together with the SNR determines the minimum detectable signal. If we assume a desired SNR of 10 dB, which will yield a BER ~ 3×10^{-6}, our peak power at the detector should be -59.6 dBm. This leaves us with around 16.6 dB link budget remaining for fiber, connectors, WDM components etc. Since we did not account for accelerated aging of LED at high temperature, this 16.6 dB link budget will also have to soak up that additional loss as well. All these losses aside we can expect to transmit across roughly 5.5 km (18187 feet) of MM fiber (assuming 3 dB/km attenuation at 880 nm) with no margin. This calculation is summarized in Table 1 below.

TABLE 1. OPTICAL LINK BUDGET FOR A HIGH TEMPERATURE MODULATED LED

LED Parameters		
Peak Optical Power	2.4	dBm @ 25 mA
High Temp Derating	-10.0	dB @ 300°C
Fiber Coupling Loss	-35.4	dB
Peak Power in Fiber @ 300°C	-43.0	dBm
Detector Parameters		
NEP	1.0E-12	W/sqrt(Hz)
Bandwidth	12.0E+3	Hz
RMS NEP	109.5E-12	Wrms
	-69.6	dBm
Desired SNR	10.0	dB
Peak Opt Power	-59.6	dBm
Link Budget		
Link Budget	16.6E+0	dB
Fiber Loss	3.0E+0	dB/km
Maximum Link Length	5.5E+0	km
	18187	feet

We can gain perhaps an additional 10 margin by switching to an avalanche photodector (APD) at the expense of added cost and complexity of the surface receiver. The LED may also be driven at higher peak currents to get more light output but this could adversely affect the aging. Lastly additional efficiency can be gained by identifying LEDs with smaller active areas. Marktech Optoelectronics offers a line of "Point Source" emitters which have circular emitting areas as small as 50µm without wire bond obstructions common to many LEDs. These devices would couple much more light into the fiber than the 400 µm x 400 µm LEDs. In summary, for short links of up to a few kilometers the LED may be a viable solution however a more in-depth analysis of the Arrhenius models at high temperature is needed to determine how much loss margin is really needed.

Appendix H

DESIGN CONSIDERATIONS FOR A DOWNHOLE MAGNETIC FLOWMETER

David A. Glowka
Red Rock Research, Inc.
Randy Normann
Perma Works, LLC

Power from a geothermal well has two major components determining the potential energy from the well; fluid temperature and volume of fluid. Today, geothermal production logging tools measure fluid temperature and relative fluid flow by the spinning of a mechanical impeller. While this technology is widely used in industry, it suffers from a couple of major shortcomings. First, the rotation of the spinner can be stopped by rocks that are flowing up with the well fluid. Secondly, the bearings can wear out quickly in geothermal applications where the well temperature can exceed 280°C and in high producing wells, the rotation of the spinner can exceed 10000 RPMs. Under the DOE Grant GO18185, Perma Works has created and tested a high-temperature solid-state flow sensor without these weaknesses by eliminating any moving parts. This flow sensor senses fluid velocity by measuring a small voltage created as the fluid flows through a magnetic field. This voltage is proportional to the velocity of the fluid.

A conceptual design is described for a downhole magnetic flow meter for measuring wellbore flow rates in geothermal wells. Enough design detail is included to demonstrate that the device could be fabricated and assembled. Design issues that have been discovered so far are identified and discussed.

Perhaps the most important design issue to consider at this point in the project is the geometry of the magmeter. To address this issue, a simple flow model was developed to determine the effects of device dimensions on the fraction of the borehole flow that passes through the magmeter versus around it. It is shown that for practical magmeter diameters, only a small fraction of the flow is expected to pass through the magmeter. Flow velocities may be marginal for making accurate measurements, depending on the size of the wellbore and the total wellbore flow rates that must be detected and measured.

This document is the first of what is envisioned to be a series of reports documenting design considerations for the magmeter as they are developed. The purpose of this approach is to facilitate a more rapid exchange of ideas among project participants and, hopefully, more rapid and well-considered evolution of the tool.

DESCRIPTION OF THE CONCEPTUAL DESIGN

Shown in Figure 1 is a schematic of the assembled magmeter in a flowing wellbore. The magmeter comprises the lower end of the logging tool. Part of the wellbore flow passes into the inner tube running the length of the magmeter and exits out the top ports, while the remainder of the wellbore flow passes into the annular space between the magmeter and the wellbore wall.

Two wire coils on either side of the inner flow tube create a magnetic field across the flow cross-section. These magnetic coils are located in the pressure-tight annular space between the inner pressure tube and the outer pressure barrel. The fluid flowing through the magnetic field develops a voltage potential that is proportional to the fluid velocity and the radial distance between two probes used to measure the voltage. These voltage probes pass through the inner pressure tube and ceramic liner to contact the fluid. The liner insulates the fluid from the electrically conductive pressure tube. Electrical leads from the coils and voltage

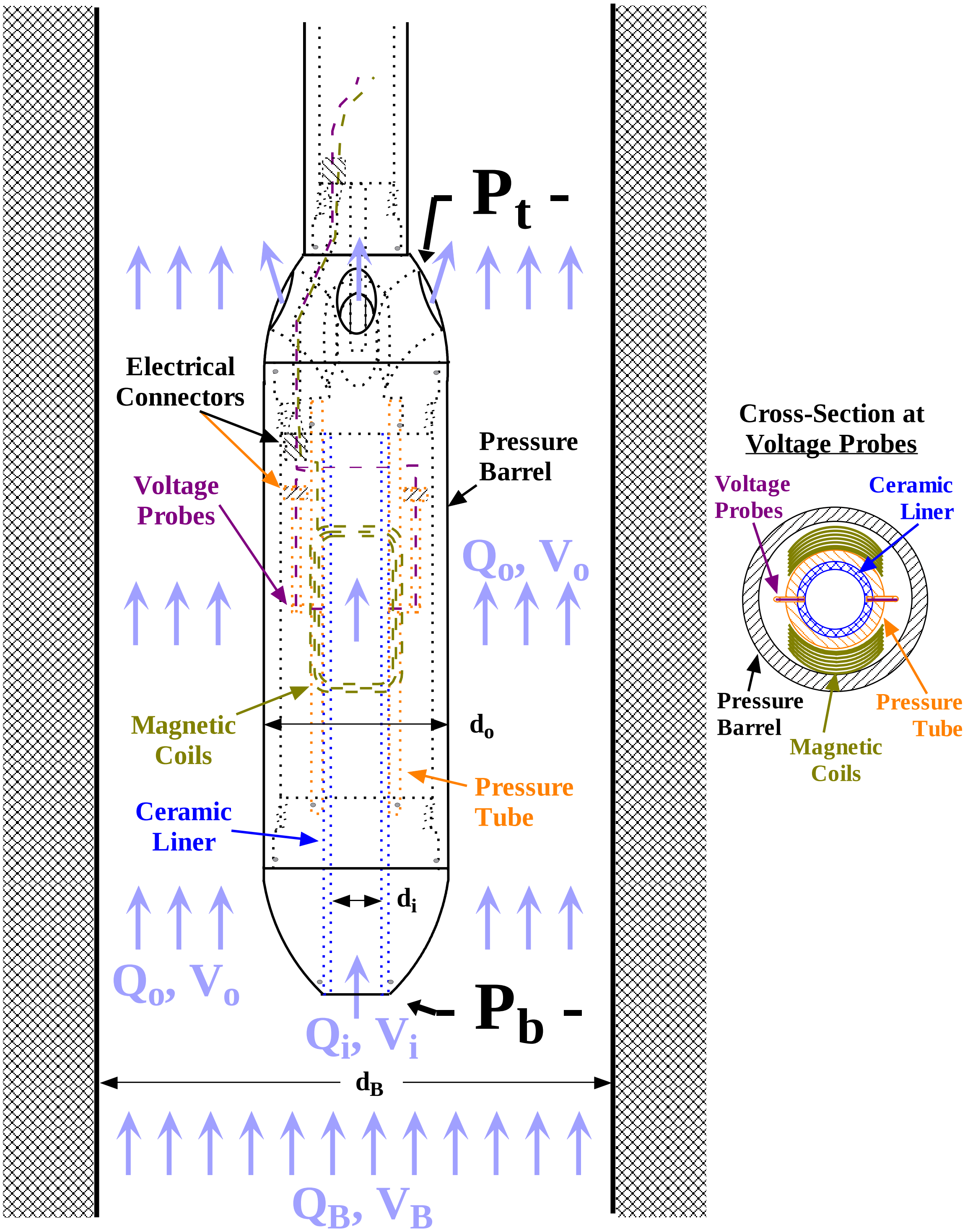


Figure 1 – Conceptual Diagram of Downhole Magnetic Flowmeter

probes pass through a connector, through the upper bulkhead, and into the instrument module above the magmeter.

Figure 2 shows how the magmeter would be constructed and assembled. A non-magnetic alloy tube is machined with o-ring grooves at each end, with an external stub Acme thread on top. Two holes, diametrically opposed, are drilled near the middle of the tube for the voltage probes. Ideally, each probe would
simply consist of a glass-sealed feed-thru, if we can find a design small enough. Otherwise, a small tube can be welded into each hole, and insulated wires can be run through the tubes and potted in place. Glass-sealed feed-thrus can then be fitted to the upper ends of the tubes to provide the pressure seals for the voltage probes.

The magnetic coils consist of multiple turns of insulated wire, the size and number of coils of which are to be determined. These coils are strapped or epoxied in place on either side of the pressure tube, as shown.

A ceramic or other non-electrically conductive tube serves as a liner through which the fluid flows. By isolating the fluid from the electrically conductive pressure tube, the liner allows the flowing fluid to develop a voltage potential across its cross-section as it passes through the magnetic field. The liner is epoxied and/or shrunk-fit into the pressure tube by heating the pressure tube to a high temperature before slipping it over the cold ceramic liner. Two diametrically-opposed holes drilled through the liner are aligned with the voltage probes that are flush with the inner surface of the pressure tube. The Flow Tube Assembly is then ready for assembly of the entire Magmeter.

The Magmeter is assembled in the sequence shown in Figure 2:

1) The assembled Flow Tube Assembly is first threaded into the bottom internal stub Acme threads of the Upper Bulkhead. Double o-rings and a metallic c-ring are used to provide sealing at this connection. Note that the Upper Bulkhead is shown with an RTD temperature probe protruding into the internal flow near the exit ports.

2) The electrical connector carrying the magnetic coil and voltage probe leads is then plugged into the connector in the bottom of the Upper Bulkhead.

3) Next, the Magmeter Pressure Barrel is slipped over the Flow Tube Assembly and threaded onto the external stub Acme threads of the Upper Bulkhead. Double o-rings and a metallic c-ring are again used to provide sealing at this connection.

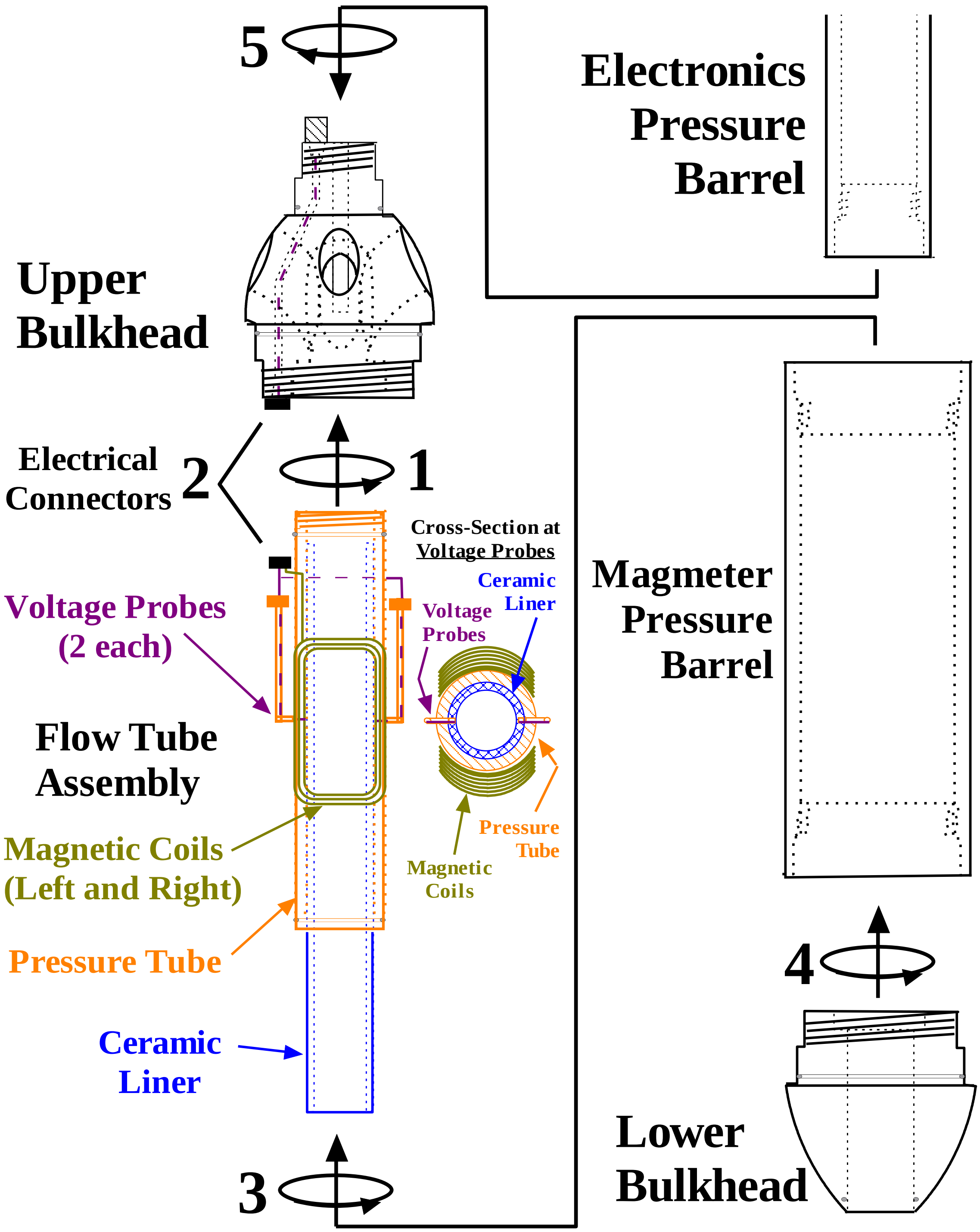


Figure 2 – Assembly of the Downhole Magnetic Flowmeter

4) The Lower Bulkhead is threaded onto the lower end of the Magmeter Pressure Barrel to complete assembly of the Magmeter. In addition to double o-ring seals and a metallic c-ring seal at this connection, double o-rings are also used to seal the lower end of the pressure tube and the
ceramic liner against the Lower Bulkhead. These latter seals need to allow for axial movement resulting from differential thermal expansion between the pressure tube, pressure barrel, and ceramic liner.

5) Finally, the assembled Magmeter is connected to the Electronics Pressure Barrel via stub Acme threads, double-o-rings, and a metallic c-ring.

FLOW MODEL DEVELOPMENT

Figures 1 and 2 are drawn to a scale such that the wellbore diameter is 8.5 inches, the magmeter OD is 3 inches, the magmeter ID is 1 inch, and the electronics pressure barrel is 1.75 inches. The question exists as to whether such dimensions would allow enough of the flow to enter the magmeter to make possible a reliable measurement and extrapolation to the full wellbore flow.

To address this issue, the following flow model is developed. As the flow encounters the magmeter, the borehole flow rate Q_B, mean velocity V_B, and pressure P_b exist near the bottom of the magmeter. Part of the flow, Q_i, enters the magmeter with a mean velocity of V_i; and the remainder of the flow goes around the magmeter with an annular flow rate Q_o and mean velocity V_o. Near the top of the magmeter, at the exit ports, the flows combine back into an all annular flow, with a pressure P_t existing near the top of the magmeter.

The total pressure change across the tool, $P_b – P_t$, is the sum of the frictional pressure change due to flow, Δp_f, and the hydrostatic pressure change due to the weight of the fluid, Δp_h. Since the total as well as the hydrostatic pressure changes are the same over the annular space as they are over the internal flow tube, it must be concluded that the frictional pressure drops are also the same. In other words,

$$(P_b – P_t)_o = (P_b – P_t)_i$$

$$(\Delta p_h)_o = (\Delta p_h)_i \quad .$$

$$(\Delta p_h)_o + (\Delta p_f)_o = (\Delta p_h)_i + (\Delta p_f)_i \quad .$$

So

$$(\Delta p_f)_o = (\Delta p_f)_i = \Delta p_f \quad \text{...} (1)$$

Therefore, we only need to determine the relationship between flow rate and pressure drop for the internal tube flow and the external annular flow in order to determine the flow distribution.

The frictional pressure drop for flow in a pipe is given in its most general form as

$$\Delta p_f = f\,(L/d)\,\rho V^2/2 \quad , \quad \text{...}(2)$$

where f is the friction factor, L is the length of pipe, d is the diameter, ρ is the fluid density, and V is the fluid velocity [Ref. 1]. The friction factor for a smooth pipe in turbulent flow has been experimentally determined as

$$f \cong 0.3164(Re_d)^{-1/4} \quad , \quad \text{...}(3)$$

where Re_d is the Reynolds number

$$Re_d = \rho V d/\mu \quad , \quad \text{...}(4)$$

ρ is the fluid density, and μ is the fluid viscosity [Ref. 2]. Eq. 3 is valid for smooth pipes with Reynolds numbers between 2500 and 100,000. Combining Eqs. 2-4 gives the result

$$\Delta p_f = 0.1532\,(\rho^{3/4}/\mu^{1/4})\,V^{7/4} / d^{5/4} \quad , \quad \text{..}(5)$$

or

$$\Delta p_f = 0.1532\,(\rho^{3/4}/\mu^{1/4})\,Q^{7/4} / A^{7/4} / d^{5/4} \quad , \quad \text{..................................}(6)$$

where A is the cross-sectional flow area.

For the inner flow tube, this equation becomes

$$(\Delta p_f)_i = 0.1532\,(\rho^{3/4}/\mu^{1/4})\,Q_i^{7/4} / A_i^{7/4} / d_i^{5/4} \quad . \quad \text{..............................}(7)$$

The concept of hydraulic diameter is now used to apply this equation to the annular flow between the magmeter and the borehole wall. By using the hydraulic diameter for a flow channel, equations that predict the pressure drop in a round pipe can be used to estimate the pressure drop in a non-circular flow channel [Ref. 3]. The hydraulic diameter is defined as

$$d_h = 4 \text{ X flow area / wetted perimeter} \quad ; \quad \text{.........}(8)$$

therefore

$$d_{hi} = 4\,(\pi/4)\,d_i^2 / (\pi d_i) = d_i \quad , \quad ..(9)$$

$$d_{ho} = 4\,(\pi/4)\,(d_B^2 - d_o^2) / [\pi(d_B + d_o)] = (d_B^2 - d_o^2) / (d_B + d_o) \quad , \quad \text{..........}(10)$$

and

$$(\Delta p_f)_o = 0.1532\ (\rho^{3/4}/\mu^{1/4})\ Q_o^{7/4} / A_o^{7/4} / d_{ho}^{5/4}\ . \qquad (11)$$

Combining Eqs. 1, 7, and 11 produces the result

$$0.1532\ (\rho^{3/4}/\mu^{1/4})\ Q_i^{7/4} / A_i^{7/4} / d_i^{5/4} = 0.1532\ (\rho^{3/4}/\mu^{1/4})\ Q_o^{7/4} / A_o^{7/4} / d_{ho}^{5/4}\ ,$$

or

$$Q_i / Q_o = (A_i/A_o)\ (d_i/d_{ho})^{5/7}\ .$$

Since $Q_o = Q_B - Q_i$, this equation becomes

$$Q_i/Q_B = 1/[(A_o/A_i)\ (d_{ho}/d_i)^{5/7} + 1] \qquad (12)$$

This equation is plotted in Figure 3 for a range of flow tube diameters and wellbore diameters. As a practical matter, an annulus of at least one inch is needed between the inner flow tube diameter and the magmeter outer diameter to accommodate the ceramic liner, pressure tube, pressure barrel, and space to house the magnetic coils and voltage probe leads and connectors. Accordingly, the magmeter OD in these calculations was set to the flow tube ID plus 2 inches.

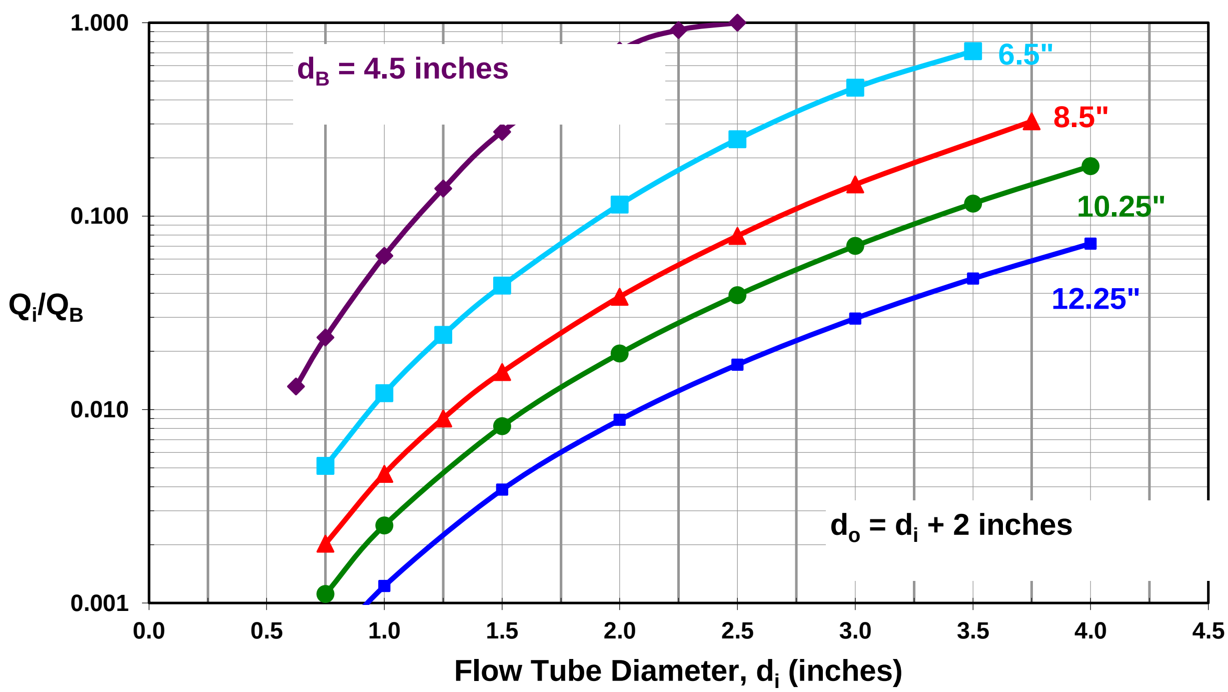


Figure 3 – Fraction of wellbore flow through the magmeter as a function of flow tube diameter and wellbore diameter.

Note that for practical values of the flow tube diameter, only a small fraction of the wellbore flow actually flows through the magmeter. For a flow tube ID of 1 inch and a magmeter OD of 3 inches, only about 6% of the total flow in a 4.5-inch wellbore goes through the magmeter. In a 12.25-inch wellbore, this fraction is only about 1.4%.

To determine whether or not such low flow rates are measurable with a magmeter, the flow velocity through the magmeter is calculated according the equation, $V_i = Q_i/A_i$. The results are shown in Figure 4 for a total wellbore flow rate of 100 gpm.

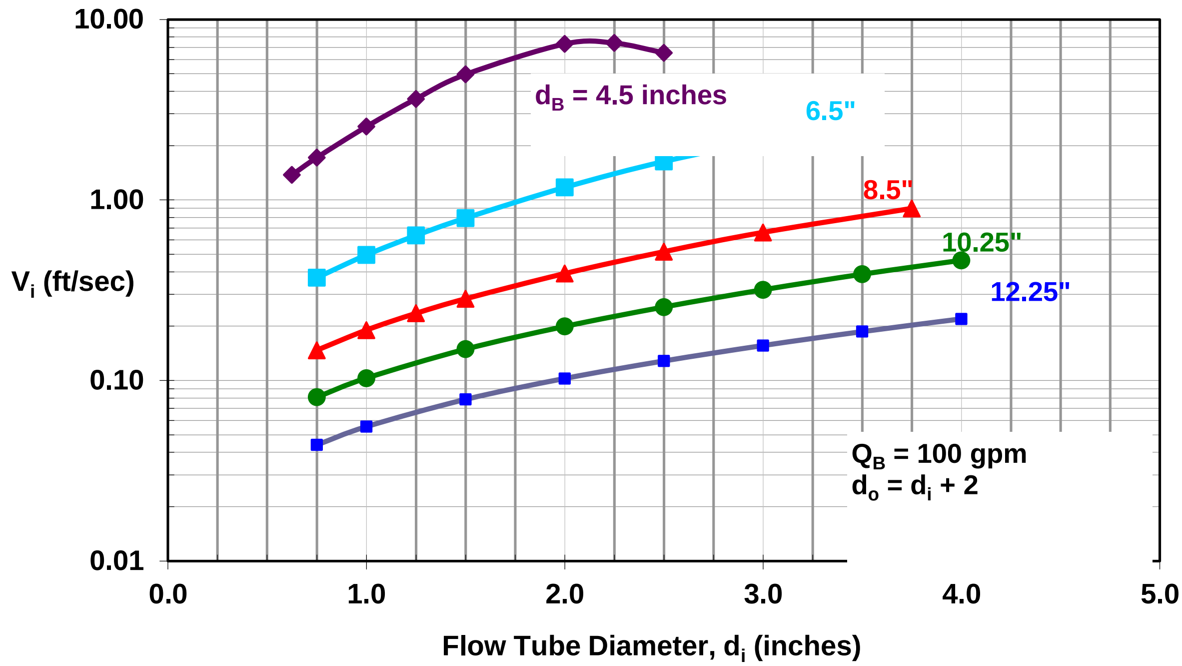


Figure 4 – Flow velocity through magmeter as a function of flow tube diameter and wellbore diameter for a 100-gpm total wellbore flow.

Note that the flow velocities range from less than 0.1 ft/sec to more than 7.0 ft/sec for reasonable flow tube diameters of 0.75 to 2.0 inches. A quick survey of Omega Engineering's magnetic flowmeters indicates that their inline magmeters, the type proposed here, can measure flow rates accurately (within 1%) as long as the mean velocity is between 0.33 and 33 ft/sec (0.1 and 10 m/sec). Insertion-type magmeters can measure flows as low as 0.16 ft/sec (0.05 m/sec).

It, therefore, appears that with a flow tube diameter of 1.0 inches, which implies a 3.0-inch OD magmeter, we should be able to measure 100 gpm and higher total borehole flows accurately in 4.5- and 6.5-inch wellbores. In an 8.5-inch wellbore, flows as low as 200 gpm should be measurable; 400 gpm in a 10.25-inch wellbore; and 700 gpm in a 12.25-inch wellbore.

TESTING THE PROTOTYPE SOLID-STATE FLOW SENSOR

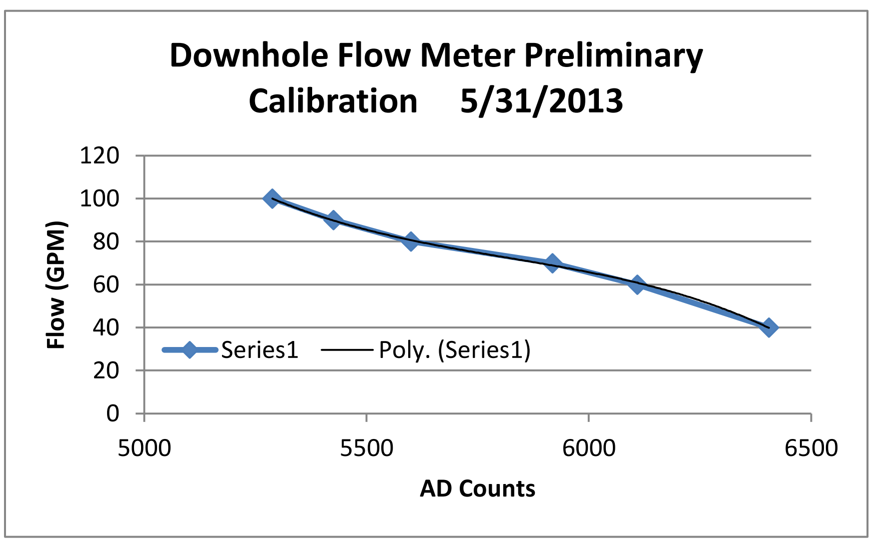
A flow loop was built and a prototype solid-state flow sensor was tested. The assembled solid-state flow sensor is in the image to the left. The top of the flow sensor allows for it to be attached to the well monitoring tool already developed.

To the right is an image of the bottom of the solid-state flow sensor while inside the flow loop.

Below is data taken from the actual solid-state flow sensor while inside a flow loop built at Perma Works. Simulating geothermal flow rates inside the lab is not possible and as such, final calibration for the sensor will require field testing.

The present design is optimized for high flow rates but the same technology could be utilized in lower producing wells, by directing more of the well fluid through the tool.

In summary, the developed technology provides a means to monitor fluid flow at the geothermal production zone found deep in the earth and thereby enabling a new way to qualify geothermal reservoirs for power production. In addition, such a flow sensor could help EGS



(Enhanced Geothermal System) applications by providing a means to monitor fluid flow real-time for many months (possibly years). This could help define fluid loss zones and provide an indication of reservoir performance over time. Also, this same technology could be evaluated for possible use to control in-situ fluid control valves. By controlling fluid downhole, the energy production from wells with multiple production zones could be optimized as is current practice in the oil industry.

FINAL DISCUSSION

Whether or not these minimum flow rates calculated are acceptable depends on the application. They would certainly work for measuring full wellbore production rates, but measuring internal wellbore flows between zones may be a different matter. We need to determine the range of wellbore flow rates that we need to accurately measure before we can make this assessment.

One way to reduce the minimum measurable flow rate is to increase the flow tube inner diameter and/or the magmeter outer diameter. Larger diameters would also provide more room for the magnetic coils and voltage probe feed-thru's, making construction of a more powerful magmeter possible. There is a practical limit, however, to the overall diameter of the tool, and we need to determine that limit as a function of wellbore diameter. It is possible that different diameter tools would be needed for different size wellbores. Or a shroud could be designed for each size wellbore that could be attached to the tool exterior to force more of the flow through the magmeter.

It should also be noted that although the flow model used here to calculate the percentage of flow going through the magmeter is relatively simplistic, it is accurate enough for identifying trends and design issues such as has been done in this analysis. A modified, non-linear analysis that considered pipe roughness for the annular flow between the borehole wall and the magmeter OD was also run for a couple of cases, and the results were similar. The conclusion is that the simple flow model is sufficient and a more accurate flow model would not tell us anything more useful at this time.

An actual solid-state flow sensor for mounting on the front end of the Perma Works HT SOI tool was constructed. The flow sensor was tested in a flow loop using clean water and with brine. The sensor worked but with very small signals coming from the sensor. Higher flow rates would generate larger signals. The work is very encouraging for future EGS development.

References

1. Mechanics of Fluids, I.H. Shames, McGraw-Hill Book Co., New York, 1962, p. 296.

2. Viscous Fluid Flow, F.M. White, McGraw-Hill Book Co., New York, 1974, p. 484.

3. Viscous Fluid Flow, F.M. White, McGraw-Hill Book Co., New York, 1974, p. 488.

Appendix I

DESIGNING LOGGING TOOLS FOR FUTURE HIGH ENTROPY GEOTHERMAL POWER

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KEYWORDS:

Supercritical Geothermal, Super Critical Geothermal, Well Logging, HT SOI, CO2

ABSTRACT

This paper looks at design issues and potential options for building logging tools for logging high entropy (>400°C) geothermal wells. At well temperatures greater than 400°C, today's logging equipment cannot be used. These extreme temperatures create issues with the tools metal pressure housing, seals, thermal insulation, batteries, electronics and cables, both slick line and wireline. This paper discusses engineering tradeoffs between real time and memory tools. Potential solutions as high-temperature electronics and active cooling are briefly discussed.

INTRODUCTION

There are efforts, as the IDDP (Icelandic Deep Drilling Project), targeting supercritical geothermal well temperatures for future geothermal power plants. In the US, there are places where geothermal fluids hit temperatures >400°C. One of the goals of the geothermal industry is to increase geothermal power production by producing power from these high entropy wells.

Little is actually known about the chemistry of geothermal fluids in high entropy reservoirs. In general all geothermal fluids vary widely from location to location at temperatures less than <400°C. For example, some geothermal reservoirs produce chlorine and/or sulfur in the fluid, while other produce almost none. Some power plants only see a dry steam from the reservoir while others have liquid dominated flow. The issue here is that the tool builder must assume all of these conditions in future high entropy wells.

This paper considers the issues and potential options the geothermal tool builder needs to consider when taking on the development of a high entropy geothermal logging tool. Tool builders have to work with chemical resistant metals and pressure seals to create pressure housing needed to protect the electronics and sensors. The pressure housing also uses a heat-shield to protect against the extreme temperatures. The heat-shield is a evacuated Dewar Flask is very expensive to manufacture offering a limited number of well exposures at temperatures above 350°C. Also, the use of batteries inside a Dewar flask creates a new set of operational safety and environmental hazards which need to considered.

Even something as simple as the logging cable needs to be considered. The first question to be answered, is the tool going to provide real time data on a wire line cable or memory tool data using a slick line cable?

SLICK LINE VS WIRE LINE

The clear advantage of running a wire line tool is having data real time. For a tool operating in a high entropy well environment, having real time data can mean the difference between knowing the tools internal temperature and having a burned out tool. Also, if the tool is lost in the well, real time data means a partial well log exists and the effort was not a complete waste of project resources.

The down side of running a wire line tool in a high entropy well is the huge operational cost. At this time, there is no known armored logging cable rated above 700°F (~300°C). As such, the wire line can be replaced with high temperature wire inside 1/4in tubing, normally made of Incoloy. Unfortunately, wires inside tubing is a poor logging cable because well temperatures will work harden the tubing making rewinding difficult. As such, wired tubing is a consumable. At a cost in dollars per foot cost for wired tubing, a real time well log becomes increasingly expensive.

Running a memory tool on a slick line greatly reduces operational costs. A slick line is a single wire of chemically resistant stainless steel. The slick line logging unit can be much smaller than a wire line unit. It is common to find slick line logging units mounted on a trailer which can be delivered to the site for a lower mobilization cost over a standard wire line logging truck.

With a smaller diameter (<0.15in) and smaller allowable bend radius, the sick line does not have issue the work hardening issue as tubing. In general, slick line is reusable.

A final advantage of the slick line is the improved heat-shield. Operating in tool electronics in memory mode eliminates an electrical connection at the top of the tool required by a real time, wire line tool. Now, the top of the tool can be fully enclosed by the heat shield. The heat-shield is now only bypassed by the temperature probe and pressure port (among other tool sensors) at the front of the tool.

One of the disadvantages of a memory mode well log has already been discussed, the well data and corresponding tools internal temperature are not be known until the tool is returned to the surface. If the tools internal temperature is increasing faster than expected during the time in the well or the tool become stuck in the well, the tool electronics and any well data taken by the tool electronics can be lost. At this point, there needs to be some discussion of the issue with batteries when running heat-shielded memory mode tools inside <u>any</u> geothermal well, not just high entropy wells.

Current battery technology for operating above 100°C is lithium based battery technology. Some lithium battery manufacturers rate up to 125°C to even up to 200°C. However, every

caution needs to be exercised when working with lithium cells inside a geothermal logging tool. The battery temperature is the battery's internal self heating **plus** battery ambient temperature. In the case of a short circuit on the battery (as occurs when a tool floods with well fluid from a failed seal or an electrical short), the battery can generate significant internal heat. Under these conditions, the lithium cell will rupture (vent) or even detonate. Electrochem publishes "Primary Lithium Battery Safety and Handling Guidelines" to help lithium battery users. The following quote was taken from that publication:
"*Only trained and equipped emergency responders shall be allowed to respond to a vented cell incident. Consult federal, state, and local regulations for emergency response regulations and training requirements.*"[i]

Anytime a tool enters a geothermal well there is a chance for a failed pressure seal or failed heat shield or simply left in the well too long given well temperature exceed the batteries temperature rating. When working with a memory tool, the logger will not know for certain the condition of the tool coming out well until the tool is opened. As such, battery operated memory tools offer a potential health risk and potential hazardous chemical incident on site. In fact, the loss of lithium battery integrity normally results in the loss of the tool and disruption of normal operation at the well site.

Perma Works is currently working with a new solid-state (no liquid or gel) battery technology which does NOT contain lithium. Prototype batteries have already been demonstrated to be safe up to 600°C+ without rupture or detonation. On the downside, they do not work well at temperatures below 100°C. In a presentation by Dr. Alexander Potanin, these new solid-state batteries are capable of 30mA @ 12V at 25°C and 300mAt @ 12V at 250°C.[ii] These values are capable of power the Perma Works flasked memory tool. Once this technology is readily available safety and environmental issues with memory tools inside even high entropy geothermal wells will be greatly reduced.

THERMAL INSULATION

Thermal insulation buys time inside the geothermal well; the hotter the well, the less operating time. The best thermal insulation is a vacuum coupled with an internal IR reflective shield. As such, the heat shield used for geothermal logging tools is a Dewar flask heat shield. The Dewar is a double walled tube built much like a Thermos bottle.

Sandia reported tested two large diameter Dewar flaskes, ~3in OD with >0.3in evacuated annulus. These large heat-shields were able to protect tool electronics for ~ 4hrs at 400°C. At temperatures above, 425°C, there is potential for damaging the heat-shield. This implies, for well temperatures over 425°C, the shield becomes an expensive expendable item. The development of a Dewar flask with greater survivability temperatures and logging cycles is needed. It is not uncommon for the Dewar flask to cost $10K USD each.

PRESSURE SEALS

In general, 400°C temperatures will destroy organic materials. This results in no common O-ring solution for pressure sealing tools used in high entropy geothermal wells. The only valid solution is some type inorganic seal as a metal-to-metal or ceramic/glass seal. At Perma Works, we have worked hard to develop a metal-to-metal seals for all our tools pressure seals.

As already discussed, the chemical interactions to be found in 400C+ geothermal well fluids are not fully defined. As such, Perma Works builds pressure housings from chemically resistant and temperature stable metals such as 17-4ph. Thermal expansion of the metal pressure housing and internal parts must be considered when building a tool for such extreme temperature range.

HIGH-TEMPERATURE ELECTRONICS

In general, standard electronics can operate up to 150°C. If used inside a Dewared flask, standard electronics can operate in a 250°C geothermal production well for 8 to 12 hrs. The operating time inside a 400C well is reduced to ~4hrs in Sandia testing.[iii] New HT SOI (High-Temperature Silicon-On-Insulator) electronics are rated to 225°C but because of their required operating life of 5 years at 225°C, they normally operate up to 300°C with shorter operating life times.

Perma Works has developed a 300°C well logging tool using 100% HT SOI electronics. Based on these electronics, a wire line tool could be built using a Dewared heat-shield and Perma Works 300°C electronics for operation inside a 400°C well for more than 6 hrs. The addition of 2 more hours is highly valued as these are well logging hours. In normal operation, there is time needed to deploy and retrieve the logging tool from the well which consumes potential tool well logging time.

Perma Works has developed circuit board technology which can withstand temperatures over 500°C. This technology was validated under a NASA program and the data can be made available to interested parties. The advantage of this technology is that, if used in a memory tool, it is possible that even a failed seal or stuck tool would NOT damage the electronics.

Consider such electronics coupled with solid-state batteries. The combination will allow the tool builder to build a tool little risk of overheating even inside a 400°C geothermal well. This would greatly reduce the risk of a tool being damaged even if it was over exposed to well temperatures. In short, the Dewar and wired tubing are still expendable items at temperatures above 425°C while the electronics and non-Dewered mechanical parts would be reusable.

Another issue with high-temperature electronics is the lack of high-temperature sensors. At the time of this paper, only temperature sensors are rated 400°C and for use inside a logging tool.

In truth, most well logging sensors are developed for the oil gas industry with a temperature rating of 150°C to 200°C. Perma Works has developed basic set of well logging electronics using all HT SOI electronics for testing any new high-temperature sensors being developed for the aircraft industry. One such sensor is a Silicon-Carbide pressure sensor designed and demonstrated at 750°C by Dr Robert Okojie, NASA Glenn Research Center.[iii] At the time of this publication, Perma Works is talking to Dr. Okojie about using one of NASA's prototype pressure transducers in a geothermal well logging test. However, aircraft only require approximately 500 psi rating while geothermal pressures normally start at 5000 psi. Fortunately, the process of increasing the pressure rating is a simply one, increase the thickness of the sensors physical diaphragm.

Another more direct solution to the lack of 400°C sensors is the use of localized active cooling.

ACTIVE COOLING

Perma Works just completed a study of active cooling for use on an image sensor chip. The hottest commercially available image sensor is only rated to 125°C. Perma Works selected dry ice cooling over other techniques as: Thermoelectric cooling, secondary Dewar inside the primary Dewar and liquid evaporation materials. Interested parties can contact Perma Works for more information on these options.

The dry ice cooling method developed at Perma Works makes use of several interesting properties of frozen carbon dioxide (CO_2), or dry ice. First, dry ice has a very low vaporization temperature of -78.5°C at atmospheric pressure, increasing to 30.5°C at 72.8 atmospheres (critical pressure). This means that the camera compartment could be kept at temperatures well below the camera chip's maximum limit of 105°C for as long as the load of dry ice takes to completely vaporize. Secondly, the latent heat of vaporization for dry ice is 2-20 times higher than the latent heat of fusion for available solid-to-liquid phase-change materials. This means that the vaporization process of CO_2 absorbs much more heat per unit mass than the melting process of the phase-change materials, and it will therefore continue to cool the camera compartment that much longer. Third, once the CO_2 vaporizes, it remains a gas and does not further dissociate or segregate like many of the other phase-change materials tend to do when they boil. And finally, dry ice is readily available in or can be transported to many geothermal locations. It can also be easily manufactured on site from the same CO_2 canisters used to mix carbonated soft drinks at a vendor stand.

In thermal modeling done by Dave Glowka shows that CO_2 cooling can keep the image sensor at temperatures well below 125°C for 4 to 6 hours at 400°C. For sensors as gamma which can be operated from inside the heat-shield, CO_2 cooling will easily keep the sensor cool for an extended about of time.

CONCLUSION

There is no silver bullet for building high entropy (400°C+) geothermal well logging tools. There are a number of tradeoffs which will allow for well logging if the well operator and service provider are willing to accept increased risk and cost compared to conventional geothermal well logging.

Currently, there isn't any 400°C armored wire line logging cable. The use of wire tubing is a potential replacement for wire line however; the cost of wired tubing and the cost of deploying wired tubing are prohibitive. Future research in 400C+ wire line cable or in lower cost wired tubing is needed.

The current state of heat shielding used in standard geothermal wells is limited to ~400°C with reduced operating time and logging cycles. Future work in Dewar flask heat-shields is needed to improve survivability temperatures and number of logging cycles to recover the cost of building the Dewar flask.

Memory mode tools running on slick line offer many cost advantages, but the lack of batteries able operate at the same temperature as new HT SOI electronics is an issue. Existing battery technology based on lithium is limited to 200°C and poses potential health and environment risk. The future development of solid-state batteries could replace lithium batteries greatly reducing risks with using memory tools.

There is a lack of sensors for logging at 400°C. Perma Works is working to move high temperature sensors developed for commercial aircraft engines to use in high entropy geothermal wells.

Perma Works has developed an active CO2 cooler which can be used to maintain the temperature of most any sensor inside a Dewar flask while logging high entropy well.

No clear solution has been presented for logging 400°C, high entropy geothermal wells. Perhaps the greatest hope is of the use of new solid-stage batteries and HT SOI electronics inside an improved Dewar flask using new aircraft sensors or sensors with localized active cooling.

References
[1] Improvements to the Long Term Stavility of Quartzdyne Pressure Transducers, Quartzdyne Inc, Sept 2002, www.quartzdyne.com
[2] Progress Update on Honeywell's DeepTrek High Temperature Electronics Project, Bruce Ohme, Drilling Engineering Association Meeting, Houston, TX, June 20, 2006.
[3] DEVELOPMENT OF FIBERS OPTIC CABLES FOR PERMANENT GEOTHERMAL WELLBORE DEPLOYMENT, R. Normann, J Weiss, and J. Krumhansl, PROCEEDINGS, Twenty-Sixth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 29-31, 2001, SGP-TR-168

Appendix J

FEASIBILITY OF EGS WELL CONTROL SYSTEMS

November 3, 2014
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Perma Works LLC
Grant No. DE-FG36-08GO18185

INTRODUCTION

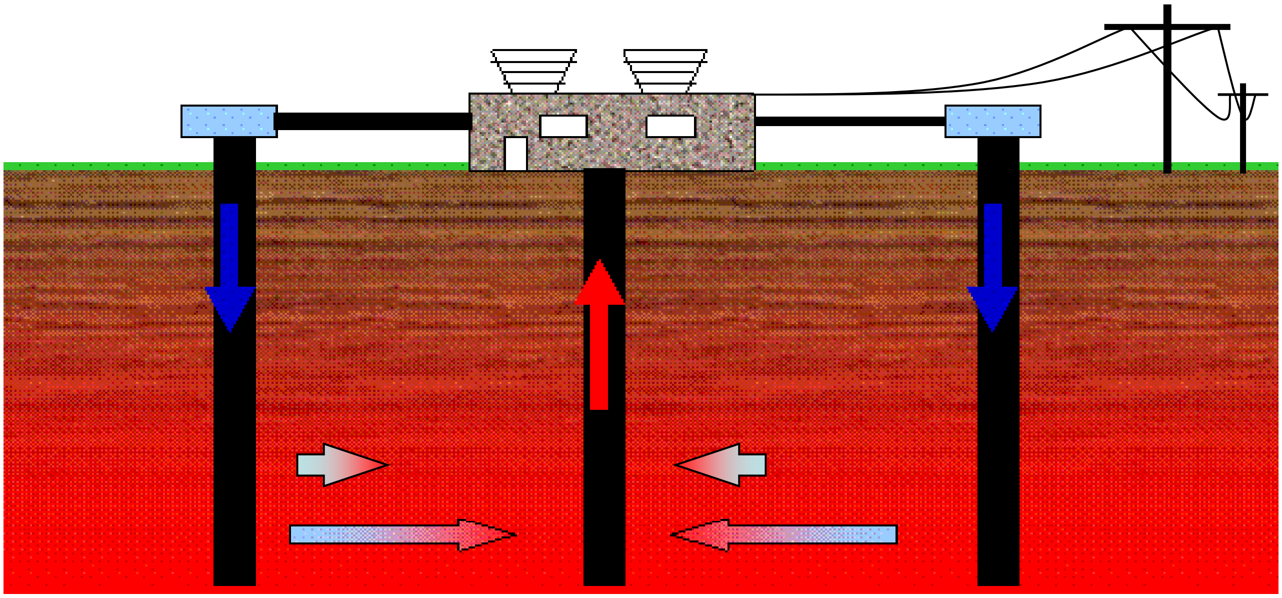
EGS (Enhanced Geothermal Systems) offers mankind a source of near infinite energy. To harness the earth's energy via EGS requires the expense of drilling deep wells and fracturing hot rock formations to mine heat for powering electrical power plants.

Future EGS wells will have multiple production and injection zones to maximize the value of each well drilled. This report envisions a well monitoring and control system supplying the following information and flow controls to the power plant operator:

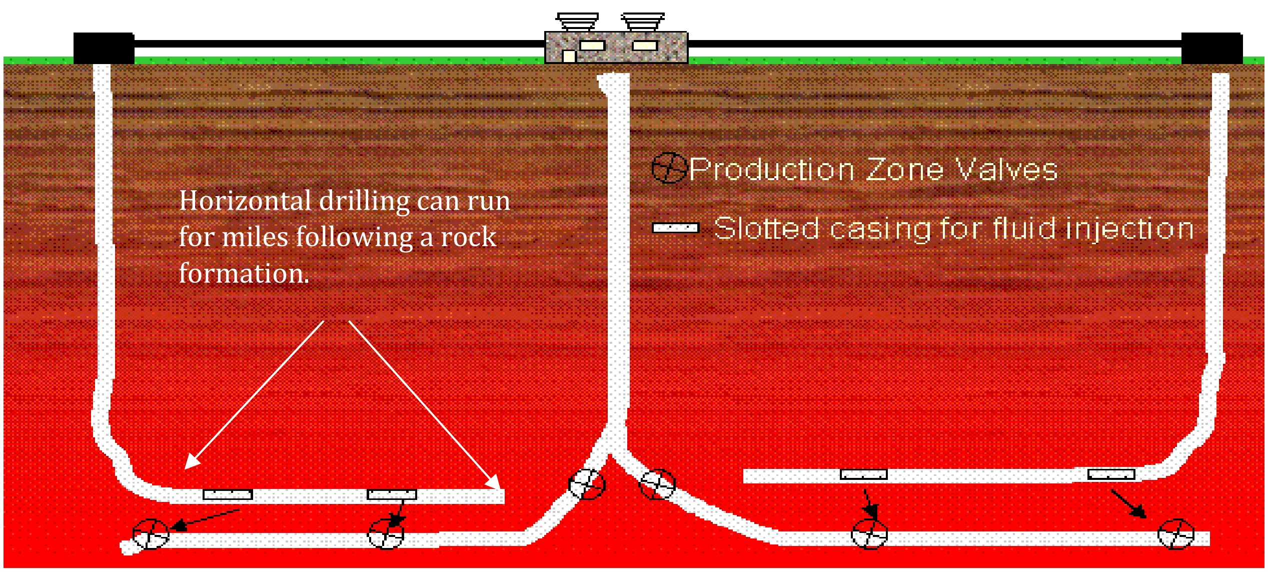
- Temperature and mass flow rates of the production fluids to determine energy entropy from any production zone in the EGS well
- Pressure to:
    - Track fluid levels in the reservoir
    - Detect well inner connectivity
- Track reservoir alterations over time by monitoring formation changes using:
    - Seismic, electromagnetic, resistivity, and other sensors
- Control flow valves on downhole production and injection zones to:
    - Optimize fluid exposure to the formation heat exchanger
    - Increase plant production to meet peak demands

Like multi-completion smart well designs used in the fossil energy industry, the future EGS well monitoring and control system will be built into production tubing with zone isolation between zones or built into well casing. As geothermal fluid production is significantly larger than fossil energy, geothermal EGS engineers may prefer building well monitoring and control systems into or behind well casing. A system built into production tubing can be replaced. For fossil energy, the replacement is normally within 5 years. A system built into or behind well casing is permanent within the well. For the purposes of this report, an operating life time of 10 years at temperatures >100°C is assumed as a reasonable target for controlling future EGS power production.

Below are two illustrations of envisioned EGS wells with monitoring and control systems. The first one is simply an EGS system with two vertical wells intersecting two heat exchanger formations with differing flow rates. The second illustration shows long horizontal wells to exploit a favorable hot rock formation. In each case, the EGS fluid production is controlled by flow valves operated by the power plant. Controlling flow can optimize the energy produced from each well providing energy to the power plant.



Above is an illustration of future EGS wells with multiple production formations from vertical wells.



Above is an illustration of future EGS wells using horizontal wells to mine heat from a favorable rock formation.

In addition to the outlined EGS power production above where deep wells tap in to high temperature formations found everywhere in the deep earth, there is great potential for shallower often lower temperature EGS systems driven by downhole pumps. These systems are generally less than 1500ft in depth with only one production zone. Here the pumps operating cost including its operating life are significant cost factors. Existing pumps cost $300K to $500K each lasting few years. A 10 year pump

Below is an outline of the required EGS technology for building a well monitoring and control system.

Required technology for building an EGS well control system at >100°C & >5K psi

1) Instrumentation
   a) Very low drift pressure, temperature, and flow sensors
   b) Very low drift well electronics
   c) Fiber optic temperature measurement
2) Zone flow control
   a) Electric motor flow control valves
   b) Hydraulic motor flow control valves
   c) Sensor feedback for valve operation
3) Pressure seals
4) Chemically resistant steel (H_2S, HCl, H_2, others)
5) Electronic devices
   a) HT SOI is more than SOI
   b) HT Silicon Carbide, HT SiC
   c) 24/7 operation?

INSTRUMENTATION

VERY LOW DRIFT SENSORS

The EGS well monitoring and control system is assumed to be continuously in the well for +10 years. These sensors need to stay within a known calibration over that period enduring well ambient temperature, pressure, and exposure to geothermal brine. Thanks to the fossil energy industry, pressure and temperature sensors have low enough drift rates, below 200°C, for this exposure. For temperatures above 200°C, it is possible to provide a general field calibration by conventionally logging the EGS well periodically. There are three measurements needed to characterize the energy being captured at a geothermal production zone: fluid temperature, mass fluid flow, and fluid (reservoir) pressure.

<u>EGS Mass Flow Measurement</u>

Today, mass fluid flow is currently a difficult measurement, even for geothermal surface instruments. For the purposes of this report, a short discussion of several fluid flow measurement techniques is outlined below without suggesting any one process over the others for future EGS well control systems.

Potential EGS flow measurements

1. Mechanical spinner: Spinners are not mass flow sensors; however, they are the most common means to measure flow in geothermal production logging tools. They provide a sense of flow

velocity by measuring the RPM of a propeller turned by flowing fluid. The spinner depends on mechanical bearings. It's unlikely spinners could be used in the EGS control system as the bearings typically fail in logging tools within ~10 hours inside the geothermal well.

2. Acoustic Doppler Effect: The acoustic Doppler Effect is used to measure the velocity of bubbles or other materials in the flowing fluid. Like the spinner, this is also a velocity measurement, not a mass flow measurement. However, the acoustic transmitter and receiver can be manufactured from long life, high temperature piezoelectric materials. The acoustic signal is 0.1M to 5MHz. There are issues with high temperature electronic acoustic drive circuits and high speed signal amplifiers at temperatures above 125°C. Buildup of scaling in the well may interfere with this measurement over time.
3. Acoustic time of flight: An acoustic transmitter/receiver pair is placed along the fluid flow path such that the acoustic signal crosses the entire fluid-filled pipe. Subtracting the time of flight of the acoustic signal traveling with the flow from the time of flight of the returning acoustic signal provides a mass flow rate measurement. Again, the acoustic transmitter/receiver pair can be produced with high temperature piezoelectric materials. Such a measurement system is sensitive to gas or steam levels in the fluid along with buildup of scale. There are issues with high temperature electronic acoustic drive circuits and high speed signal amplifiers at temperatures above 125°C.
4. Orifice pressure drop: Measuring the pressure drop across a slight restriction in the flow area (pipe) allows for an accurate mass flow measurement. Only quartz-based pressure transducers are sensitive enough for differential pressure measurements across an orifice. Again, the buildup of scaling in the well can affect the measurement.
5. Eddy current: By generating a magnetic field across the flow area inside the pipe, a small eddy current will be created in the fluid that is proportional to the mass flow rate. This eddy current can be measured as a small voltage by electrical probes in the fluid. The DC nature of this sensor measurement gives it an advantage over acoustic for measurements at geothermal temperatures. However, well scaling will interfere with the probes over time.

Geothermal Pressure Measurements

It's safe to say that pressure is the number one measurement of value in the fossil energy industry. As such, many companies produce excellent pressure transducers for temperatures below 250°C.

Quartzdyne Inc. sells quartz-based pressure transducers with excellent low drift values, -2.8 psi/yr with a temperature rating of 150°C.[1] The Quartzdyne transducer electronics have a built-in reference crystal that is not exposed to the pressure, which aids in compensating for effects of temperature and aging.

More common and less expensive than quartz-based pressure transducers are strain-based transducers. Here, a bridge circuit of 4 strain resistors is used. One leg of the resistor bridge is mounted on a pressure-sensitive diaphragm. The other leg is located nearby on a non-pressure sensitive surface. The second leg provides a means to compensate for temperature and aging of the resistors. Strain pressure transducers operate to higher temperatures than quartz; however, for monitoring reservoir fluid levels, strain transducers have excessive drift over a period of 10 years. At temperatures above 250°C, there is a lack of any strain-based pressure transducer for well monitoring the reservoir fluid level for even 1 year. Strain-based pressure transducers would benefit from absolute pressure reading corrections by periodic well logging.

Geothermal Temperature Measurements

While pressure may be the number one reservoir measurement in the fossil energy industry, temperature is the number one measurement in the geothermal industry. There are several temperature sensors with ratings up to 400°C and higher. The most common temperature sensor used in geothermal logging is the RTD (resistive temperature device).

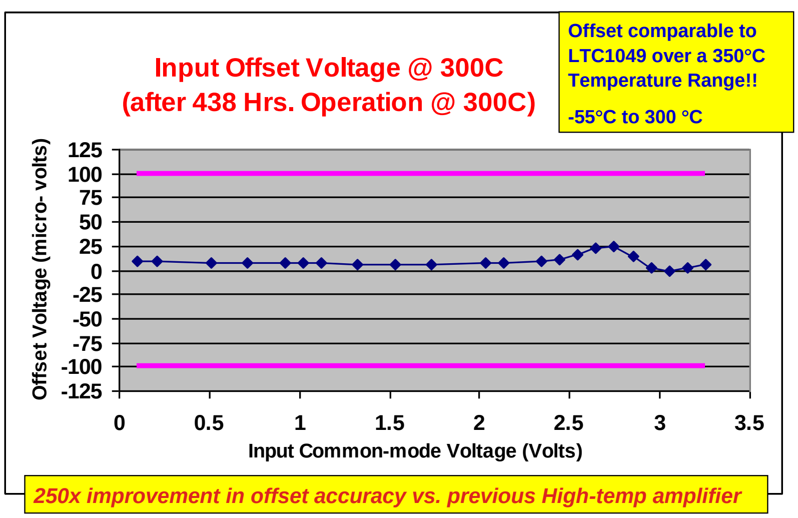
The RTD is an easy measurement using existing high temperature electronics. A 1000 ohm RTD has a linear response of ~ 3.85 ohms/C. Long-term testing in geothermal wells by Sandia National Labs showed small RTD temperature measurement drift over time. This drift is too much for a 10-year monitoring objective. However, running a well log could recalibrate the RTD's absolute temperature value every few years. A potentially better choice is a thermistor temperature sensor.

A thermistor is a bulk resistive device with an exponential temperature response. This limits the practical operating range of any one thermistor sensor used to monitor well temperature. In short, the well temperature needs to be known within ~30°C in order to select the right range of thermistor resistance. Little public testing has been performed on thermistors exposed to geothermal environments; however, a 1-year test in a geothermal well performed by Sandia Labs suggests long term stability may be possible.

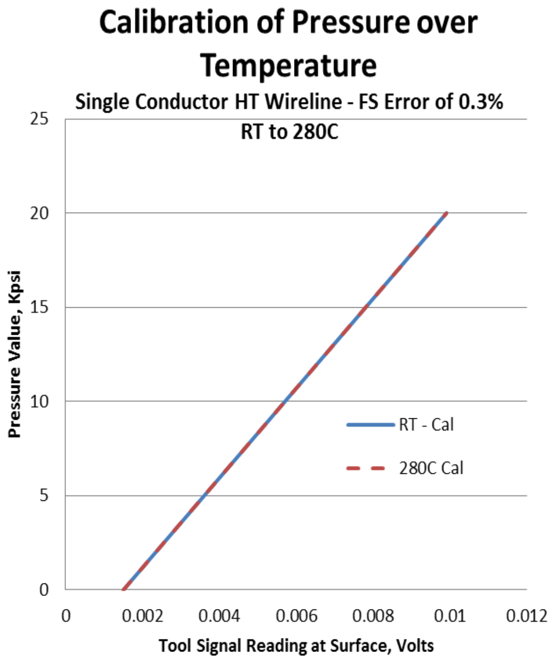
VERY LOW DRIFT WELL ELECTRONICS

One of the major developments coming from the Perma Works' grant is a means to compensate for electronic measurement drift over time and temperature of electronics downhole. Even if the drift of the sensors is minimized, most sensors require amplification before the readings can be converted to digital values useful to the EGS reservoir engineer.

For example, consider the strain-type pressure transducer measurement. The strain-type pressure transducer's full scale output is only 0.022v to 0.1v. The range of the high temperature amplifier and AD (analog to digital converter) is 5V. At 0.1v, so the sensor would only be using 2% of the available resolution. Normal practice is to gain the signal so that nominal values are at 75% of the AD range. So, a precision amplifier is need along with a precision voltage reference for accurate AD conversions.



Perma Works uses the Honeywell OP01 amplifier to amplify the sensor signals. As can be seen in the figure [2] to the right, the error in amplification is <0.000025V even at 300°C. The Honeywell voltage reference needed by the AD is also rated for temperatures up to 300°C; however, there is significant variation over temperature and time. Aging of the voltage reference will cause drift in the sensor readings of analog sensors.



Perma Works has developed a proprietary means to correct for this error. At left is a calibration plot for pressure readings from room temperature to 280°C. This measurement is without computer correction for temperature; only the tool's auto correction was used.

In the future, SiC electronic devices could significantly reduce electronic drift of analog electronics at temperatures above 200°C. One of the first devices developed should be a SiC voltage reference.

FIBER OPTIC TEMPERATURE MEASUREMENT

In the past, DTS (distributed temperature system) fiber optic cables deployed in geothermal wells suffered from the creation of OH[3] from brines containing free hydrogen. Today, a number of fiber manufacturers have improved hydrogen resistant fiber cables. The author does not know of any actual long-term DTS cable test in a geothermal well above 180°C. It seems reasonable to believe the operating life of a DTS fiber below 180°C could meet a 10-year operating life. Based on fiber testing at Sandia National Labs, the operating life of fiber above 250°C could be limited by temperature-induced fiber stress creating hydrogen bonding sites inside any fiber.

ZONE FLOW CONTROL

The EGS fluid flow between injection wells and production wells must be controlled to optimize heat mining from the earth's hot rock formations. In the general case of one injection zone or one production zone, the flow rate of the fluid could be controlled at the surface. However, as in smart well technology in the oil industry, future EGS wells will have many production zones.

As in the oil industry, the cost of drilling deep EGS wells can be offset with one well intercepting many layers of hot rock formations. The issue for EGS is how to control the injection or production rates of the different rock layers. Here the idea of zone flow control for future EGS wells is considered. In the existing lower temperature fossil energy industry 'smart' wells, there are two types of downhole valves: electrically operated and hydraulic operated.

ELECTRIC MOTOR FLOW CONTROL VALVES

The author is unaware of any existing flow control valves installed deep in a geothermal well. However, testing of inductors at Perma Works suggests it is possible to build high torque electric motors for geothermal temperatures. The magnetic steels will maintain most of their magnetic properties at EGS temperatures. In extreme temperatures, ceramic-coated wire can be used in the motor windings, replacing enameled wire. The engineering issues of thermal expansion for bearings, rotating face seals, and bearing ware over time are obvious issues. These issues are outside of Perma Works' grant; however, the use of oil-filled motors to balance well pressures could reduce issues related to face seals and bearing ware.

A greater issue dealing with electric motors is supplying power to the motor downhole. Existing technology for cabling signal and power down the geothermal well is to place wires inside steel tubing. The use of ¼ inch tubing has been used in the geothermal industry for low power well monitoring electronics. Adding power for a high torque motor downhole will require much larger wire and tubing. As the tubing diameter increases, the pressure rating decreases unless the tubing wall is made thicker. This makes the tubing increasingly expensive and more difficult to work with.

One potential solution is to use high voltage wire to reduce the current running down the cable. This requires a high voltage, high temperature power converter downhole. There is a bright future for such electronics within the power electronics industry based on SiC power electronics. Unfortunately, today there is no solution for the high voltage, high temperature capacitor required by the power converter. For the power electronics industry, very large capacitors pose an inconvenience since inside the geothermal well, space is tight, and the form factor is tubular. There are no 100V, 100uF capacitors for use in geothermal wells.

Rechargeable batteries have been used in the fossil energy industry for motor power downhole.

RECHARGEABLE BATTERY TECHNOLOGY

Battery power is used in fossil energy smart wells to close electric motor driven valves installed in the well. In the fossil energy industry, well instrumentation provides reservoir data to determine the oil-brine cut coming from different production zones in a multi-completion well. During the life of the well, the oil-brine cut starts to favor the brine to the point a production zone is unprofitable. At that point, a valve is closed, sealing off unwanted production.

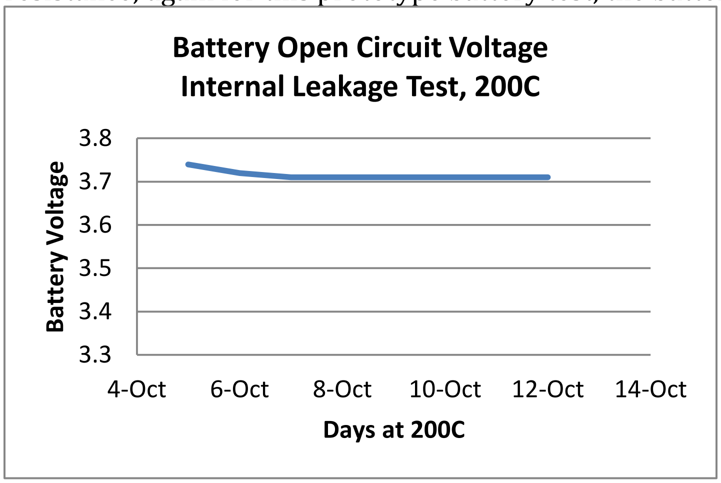
For geothermal EGS controls, the control valve may need to open or close or even throttle back fluid production to enhance heat transfer to the fluid. The EGS production zones will require high temperature and high torque motors with directional controls. These high torque motors require high currents. This current is difficult to drive down a long cable from the surface. A local rechargeable battery can source the motor's current while accepting a small recharge current from the cable. It is reasonable to assume the valve motor is inactive (>98% of the time).

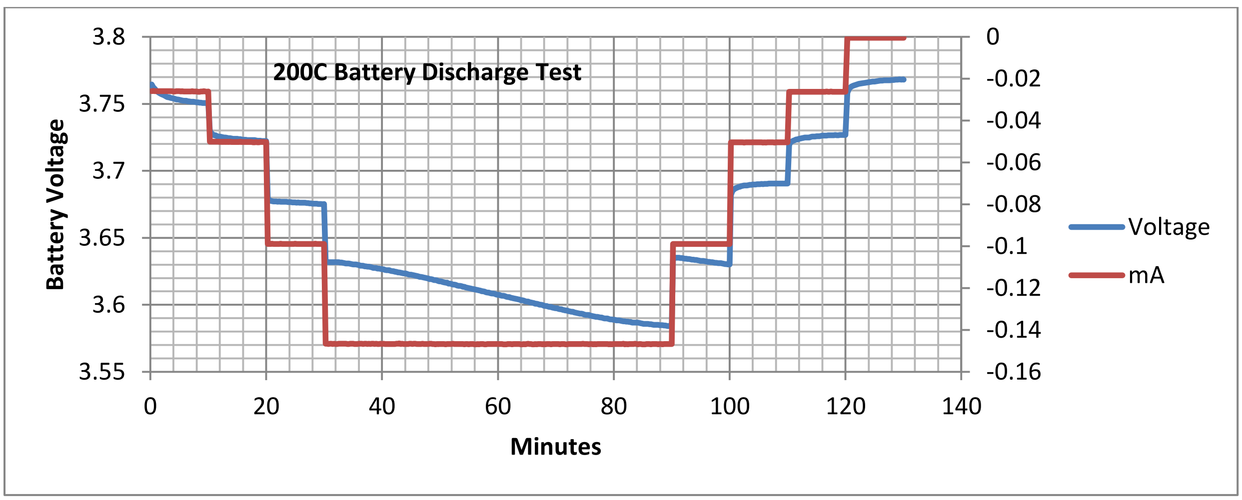
Requirements for a rechargeable geothermal battery:

- Operate at geothermal temperatures: >100°C
- Accept a recharge at geothermal temperatures greater than the battery's leakage current
- Provide 10 or more years of operation at geothermal temperatures

Current battery technology for operating above 100°C is lithium based. Rechargeable lithium batteries are rated up to 125°C (primary cells can reach 200°C). However, every caution needs to be exercised when working with lithium cells inside a geothermal well. The battery temperature is the battery's internal self-heating **plus** well ambient temperature. In the case of a short circuit on the battery (as occurs when a tool floods with well fluid from a failed seal or simply an electrical short), the battery can generate significant internal heat to melt the lithium metal. Under these conditions, the lithium cell will rupture (vent) or even detonate.

It is unlikely future EGS well control system designers will accept rechargeable lithium batteries for valve motor drive systems. However, recent developments in fluoride-based rechargeable solid-state batteries may offer a possible solution to EGS well control motor drive circuits. Solid-state batteries based on fluoride ionic conductors can operate at geothermal temperatures and operate without risk of detonation. This new technology is still in the prototype stage. However, testing at Perma Works on solid-state batteries developed by Dr. Potanin is promising. Below are the results of a 2-week ambient 200°C battery test. The battery was not loaded. For at least two weeks at 200°C, there was no detection of energy loss caused by internal leakage current as indicated by the flat voltage measurement. Following the 2-week 200°C exposure, the battery was discharged at several current loads to monitor the battery's internal resistance; again for this prototype battery test, the battery worked well.





HYDRAULIC MOTOR FLOW CONTROL VALVES

Hydraulic driven motors have been used in the fossil energy industry. This concept is outside the research at Perma Works under the grant. To enhance future discussion, some basic information is provided. In general, the hydraulic motor is driven from the surface by hydraulic pumps outside of the well. The hydraulic pressure is transmitted via hydraulic tubing to the flow control valve hydraulic motor downhole. The clear benefit of hydraulics is that no power electronics or batteries are needed. Also, hydraulic motors are simpler in their design. The down side is that additional tubing is installed in the well: tubing for both the hydraulic lines and the well monitoring electronics. Increasing the number of tubes greatly increases the complexity of the installation process and increases risk of crushed or creased wired tubing or hydraulic tubing.

SENSOR FEEDBACK FOR VALVE OPERATION

Feedback is a general requirement for all control systems. In aircraft control systems, it is common to request a function (such as cut back fuel pressure) followed quickly by sensor confirmation (reduced engine trust). Building from what the aircraft engine industry is providing can benefit the EGS control system.

For example, monitoring an electric motor current and tracking it over time provides a good measure of motor stress required for moving the valve. Indexing the valve with a sensor allows the operator to know the valve's position independent of the motor operation. The measure of vibration at the control valve might be a good indication of changing fluid flow through the valve. These types of control sensors are common to the aircraft and will aid in future EGS well control systems.

PRESSURE SEALS

In general, geothermal temperatures will destroy organic materials over a 10-year period. For EGS control systems, there are no cheap O-ring solutions for pressure sealing tools. The only valid solutions are inorganic seals such as a metal-to-metal or ceramic/glass to metal seals. At Perma Works, we have worked hard to develop removable metal-to-metal C-ring seals for all our tools' pressure seals. Even these seals suffer small microscopic leaks, which will lead to failure over 10 years in the well.

The best seals are large-area glass/ceramic to metal seals, welded joints, and some crush seals as used by Swagelok for pipe fittings. All of these seals are one-time use. The tool cannot be reopened and repaired in the field if an installation process runs into a fit issue. Also, welding a tool joint with electronics inside creates the potential danger of overheating the electronic assembly.

Another concept investigated at Perma Works but never well tested was to acid treat the steel joint and then solder the joint closed. Here, the solder was either a lead-based solder (~400°C) or low temperature silver braze (<900°C). The benefit of these processes is to reduce the heat needed to create a weld-like seal.

CHEMICALLY RESISTANT STEEL (H2S, HCL, H2 OTHERS)

The fossil energy industry has specifications for metals used in sour wells up to temperatures of 175°C. These specifications are commonly referenced by tool builders in the geothermal industry. For temperatures above 200°C, there is little information. As such, Perma Works builds pressure housings and cables from expensive chemically resistant and temperature stable metals such as 17-4ph for pressure housings and Incoloy for wired tubing.

Future EGS well control systems could benefit from research on the long-term effects of different alloys in geothermal brines at differing temperatures. Research on other non-metal materials such as ceramic pressure housings might lead to new types of materials for solving EGS well control system issues.

ELECTRONIC DEVICES

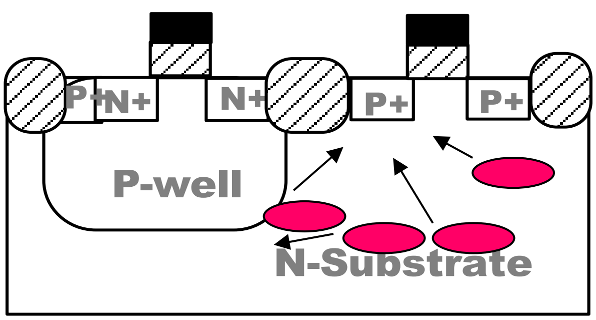
HT SOI IS MORE THAN SOI

In the 1980s, it was realized that SOI electronic devices would operate to higher temperatures than bulk silicon. Today three additional SOI enhancements are used to create high temperature SOI (HT SOI). HT SOI electronics can operate to temperatures over 300°C and operate reliably at for years at temperatures 225°C or even higher. The three changes required to make HT SOI are:

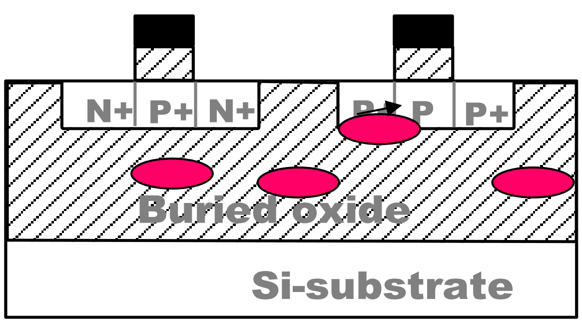
1. Model the transistor for higher temperatures. The old transistor models taken from bulk silicon up to 175°C will not accurately predict HT SOI transistor behavior at +200°C. (Many people have spent good money simply moving existing circuit designs to SOI to find they simply don't work.)
2. Increase the logic level threshold for the MOSFET gate from ~0.9V to 1.0V. This allows digital circuits to continue operating with increased gate current.
3. Improve metallization on the silicon chip. Low temperature silicon devices can work well with aluminum pads on the silicon. However, at higher temperatures the aluminum migrates into the silicon and weakens the electrical connection to the point of failure.

<u>Why SOI?</u>

When silicon electronic devices are heated, there is an increase in thermally generated free electrons. This excess of electrons is called a 'dark current.' The higher the temperature, the more free electrons are created and thus the higher the dark current.



A: Cross-section of bulk CMOS inverter



B: Cross-section of a SOI CMOS inverter

Standard bulk silicon electronic devices build transistors into a doped silicon substrate that is a conductor (see figure 'A' at left). Any dark current created in the substrate can flow to active circuit transistors, as seen as pink circles. At some elevated temperature, the dark current will swamp a transistor, and the circuit will fail to function. For bulk silicon devices, the analog circuits are sensitive to dark currents as low as 125°C, while digital circuits can run a little hotter, 150°C to 200°C. To reduce the creation of a dark current interfering in the working electronic circuit, HT SOI isolates circuit transistors on a nonconductive layer of silicon oxide. With HT SOI, the dark current generated in the oxide is unable to travel (see figure 'B' at left). Only dark currents created inside the transistor silicon are problematic in HT SOI. It's generally accepted that dark currents are reduced in HT SOI by approximately X100. Under oven testing, HT SOI analog devices provide reasonable performance up to 275°C, while digital circuits can run over 300°C. Digital circuits normally fail with a logic gate being locked to a '1' as the dark current is over whelming the device's ability to pull a logic '0'.

SOI construction adds only a small improvement in operating life. The number one aging factor for electronic components is metal migration.

<u>Metal migration shortens the life of HT SOI</u>

All transistors on the IC are interconnected by a metal layer. The type of metal used in the metal layer is called the device's metallization. Standard electronic components use Al (aluminum) for the metallization on the IC. Unfortunately, Al is a light metal. As such, Al atoms will migrate into the silicon as a function of time, current density, and temperature. To illustrate changing current density, metal and temperature on metal migration, several engineering choices are given below.

Silicon ICS[2]			
Metal	Temp	Current Density	Estimated Life
Al	150C	5mA/cm2	1.8 years
AlCu	225C	0.5mA/cm2	5 years
W	300C	5mA/cm2	20 years

In the table above, the use of tungsten (W) looks to be the best option; however, tungsten is a poor conductor, which reduces the circuit's bandwidth for high speed circuits. Also, although a 20-year operating life at 300°C is very encouraging, other failure modes within the silicon device will now dominate the expected operating life, preventing the designer from realizing such an extreme life.

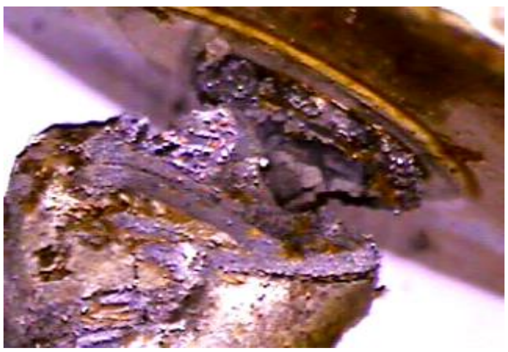
Other issues with long life electronic circuits at geothermal temperatures

Capacitors have greatly improved over the past 4 years during the grant work. The capacitors Perma Works started with are not the ones used today. Today, Perma Works is using high temperature NPO ceramic capacitors for small signal circuits. A 50V rated NPO capacitor designed for high temperatures and operated at 5V has a good chance of operating for 10 years in most EGS temperatures. Unfortunately, there is always the potential for an early failure of a ceramic capacitor. Ceramic capacitors fail without warning and most often in a catastrophic short circuit. A failed ceramic capacitor short circuit is so hard that circuit traces on the circuit board are normally melted away. Any one ceramic capacitor failure results in the complete loss of the circuit it is in.

It is possible to fuse the capacitor for an added cost and reduced circuit performance. Under the DOE grant, Perma Works uses a small fuse on the capacitors used in the tool power circuits.

Large valued capacitors for temperature >150°C are a major issue. Ceramic capacitors can be produced up to ~10uF. For motor drive circuits or other higher power circuits, the designer needs 50uF or large capacitors. At lower temperatures, electrolytic, tantalum, or polymer capacitors can be used, but these capacitors simply do not exist for higher temperatures. Both electrolytic and tantalum capacitors have been pushed to 225°C but suffer from significantly shortened operating lives (a few 1000 hours) at those temperatures. Polymer capacitors have a unique ability to fail as an open circuit. They are a preferred capacitor for high power circuits on aircraft. However, at temperatures over 200°C, they lack mechanical stability in packaging.

Solders are an issue in part because of intermetallic growth and simply because the geothermal market is so small. For a 10-year life at temperatures above 125°C, the use of standard 60/40 tin/lead solder with copper wire and circuit board traces is not possible. These metals form an intermetallic that causes the solder joint to fail over time. The image to the right is a failed solder joint after 1 year and 193°C. At Perma Works, we use MHP solder with 95% lead and gold-nickel plated circuit board trances



and nickel clad copper wire. Now the intermetallic issues are pushed to over 300°C.

This is not a popular solution. The MHP solders are difficult to work with. The assembly of HT SOI circuits for geothermal well monitoring and control tools requires highly trained technicians using hand soldering. Given the increased complexity of future EGS control electronics, there is always a chance for human error in soldering electronic components.

A new solder for geothermal temperatures that is as easy to use as a standard 60/40 solder would benefit the assembly of geothermal tools. Even better, a means for automated soldering or other circuit interconnection process for high temperature circuits would reduce the chance of human error. The aircraft engine industry with 100,000+ sales in electronic control systems can easily afford fully automated assembly to reduce human error.

HT SILICON CARBIDE, HT SIC

Silicon Carbide (SiC) is a wide bandgap semiconductor. This means the energy needed to free an electron from the SiC lattice is higher than the energy needed to free an electron from silicon. The bandgap for SiC is ~3.2 eV (4H lattice), while for silicon it's 1.1 eV. The wider bandgap greatly reduces thermally generated electrons in the SiC semiconductor lattice. SiC electronic devices are commonly tested to temperatures of 500°C.

SiC is better at conducting heat than Silicon. SiC thermo conductivity is 3.7 $W \cdot cm^{-1} \cdot K^{-1}$, while silicon is 1.3 $W \cdot cm^{-1} \cdot K^{-1}$. This is an important value for EGS well monitoring and control systems. Heat is generated in all electronic devices. This heat is produced at a localized point in a junction inside a transistor located inside the device. For geothermal with ambient temperatures already >100°C, the transistor junction temperature is ambient plus self-heating. For power devices handling watts of energy, the transistor junction temperature can quickly exceed the device operating temperature. Knowing that the metallization life of an IC is a function of time, temperature, and current density, the local effects on a transistor's metallization can cause early failure. The life of the EGS well monitoring and control system is based on the weakest link, which in most cases is going to be the power circuit.

At Perma Works, we have evaluated some SiC power devices for operation at temperatures of 250°C. These devices have had poor life performance. Manufacturers have been slow to design SiC for high temperature applications. Just like silicon HT SOI, SiC needs more than a wide bandgap; SiC devices must be designed and packaged for high temperatures.

At the time of this report, GE's Avinash Kashyap from GE Global Research announced at the SAE 2014 Aerospace Systems and Technology Conference that GE had broken through two of the primary issues limiting the use of SiC as a major contributor to the commercial production of high density, high temperature electronic devices:

1) commercially producible MOSFET transistors for large scale ICs and
2) metallization and device packaging demonstrated at 500°C.

The development commercially producible MOSFET SiC transistor integrated circuits will lead to very high temperature devices as sensor amplifiers, voltage references and potentially even microprocessors. GE suggests SiC ICs manufacturing can become commercially available in the near future.

GE's demonstration of SiC metallization and device packaging 500°C suggests improved operational life at lower EGS temperature as high as 300°C. Continued research in SiC operation life at EGS temperatures is suggested. Testing SiC designed for power circuits, such as motor drive circuits, should include power cycling to expose transistor junctions to temperature cycling created by self-heating.

A note of caution, there is a general rule which in the history of electronic components has consistently proven true. If it can be done with silicon, silicon wins. In short, silicon electronic devices have every commercial advantage over all other semiconductors (Ge, SiC, GaN, GaAs)—it has unmatched wafer size, unmatched crystal purity, all transistor types, lowest cost of fabrication, and so on. The geothermal industry will benefit from high temperature electronics that also find success in larger markets. For example, an HT SiC analog-to-digital converter (AD) would benefit the over 200°C EGS well monitoring and control system. However, if the only market is geothermal, such a part might cost ~$50,000 each. In the electronics industry, a 1Million/year production is considered a small market.

24/7 OPERATION?

As already noted, two of the main failure processes limiting circuit life for EGS well monitoring and control systems involves bias voltage (for capacitors) and current density (for HT SOI & HT SiC ICs). If the well monitoring and control system is cycled on for only a few minutes per day or week, the expected operating life time is significantly increased.

For new EGS systems, running the well monitoring circuits may require 24/7 to track and model the reservoir to optimize power production. After the EGS system settles in to a steady-state mode, the well monitoring system could be used to monitor the reservoir daily or weekly.

Other sensors such as seismic monitoring that need to be on 24/7 to capture unexpected reservoir events should be electrically fused and run on a separate power circuit from the other sensors such as temperature, pressure, and flow.

CONCLUSION

It is possible to design EGS well monitoring systems for a 10-year life below temperatures of 225°C. The number one limitation for EGS well control systems is the lack of a downhole flow control valve and the lack of large valued, high temperature capacitors.

It seems possible to design EGS well monitoring systems for temperatures of 225°C to 300°C and life <10 years. The internal compensation of electronic measurement circuits developed by Perma Works will aid in realizing these high-temperature EGS resources. Moving US manufacturers from AlCu metallization to W will improve the operating lives of HT SOI for these higher temperatures. Periodic well logging will be needed to correct sensor drift of pressure and temperature sensors. Production and injection zone flow sensors require additional research on the long-term effects of geothermal brines. They will also require periodic well logs for correction of absolute flow measurements.

HT SiC electronics will enhance the creation of well monitoring and control systems in the future. The areas of most benefit are in power and analog circuits. An HT SiC voltage reference needed for AD conversion is one example. Today silicon voltage references are operational to 300°C, but error in the reference value above 275°C is significant.

For new EGS systems, running the well monitoring circuits 24/7 to track and model the reservoir to optimize reservoir power production will be required. After the EGS system finds its steady-state mode of operation, the well monitoring system could be powered to monitor the reservoir only daily or weekly. Reducing the powered on time of capacitors and ICs increases their operating life.

Other sensors such as seismic monitoring which need to be on 24/7 to capture reservoir events should be fused and run on a separate power circuit from the steady-state sensors such as temperature, pressure, and flow.

Future EGS well control systems can benefit from research on the long-term effects of geothermal brine on metal alloys. Research on other non-metal materials such as ceramic pressure housings might lead to new concepts for solving EGS well control system issues and reducing system costs.

A new solder for geothermal temperatures that is as easy to use as the standard 60/40 solder would benefit the assembly of geothermal tools. Even better, a means for automated soldering or other circuit interconnection process for high temperature circuits would reduce the chance of human error.

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[i] Electrochem Solutions, "Primary Lithium Battery Safety and Handling Guidelines", Rev 2010A1, web site: http://www.electrochemsolutions.com/pdf/Safety_and_Handling_Guide.pdf

[ii] Dr. Alexander Potanin for High- temperature Wells": Oral presentation, High Temperature Electronics Conference (HiTEC), May 13, 2014, Albuquerque, New Mexico, USA, Oral presentation

[iii] Robert Okojie, "Demonstration of SiC Pressure Sensors at 750°C": Oral presentation, High Temperature Electronics Conference (HiTEC), May 13, 2014, Albuquerque, New Mexico, USA.