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Developing 300°C Analog Tool for EGS

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Disclaimer

Abstract:

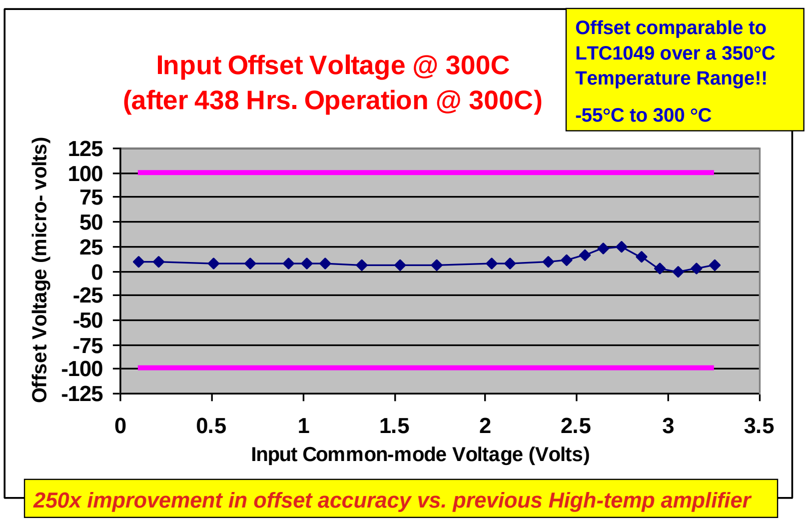
This paper covers the development of a 300°C geothermal well monitoring tool for supporting future EGS (enhanced geothermal systems) power production. This is the first of 3 tools planed. This is an analog tool designed for monitoring well pressure and temperature. There is discussion on 3 different circuit topologies and the development of the supporting surface electronics and software. There is information on testing electronic circuits and component. One of the major components is the cable used to connect the analog tool to the surface.

DEVELOPMENT OF A 300°C ANALOG TOOL

Perma Works proposed in the grant to upgrade the existing Sandia HT SOI well monitoring tool concept to better support enhanced geothermal systems (EGS) hydraulic-fracturing operations within the first year of the grant.

The new analog tool provides real-time pressure drop-offs at the point of hydraulic fracturing during geothermal well stimulation. Having accurate high-speed pressure fall-offs improves the accuracy of calculated fracture volumes and fluid flow. The tool can stay in the well for months following hydraulic-fracturing operations, allowing well owners to fully characterize their resource by conducting reservoir pull-down and recover tests, pulse injection tests for well conductivity, and anything else the reservoir engineer can think of. All of these reservoir tests will be conducted for less money by eliminating logging crews normally required to run a conventional heat-shielded tool in and out of the well for every test.

The surface electronics are able to operate from a solar panel and 12-volt battery for remote data collection, using on-board memory. Unlike the Sandia tool, new, highly improved HT SOI Honeywell amplifiers (HTOP01) will greatly improve the accuracy of the well monitoring tool. The HTOP01 has nearly 100× the DC amplification accuracy of the previous HT SOI general-purpose amplifier from Honeywell. The data plot to the left is from Honeywell. Here they show the offset DC error on this test device to be inside of $25X10^{-6}$ volts. The DC offset of the Honeywell HT1104 is ~2×10^{-3}.



Also, the Sandia tool does not have real software support for collecting and presenting data to the reservoir engineer. Software is important to the service company because well owners want data in the standard LAS format used by the logging industry.

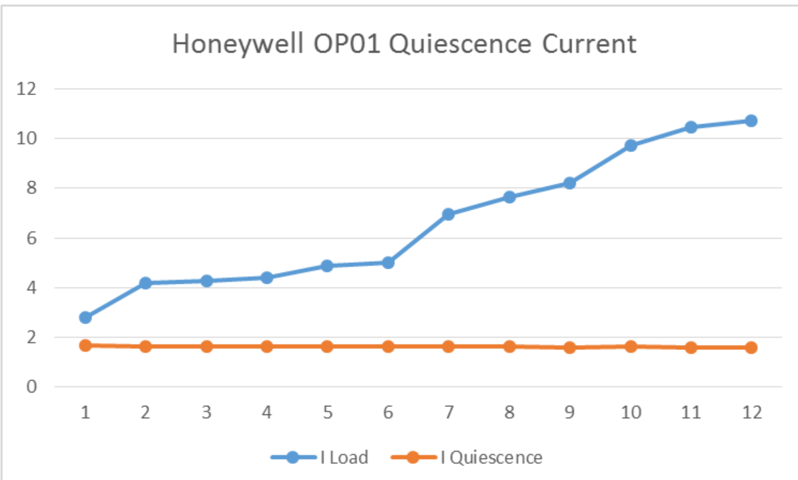
REQUIRED COMPONENT TESTING

In general, HT SOI electronic parts are designed for five years of operating life at 225°C with a degraded life and performance at higher temperatures up to 300°C. These components have been designed for use on commercial aircraft engine control systems. Control electronics are not ideal for use in well logging electronics, as logging systems are directed toward scientific sensor measurements and not control functions. One of the most significant differences is in the analog to digital (A/D) converter ICs. An aircraft knowing the movement of an exhaust break on an engine only needs 8 bits of accuracy (2^8 = 256 positions), while the A/D for tracking 20,000 psi of well geothermal pressure requires ~1 psi resolution as in a 14 bit A/D, (2^{14} = 16,384 positions).

In this projects, Perma Works worked with engineers at Honeywell to develop to commercial readiness three ICs needed for building geothermal tools. These ICs are all HT SOI devices: a 12-bit A/D IC, an electrically erasable programmable read only memory (EEPROM), and an 8-bit latch. The latch was needed to support the existing Honeywell HT8051 microprocessor that could use the EEPROM. More on these devices will be discussed in the follow-on document for the Perma Works digital tool. It is important to understand that, before having a digital tool, the tool designer needs to have analog sensors and electronic amplifiers on the front end, with the accuracy and resolution supporting the digital circuits. In this case, we need at least 12-bit A/D resolution.

The analog tool is a needed first step. It is also the simplest and least expensive type of logging tool to buy and sell. In building the analog tool, Perma Works leaned a lot about the issues for building geothermal logging and well monitoring tools, and about the market needs of the geothermal industry.

Perma Works worked exclusively with HT SOI electronics with a manufacturer rating of 225°C. Unlike standard commercial electronics, many of the new HT SOI parts have unique, undocumented attributes. This is most likely caused by new HT SOI manufacturers pushing to get their new products out on the market with a minimum of design cycles. In order to really test circuits to geothermal temperatures requires building complete analog tool designs to capture the circuit's performance with all the parts working together. Simple things as the clocking of the analog mux would double the clock at temperature because the rise time was too slow, or one of the analog operational amplifiers has an unusual output feedback path internal to the device, causing its input impedance to change significantly with temperature.



The data plot above on the Honeywell HTOP01 is an HT SOI signal amplifier. Here, testing was done to validate the quiescence supply current the amplifier draws as a function of the output signal current. This was needed because one of the analog tool options was to use the supply current as a means to transmit data to the surface. In this case, success is measured by how flat the quiescence current is maintained. This device looks good.

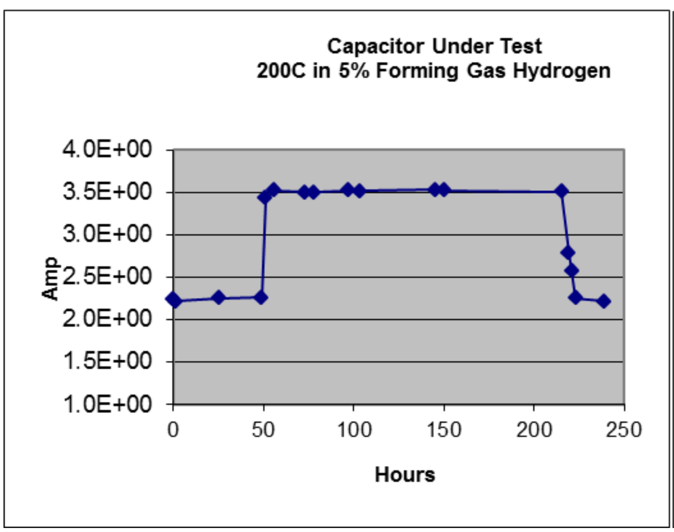
HYDROGEN TESTING

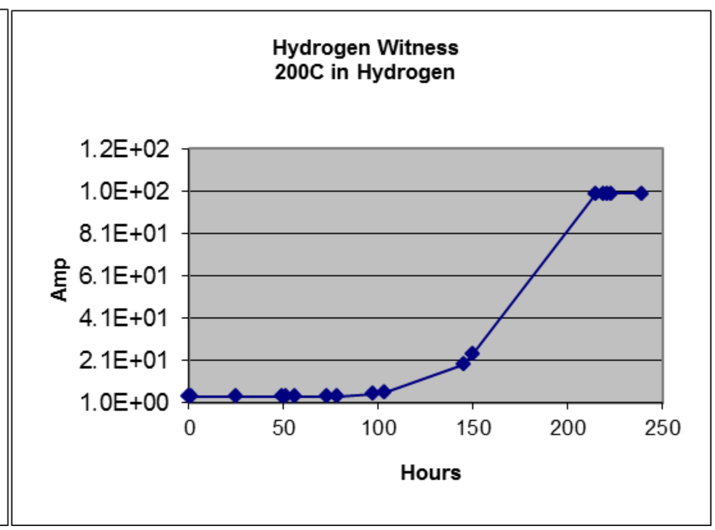
There is some small amount of free hydrogen in all wells, including geothermal wells. One of the sources of hydrogen comes from geothermal brine interacting with steel, as in the well steel casing or the steel of the logging tool's pressure housing. The hydrogen atom is so small and so active at elevated temperatures that hydrogen will penetrate a tool's high-pressure steel housing and interact with the logging tool's electronics within 24 h 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 H_2O inside the tool. Second, hydrogen damages some components, most notably resistors. Resistors are used to fix the 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 h 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. 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 a hydrogen-forming gas that 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 oven's metal housing. The ability of the oven to hold a constant hydrogen level is shown in the capacitor test example given below.

In almost 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 below, a capacitor and a resistor with known hydrogen sensitivity were placed in the Perma Works hydrogen test oven.





The devices were subjected to an oven temperature of 200°C for 50 h in local Albuquerque air in order to validate that there was no effect due to the elevated temperature for these high-temperature devices. After 50 h, 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 was immediate. The response by the witness resistors was also immediate but at a slower building rate. After about 200 h, the hydrogen-forming gas was turned off and the leakage current in the capacitor dropped back to normal, and the witness resistors' values stabilized at new peak values.

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 --- Unusable

Resistor thin film --- Slow increase in resistance over time

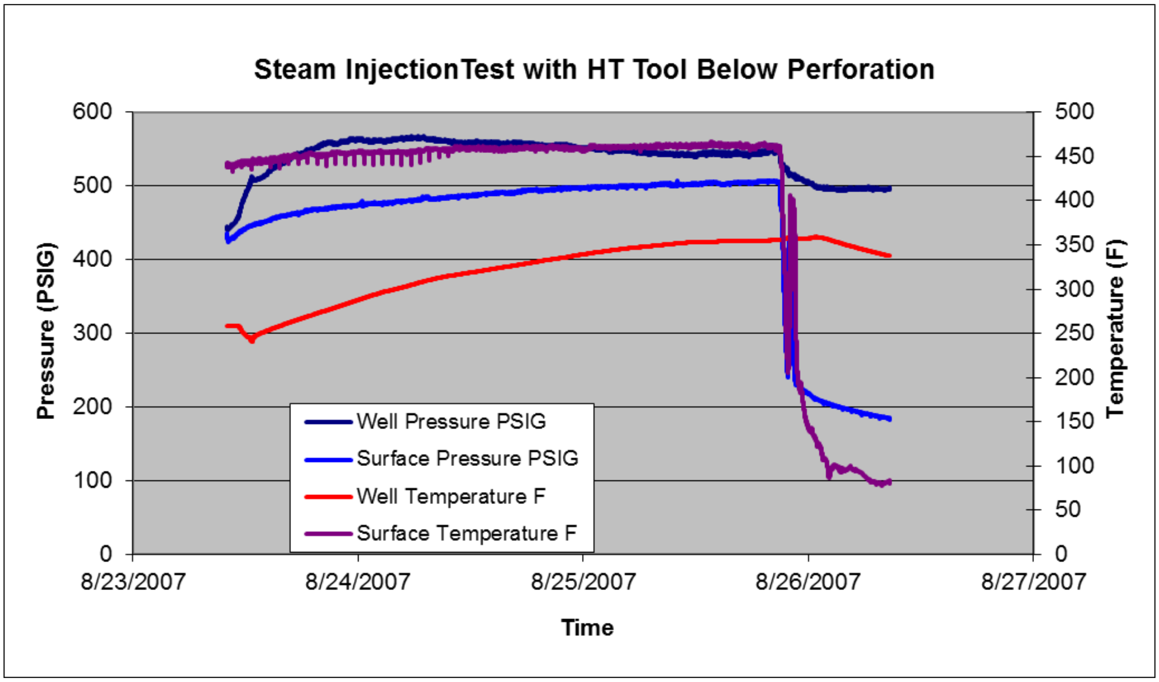
Resistor metal film --- Little change

Resistor wire wound --- Stable (might also be the result of being physically large that more time is needed)

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 H_2O. At geothermal temperatures, the H_2O 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 WELL MONITORING TOOL STARTING POINT

Getting the analog circuits right is critical to all future high-temperature tool development. In the original program plan, Perma Works was taking advantage of research started at Sandia National Labs and moving it to a commercial use. The 250°C well monitoring tool was demonstrated by Sandia Labs in a steam injection well outside of Bakersfield, CA. An example of data from the well is below.



The older Sandia analog tool only made pressure and temperature measurements. Each measurement was transmitted to the surface using a voltage-controlled oscillator (VCO). As the sensor changed value, the VCO output frequency changed. The pressure and temperature measurements were alternating between each other, driving the VCO signal on to the cable. The cable was ¼ inch tubing with a high-temperature fiber insulated wire inside it. The wire was manually placed into the tubing. Manually pulling wire into the tubing is only possible for short lengths, <900ft as steam injections wells. Under this grant, Perma Works worked with Draka Cableteq USA to automate building the wire inside the tubing for future geothermal wells. The wire inside the tubing was carrying DC power down to the tool and the VCO signal back up to the surface receiver. The metal tubing itself was used for power and signal grounding.

In the data plot above, there are two sets of pressure and two sets of temperature. Well pressure and temperature is coming from the tool downhole and the surface pressure and temperature are coming from sensors mounted at the well head. It is always good to track well head measurements with downhole measurements. The reservoir engineer wants to understand how the reservoir is creating or reacting to changes in production or injection seen at the well head. Knowing what is happening at the surface helps correlate responses with stimulus for future EGS development. The Perma Works surface equipment was also designed to track tool data with well head data.

The Sandia tool had been built using electronics known to work up to 300°C. However, Sandia lacked circuit boards and test ovens for testing a complete tool beyond 250°C. Under this grant, Perma Works built long test ovens rated over 300°C. Perma Works also developed 300°C circuit boards and tested high-temperature solders. Perma Works also built a hydrogen test oven to test component stability at temperature and well hydrogen exposure.

DESIGNING A 300°C WELL MONITORING TOOL ELECTRONICS SUPPORTING EGS

The first tool development under the grant was an analog tool, meaning the sensor measurements are amplified and placed on the logging cable where the surface receiver performs the conversion to a digital value. This greatly reduces the circuit complexity downhole. Reducing circuit complexity generally results in higher reliability. Also, all the circuits of the analog tool will be needed for the future digital tool. The clear benefit of a digital tool is that digital data transition on the cable is lossless. By far, most logging tools are digital tools. The Perma Works analog tool needs to perform with enough measurement accuracy to track the small changes in reservoir temperature and pressure valued by the reservoir engineer to justify the cost. Given geothermal well temperatures and that most logging trucks have 10,000 ft. or more of cable, this is no easy task.

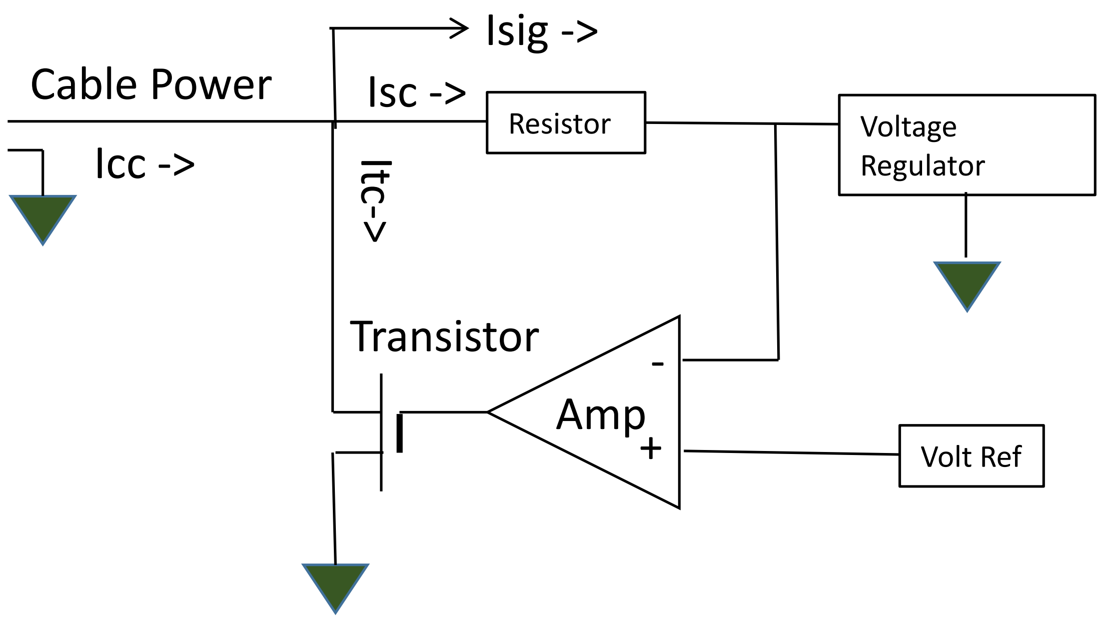
There are three basic instrumentation concepts generally used to design an analog tool operating on a long cable. These are listed below.

1. **Constant current.** Generally, sensors are powered from a constant current circuit at the end of the cable. A standard commercial value is 4-20mA. Here, the circuit draws a fixed supply current of 4mA while the sensor amplifier draws the difference based on sensor value. So, a cable drawing 10.542mA on a 4-20mA circuit would be a signal of 6.542mA. Calibration for temperature and pressure are C/mA and PSI/mA, respectfully.
2. **Voltage-controlled oscillator.** 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, 1 KHz might mean 0°C and 1.3 KHz might mean 300°C for a temperature measurement calibrated as C/Hz.
3. **Multi-wire.** Here each sensor located in the downhole tool has a wire leading to the surface. For a pressure and temperature tool, four wires are required: two signal wires plus power and ground. This is the easiest to design for but increases the cost of the cable. Given that future EGS wells might be 5K ft. to 30K ft. deep, cable costs quickly become a major cost factor.

The following discussion on each of the methods above will be useful.

Constant Current. Complete downhole tool circuits based a constant current type circuit were designed by Perma Works under this grant. This method does functional work at 300°C. A commercial constant current setup is 4-20mA, where 4mA is zero signal (all 4mA is for nominal operation of the electronics) and 20mA would be full-scale sensor output. The full scale of the sensors is 20mA-4mA or 16mA.

Perma Works was not able to use standard 4-20mA currents because the HT SOI circuits for measuring temperature and pressure require approximately 12mA at room temperature without sensor input. This is not a fault of HT SOI electronics but just the fact that most HT SOI electronics parts are designed to be general-purpose control electronics, good for high temperatures but nominal in every other way. Unfortunately, near 300°C, the needed supply current for the electronics increases to ~35mA. This increase in supply current is normal for HT SOI electronics. The tool’s constant current setting must be above the highest level of supply current needed, with all sensor levels at 0. We needed a 40mA base current for our 300°C tool.



In the above circuit, the goal is to hold the supply current to the tool electronics to be constant even when the tool's supply voltage is changing. The current created by the sensors (Isig) is allowed to change as needed. From above:

> Isc + Itc = 40mA; where Isc is the current to run the electronics, Itc is excess current thrown away to keep a constant 40mA for tool electronics
>
> Icc = Isc + Itc + Isig OR AS Icc = 40mA + Isig; where Icc is the cable current and Isig is the sensor-generated current

As long as the cable is a good working cable, the current Icc is the same at the tool as seen at the surface receiver. Now, the surface receiver electronics only need to subtract 40mA to measure the sensor current and convert that value to a sensor reading.

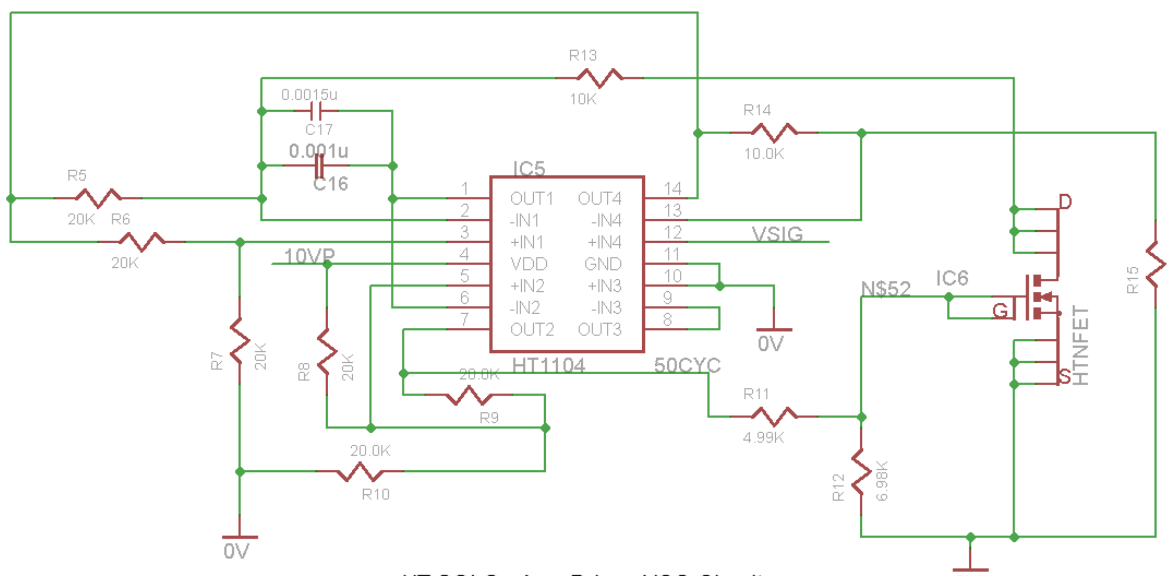
After building and testing this concept, Perma Works decided against this design. There are two reasons. First, the circuit has three large power devices, a voltage regulator and two power transistors. One power transistor is for holding a constant 40mA and the other is for creating signal current. These three power devices are heat generators inside the tool, increasing the tool's internal temperature above the well temperature. In short, this tool design draws maximum power at all well temperatures because cable currents can only add not subtract. This increased heat will reduce the tool's operating life.

Second, 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 4-20mA circuits, the signal current is ~4X the supply (4mA) current. Having a higher signal current reduces the impact of error in the electronics supply current. For our 300°C tool electronics with a constant current at 40mA, a 4X signal current requires a 160mA signal. This high a tool current is not practical given the cable resistance of high-temperature geothermal cables. (See the discussion on geothermal cables elsewhere in this report.)

Voltage-controlled oscillator. Here the sensor signal is amplified and applied to an oscillating circuit, which is driving the cable back to the surface. The oscillator's frequency is dependent on the sensors' output voltage, as in a VCO.

There are two benefits of this type of circuit. First, like the constant current circuit, the cable will not change the frequency. Also, counting frequency by a surface receiver microprocessor is easy and normally of high accuracy. The downside is the VCO circuit. Unlike a sensor driving a DC current, all VCOs are dependent on the ambient temperature. The VCO frequency response must be digitally corrected for ambient well temperature at all times.

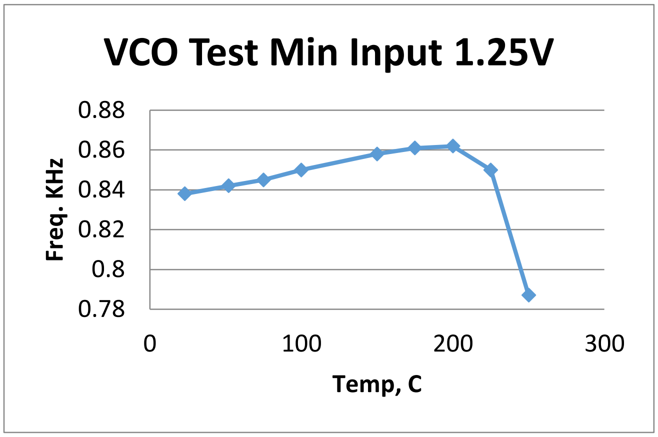
At Perma Works, we built two different VCO circuits using HT SOI parts. One was an op-amp–driven design and the other a standard 555 chip design. Below is the op-amp design.

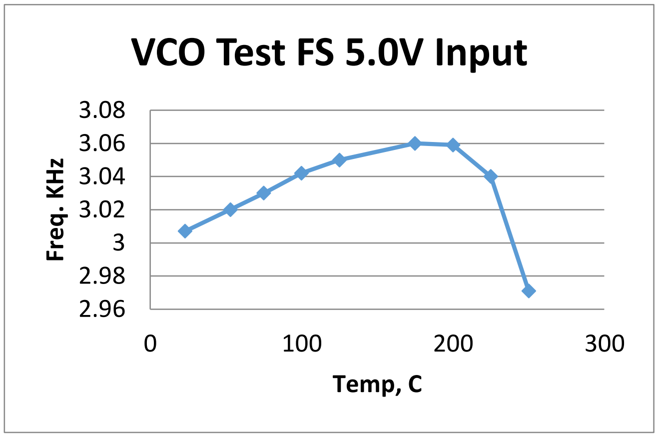


HT SOI Op-Amp Driven VCO Circuit

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. It speeds up the discharge of C16 + C17 on the down cycle of the oscillator. Several frequency rangers were tested by changing the values of C16 + C17. Higher frequencies improve resolution but are harder to transmit on long logging cables. The data presented below is using a capacitance of 10.2nF for a full scale (FS) of ~3KHz@5.0V sensor input. The lower scale falls at 850Hz@1.25V sensor input. This creates a general calibration = 0.001744V/Hz.

Perma Works tried both the Honeywell HT1104 and the Cissoid CHT-OPA in the op-amp design. These are both HT SOI, quad op-amps. Unfortunately, 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 dominate over input from the sensor. The data below is from the Honeywell HT1104 with a 1.25V (0°C) input and a 5.0V (300°C) input to the VCO.





At higher temperatures, the frequency output is dropping. This creates an obvious problem; there are two output frequencies for every input voltage. The surface receiver could be confused when correction is made for temperature effects on the VCOs.

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 in analog circuits is the reason Cissoid created an 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 250°C, the device simply stops holding a nominal frequency. This device cannot be used for a 300°C tool.

Multi-wire. Assuming a multi-wire cable where each sensor output has its own signal wire greatly reduces the complexity of the downhole electronics. For a pressure and temperature tool, four wires are needed. However, discussion with PPS and Geodynamics quickly resulted in availability/cost issues with multi-wire cable for 300°C geothermal wells. There is a lot of pressure from industry to use the standard 7/32, 600°F armored mono-conductor cable found on most geothermal logging trucks.

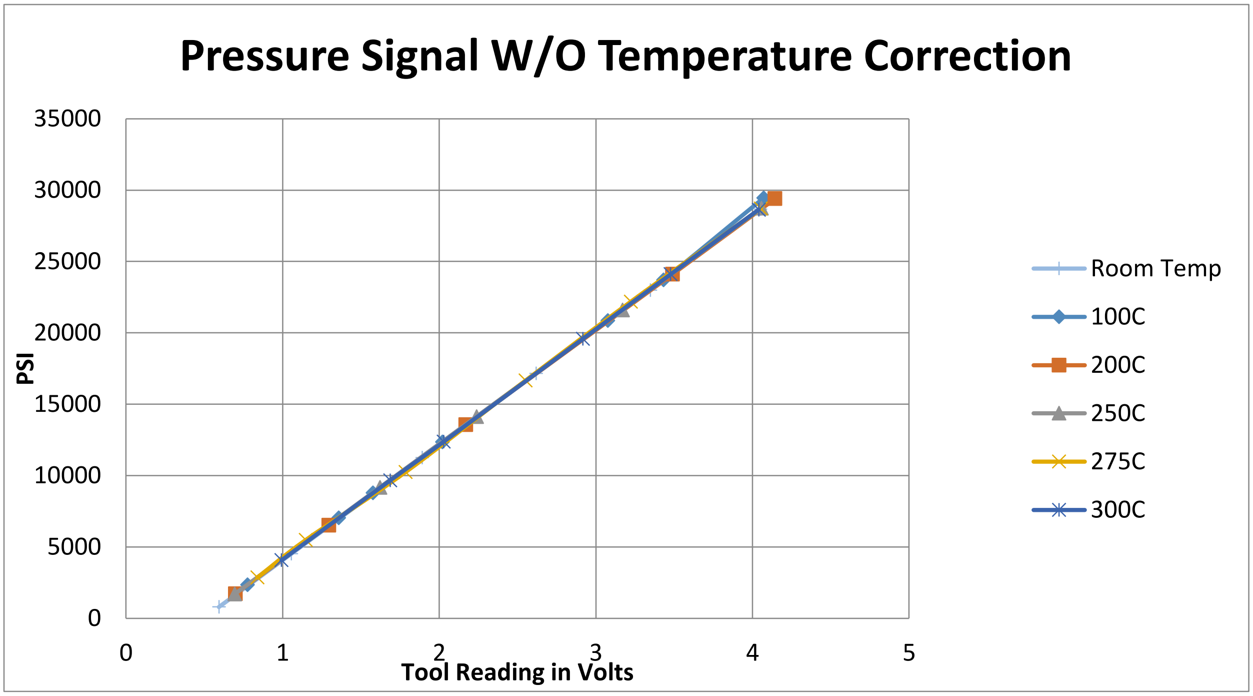
A clear outcome of this grant is: to support future EGS well development and testing, the EGS tool must run on standard 7/32, 600°F logging cable. For very long-term well monitoring projects, wired tubing is acceptable as an expendable item.

THE FINAL 300°C ANALOG TOOL SOLUTION

This section is proprietary.

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 circuit. The remaining error has already been shown to be less than 25uV up to 300°C.

At the 2010 DOE Geothermal program review, Perma Works presented the 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 210 times the sensor signal, which is required for the Paine pressure transducers. In fact, a signal amplification of 210 is a lot for any electronics amplifier given the electronic noise floor increases with temperature. For example, Paine transducer used by Perma Works has a full scale calibration of

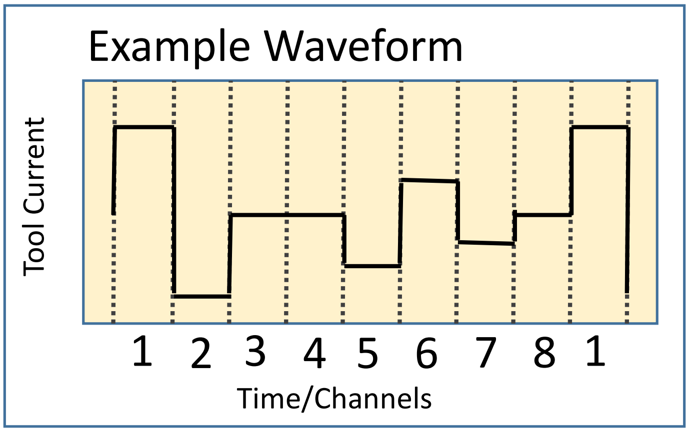


0.022V/30,000psi. That's only 0.73 X10-6 V per psi. The geothermal reservoir engineer wants to track changes in the reservoir level within a few psi over a period of a year! So the question is how to best get this signal to the surface with most accuracy and best signal to noise ratio?

The means for transmitting sensor values to the surface chosen is PAM, pulse amplitude modulation. PAM is very "old school" in the world of electronics. Perma Works is using the tool supply current as the signal carrier. The higher the sensor signal, the higher the tool's current. Only one sensor signal is amplified by the tool's electronics at a time, so the current is always tool total current plus sensor current. The only difference between this and the previously discussed constant current technologies is that Perma Works is ALLOWING the tool current to be anything.

The surface receivers measure a different tool current for each sensor and only needs to subtract the second reading from the remaining readings to get each sensor output. A more detailed understanding of PAM might be helpful.

Each of these PAMs are called channels. The series of channel readings is called the format. The sync is by design the largest amplitude signal coming from the tool. The sync is a constant value. The sync triggers the start of a new set of readings. (See the example waveform drawing below.) After the sync signal follows the zero pressure signal. Zero pressure is by design the smallest or lowest amplitude signal transmitted. As such, the difference between the sync and zero pressure is the widest range (full scale) the tool can produce. Knowing the range and verifying its value at the surface assures the cable is not losing signal and the cable driver inside the tool is functioning correctly. Also, the surface receiver can use a falling edge between the sync and zero pressure to validate the tool's timing circuits. Timing is always eight readings apart. In short, the surface receiver microprocessor only needs to find the largest repeating change in tool current to mark channel 1 and channel 2. Divide the timing for eight channels in the frame. Take the center current reading for each channel; again channel 1 is marked as the highest amplitude and now all the reading can be recorded and saved as a frame.



The use of two well pressure channels was to provide better signal averaging to reduce noise. The pressure reading is amplified by tool's electronics over 210 times, while temperature is only amplified 7 times. The pressure reading is naturally noisier than the temperature reading.

For general interest, another reason for using eight channels is to fill all the available "states" of the "state machine." In the electronics measurement world, microprocessors dominate measurement instrumentation electronics, but they have one weakness: A microprocessor can drop a bit and become locked up or even write an erroneous instruction into its program memory. The only solution is to reboot the processor.

The state machine is the uncontested ruler of reliability. A state machine is a digital circuit that operates in a loop with all possible logic combinations accounted for. The Perma Works 300°C tool is a state machine with eight states. While a microprocessor can become locked up, requiring a reset or reboot, if a state machine drops a bit, the circuit simply cycles though and re-synchronizes automatically. At most, only a single frame of data is compromised.

GENERAL TOOL OPERATION

The Perma Works 300°C tool was designed for geothermal well logging at temperatures of 275°C and up to 25,000 psi to support geothermal well production testing and EGS production stimulation (hydro-fracturing).

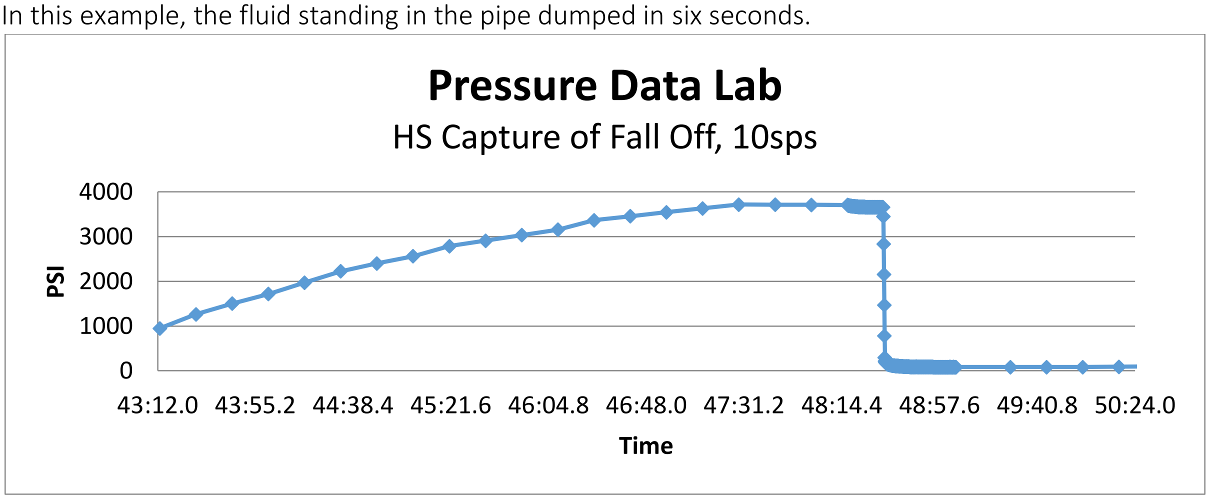
This tool can operate on either standard 600°F mono-conductor wireline logging cable or special cables containing an isolated signal wire. The tool housing and all metal parts are power ground and signal returned to the surface. All of the tool pressure seals are metal to metal or glass to metal. The tool is not dependent on organic rubber seals. **A complete set of mechanical tool drawings are provided as an appendix to this document.**

For cases where there is an additional second wire inside the armored cable, the measurement signals can be run independent of the power and ground wires. This improves the signal-to-noise ratio. For long-term well monitoring, the best cable is made using ¼ inch solid tubing with a second signal wire inside the tubing. 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.

Under the grant, four sets of mechanical tool hardware were built. The first set was a standard 1¾ inch OD with a 12,000 psi, 300°C pressure rating. This set was two tools built for well monitoring, with two 2000 ft. wired tubing rolls. The second set was for two tools built for EGS well stimulation. This set has a 25,000 psi, 300°C pressure rating. To conserve funding, both sets of tool housings used the 30,000 psi, 600°F rated pressure transducers sold by Paine Electric, outside of Seattle, Washington.

In general, the tool electronics cycle through all eight sensors in about 15 seconds. If the tool is stopped at any one channel, the sample rate can be increased up to 10 or more samples per second. It's also possible to attach an oscilloscope to monitor tool output at the surface with >5 KHz bandwidth. This function was designed to provide real-time data for well stimulation efforts supporting EGS.

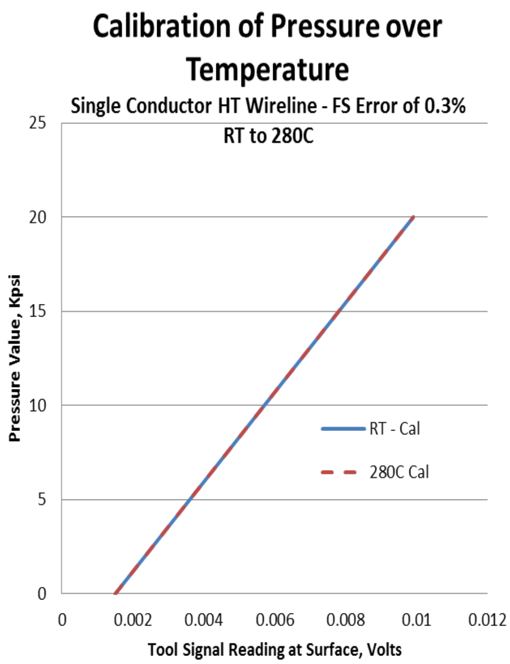
Below is a lab simulation where the tool is stopped at pressure sensors' readings during well fracturing. When the rock fractures, the reservoir engineer wants to know how fast the water moved into the fracture, to gain insight into the size and volume of the newly created fracture. The tool pressure readings were every 15 seconds and then switched to 10 readings a second prior to the simulated fracture event. In this example, the fluid standing in the pipe dumped in six seconds.

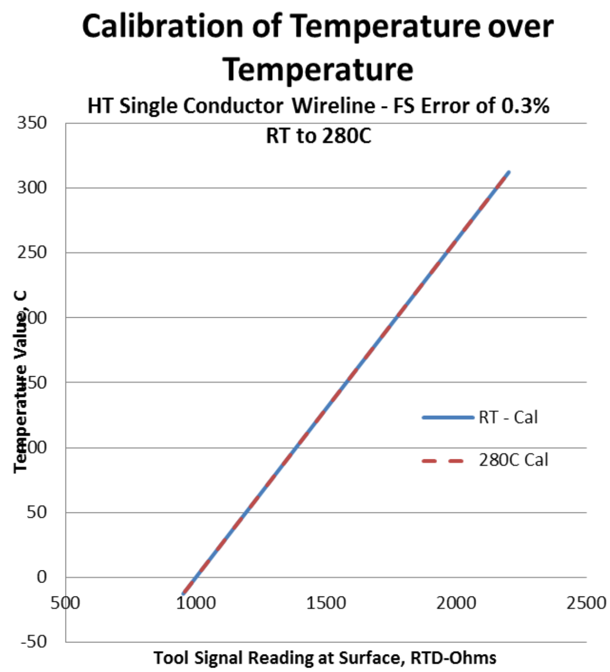


HOLDING CALIBRATION OVER TEMPERATURE

The analog tool transmits a number of internal signals that compensate for the extreme temperatures the tool must operate in. These internal signals' compensation for increasing temperature-dependent supply currents and changes the offset voltage of the tool's voltage reference and signal amplifiers.

Below are two calibration runs where the well pressure and well temperature sensors are holding calibration without any calibration compensation for temperature.



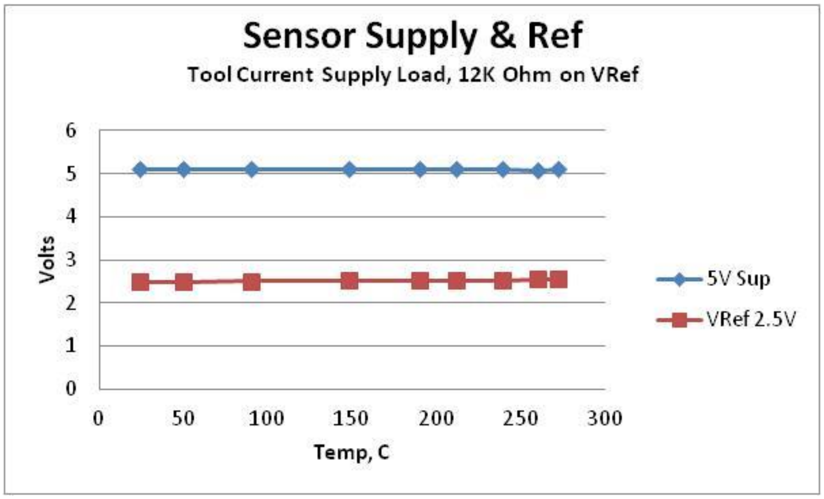


For these plots, the pressure sensor data (left) is in volts per Kpsi. The temperature sensor data is in ohms per degree C. In both cases, the room temperature plot sits on top of the 280°C plot. Even as the tool is rated to 275°C, testing is run to 280 °C. In fact, the tool electronics can be run to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

REDUCING ELECTRONIC NOISE FROM THE MEASUREMENTS

Following the work in Australia, it become obvious that the 300°C analog tool electronics were designed solely for long-term reliability. (Field report on Habanero 4 is the second appendix to this report.) Long-term reliability requires minimizing the number of electronic devices, especially the ceramic capacitors in number and size. An improved set of electronics was built specially for noise testing and potentially for testing new types of high-temperature sensors as might be used in aircraft engines. The new set of tool electronics has the same pressure and temperature sensor circuit only with larger valued capacitors plus three simple unamplified sensor inputs, which can be used to measure base noise levels. The 5V DC tool supply and 2.5 tool reference voltage were also made accessible outside of the oven by an HT twisted pair wire.

The tool electronics were mounted on an aluminum board carrier with room for adding additional sensor electronics at one end. The tool electronics were run inside the oven at elevated temperatures. For the temperature values below, the measured temperature of the board carrier was used.



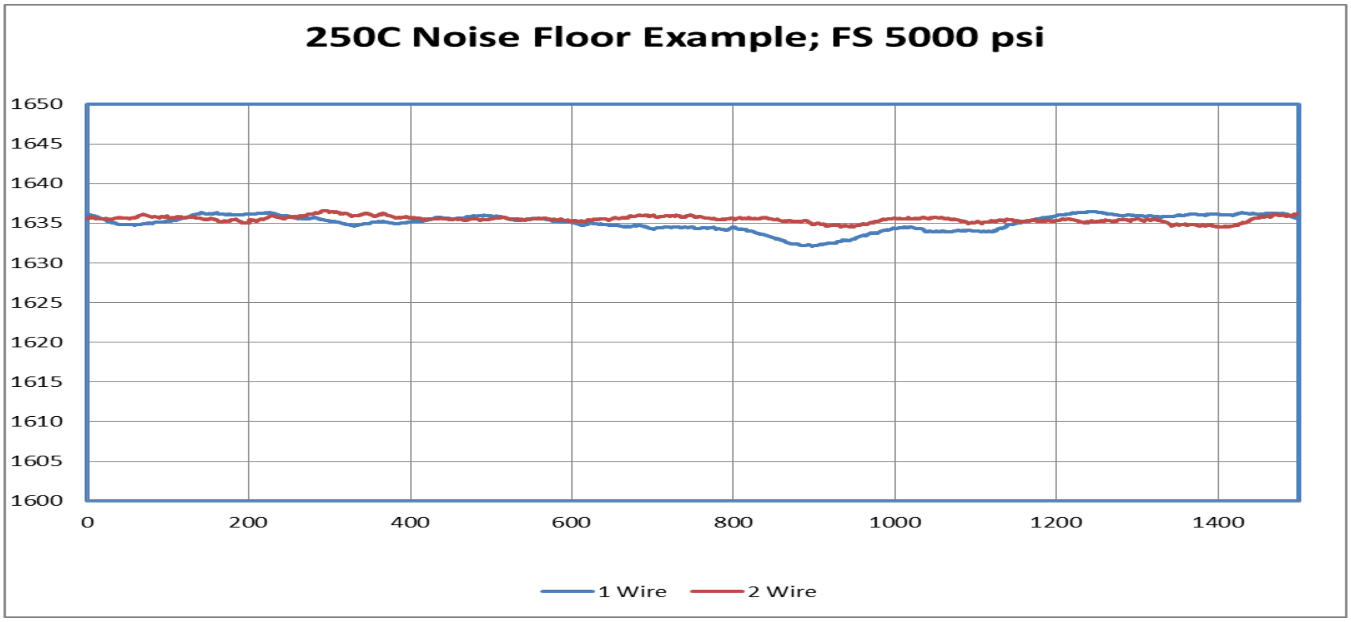
The plotted 5V DC tool supply and 2.5V reference voltage is shown to the left. The 5V supply is performing well with only an only a ~15mA load. This leaves room for adding other sensors in the future. The reference voltage started at 2.4948V and finished at 2.543V. The issue with the reference voltage is that any voltage change or noise on the voltage reverence will also be seen on the sensor readings. A change of 48.2mV is significant.

Tool electronics quiescence current during this test started at 13.6mA and finished at 19.8mA at 275°C.

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 second wire output after the surface receiver's buffer amplifier. These measurements are not dependent on the reference voltage. These are DC measurements using lab equipment.

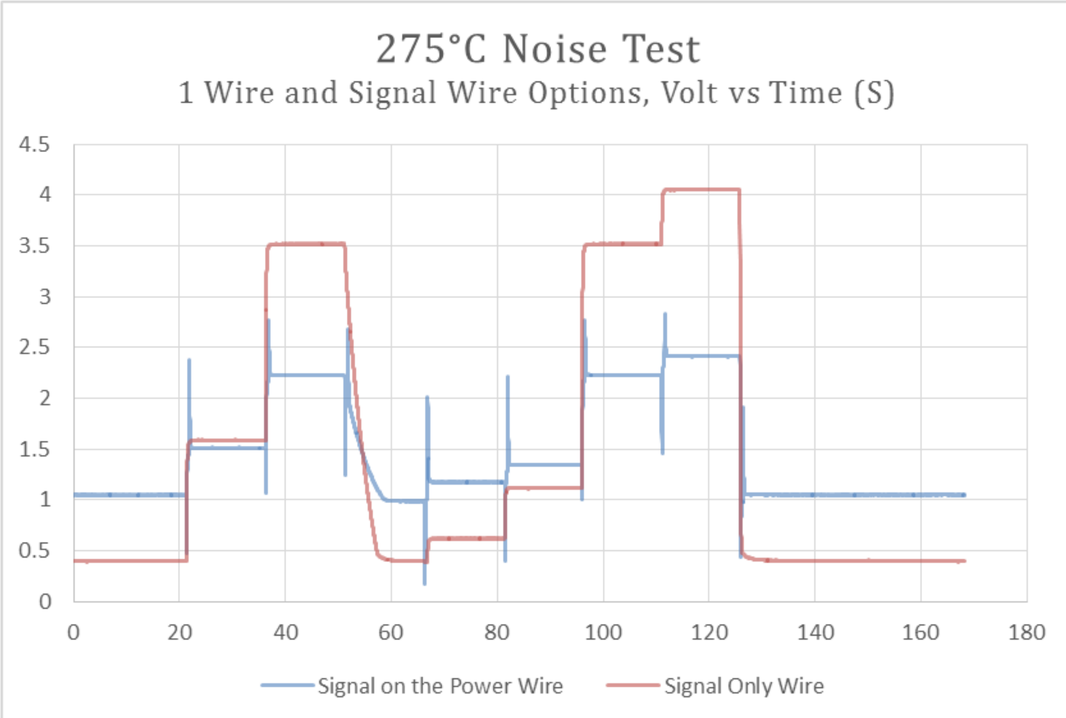
Open Channel DC Readings			
Room Temp		**260°C Temp**	
Input	Output	Input	Output
0.499	0.502	0.502	0.505
1.006	1.008	1.005	1.007
1.505	1.506	1.506	1.505
1.991	1.988	1.992	1.991
2.510	2.520	2.500	2.490
3.000	3.020	3.000	2.970
3.500	3.520	3.500	3.470

The receiver output follows the sensor channel inputs nicely. In this case, the tool is only placing the sensor channel values on the second wire of the logging. The receiver passes the tool signals through a 1Hz low pass filter to reduce noise during bench testing as here. For the benefit of the type of EGS well test, this filter can be significantly opened. However, in the real world of well logging, the changes in the measured well temperature and pressure can be controlled by the rate of the well log. For this configuration, a logging rate of 20 ft./min should be considered.



In the above signal trace, the tool's electronics are fixed on the pressure channel. Here the pressure has an electronics gain of 160X inside the tool. Pressure is the tool's noisiest reading because of the high amplifier gain. The Paine 600°F pressure transducer has a full scale reading of ~22mV @ 5000 psi. The pressure sensor in this test is simulated at a fixed 1630 psi out of a full scale of 5000 psi. The 1 wire signal is the blue trace. The 1 wire has the pressure sensor signal riding on top of the tools DC power. The red trace is using a second wire (third signal wire) where only the signal is on the wire. Power and ground have their own wires. Naturally, as expected, the noise levels on the 1 wire are slightly higher than on the separate signal wire.

In the above data, the noise floor at 250°C: 3 Std. Dev. is <0.0013V out of a 3.5V FS (~1.86psi @5000psi FS) for a cable with a signal only wire. These results are significantly improved over the well monitoring system used in Australia. The tool capacitors on the signal amplifiers have been increased from 0.1uF to 0.22uF and 1uF. Also, the surface receiver has a four-pole, 1 Hz low pass filter. Perma Works believes this is fast enough to pass typical well changes over time and for 20 f.t/min well logging. Below is a scope trace of PAM from the 300°C analog tool. The red trace is the signal-only wire PAM. The blue trace is the PAM signal coming off the power wire. The X axis is in seconds. The response of the system to changes in PAM is fast even with a 1 Hz filter. The blue trace has noise spikes at the edges of the changes in signal amplitude. This is caused by the power capacitors in the receiver. This is easily omitted when sampling data.



Also interesting in the above plot, the amplitude of the signal-only wire is much higher. This is true because the Perma Works tool has two-way communication. The surface communication to the tool is always on the power wire. To avoid conflicts, the surface communication to the tool is much larger and overrides the tool's PAM signal. Then, using a signal-only wire, the PAM signal is unbound.

For supporting EGS well fracturing, more research is really needed to better understand how fracturing events occur and how the data will be used. To support a wider version of options, the surface receiver will have a secondary data collection process that will allow the user to bypass the 1 Hz low pass filter.

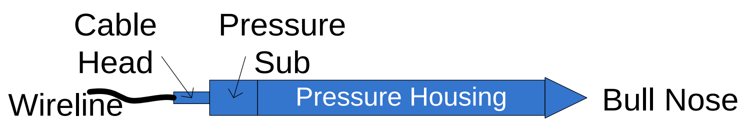
300°C TOOL MECHANICAL CONFIGURATION

A complete set of mechanical drawing are provided as an appendix to the final report covering this grant.

Start with the top of the tool, called the cable head. This is where the cable attached to the tool and a sealed, high-pressure electrical feed-through passes the tools DC power and signal out. Depending on the cable, Perma Works has either a standard 7/32 inch, mono-conductor wireline cable head or a ¼ inch wired tubing. The wired tubing can have one wire or two wires. In general, permanent installation requires ¼ inch Incoloy© tubing.

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 most loggings tools. The Paine pressure transducer is mounted in the center of the pressure sub.

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. For the 25,000 psi tool, the pressure housing is 2.25 inches in diameter and made from 17-4ph stainless steel. Compared to common 316 stainless steel, 17-4ph stainless steel is significantly more chemically resistant and significantly stronger. Where 316 stainless steel has a tensile strength of 89,900, 17-4ph has a tensile strength of 160,000. Naturally, 17-4ph is more expensive to buy and more expensive to machine. Many machine shops will not take on building pressure barrels for geothermal logging tools. Following the pressure housing is the bull nose.



The bull nose is where most sensors get access to the well fluids. The Perma Works tool has the well fluid temperature probe located here. The Perma Works tool is using a 1000 ohm resistive temperature device (RTD) sensor. The resistance is 1000 ohms at 0°C and increases 3.85 ohms per degree C. The only requirement of the bull nose is to have a round shape to allow the tool to easily slide down the well.

UNDERSTANDING HIGH TEMPERATURE CABLES

In this grant, Perma Works initially started with ¼ inch tubing with high-temperature wires inside. This is the most durable solution for very long-term well monitoring. The cost of wired tubing is expensive and generally only a one-time use. One-time use isn't an issue for permanent well monitoring. If the well owner wants to move the system between wells, that is another issue. The tubing work hardens in the well at geothermal temperatures. Work hardening means the tube resists being rewound back on the logging truck drum. Dave Glowka calculated the size of the drum needed for work-hardened stainless steel to be ~24 ft. in diameter. It is possible to reuse the tubing even with a conventional logging truck, but the chance of damaging the tubing is significantly increased after work hardening the steel. In short, service companies general require the well owner to purchase the tubing and wire as an expendable item even if the test lasts for a week or two.

In the images to the right, the top image is an Incoloy ¼ inch stainless steel tubing with two glass insulated wires. These wires are nickel-clad copper. The lower image is of a standard 600°F, armored logging cable with Teflon-insulated center conductor, which is also nickel-clad copper. Nickel cladding is used to straighten copper wires and increase corrosion resistance. The nickel cladding is 27% of the wire. Nickel has one of the highest temperature coefficients of resistance of all metal conductors. The list below compares nickel to other conductive metals.

Nickel TCR = 0.005866
Aluminum TCR = 0.004308
Copper TCR = 0.004041
Silver TCR = 0.003819
Steel TCR = 0.003

TOOL POWER ON GEOTHERMAL CABLES

To illustrate the issue with high-temperature effects on geothermal cables, it's best to understand the changes in cable resistance caused by geothermal well temperature.

Manufacturers provide resistance values per Kft for their cable based on a standard 20°C temperature. This is a wire standard having nothing to do with the geothermal industry. Using this known value, the total resistance of the cable is estimated by the equation below.

Cable resistance (CR): CR = CCR + AR;
CCR is the total resistance of the center conductor
AR is the total resistance of the armor conductor

Also note that CCR and AR are a function of cable length and cable temperature. For discussion, we will assume the entire cable is at a known constant geothermal temperature. In general, the tool operator does not know the well temperature or the temperature gradient of the well.

The Rochester mono-conductor wireline with a 7/32 diameter is a common well logging cable found on geothermal logging trucks. Below are the Rochester specifications for a 500°F- (fossil energy) rated cable and a 600°F- (geothermal) rated cable. The comparison illustrates an 18% increase in the nominal 20°C resistance of the 600°F cable over the 500°F cable. Rochester does not provide coefficients for resistance changes for increased temperatures. For the following calculations, the coefficients given for metals will be used.

Part #	Center Cond.	Armor	Temp.	Center Cond.	Center Cond.
	Ohms/Kft	Ohms/Kft	Rating	Insulation	Wire
1-H-220K	4.5	4.5	500°F	ETFE	Copper
1-H-220M	5.3	4.5	600°F	PTFE	Nickel-Copper

Assuming a 10,000-ft. logging cable at 20°C, what is the voltage drop to the constant current tool with a 40mA tool current and 10mA full scale signal current using 600°F Rochester mono-conductor cable?

Voltage drop = I * R; I is the current on the cable and R is the total resistance of the cable at 20°C.

CR = CCR + AR
CR = (length in Kft) * (CCR + AR); where CCR and AR are in ohms/Kft

CR = 10*5.3 + 10*4.5 = 98 ohms

The voltage drop = 40mA*98 ohm or 3.92V for sensor current at 0.0mA and 4.9V at full-scale sensor current. The tool requires 12V minimum, so the surface must supply 16.9V at the logging truck.

To adjust our cable resistance for a well temperature of 275°C, the values for metal temperature coefficients must be used for the percentages of nickel and copper in the center conductor.

Wire resistance for new temperature = R_{20} * [1 + TCR * (T_w – 20°C)]
R20 is the wire resistance at 20°C from the manufacturer
TC is the temperature coefficient of the wire
TW is the well temperature

As the high-temperature cable center conductor is a copper-clad nickel, an adjustment is made to its TCR as TCR = 0.27*TCR_N + 0.63*TCR_{CO} using values from the table listing metal temperature coefficients above. The temperature coefficient for resistance of the center conductor is TCR = 0.004130. The cable's armor is assumed to be steel with a TCR of 0.003.

The resistance of the 10K ft. center conductor is 53 * [1 + 0.004130*(275 – 20)] = 108.8 ohms.
The resistance of the 10K ft. of armor is 45 * [1 + 0.003*(275 – 20)] = 79.4 ohms.

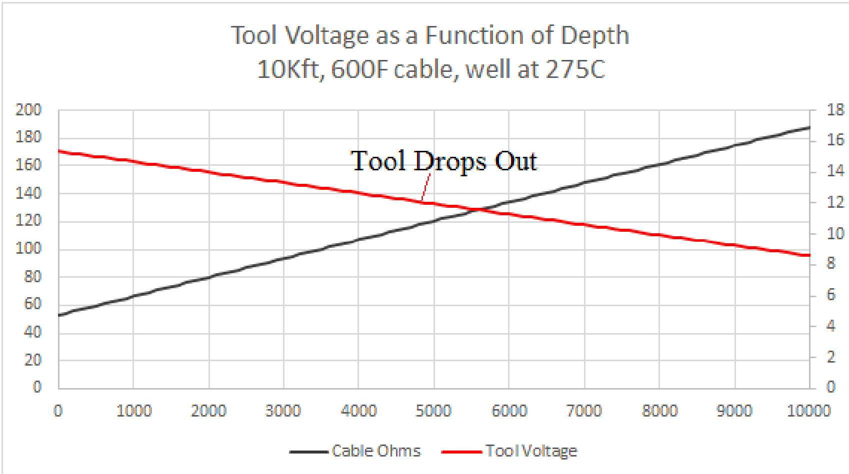
Voltage drop = 40mA*188.2 ohm = 7.53V for the sensor current at 0.0mA and 9.41V at full-scale sensor current. Again, the tools minimum voltage is 12V, so the supply voltage at the logging truck must be 21.41V.

The result of heating the cable to geothermal temperatures doubles the cable's resistance and so also the voltage drop going to the tool. This is a significant change that can result in a tool simply not working downhole. This became a significant issue for the Perma Works analog tool for supporting EGS. Here is why.

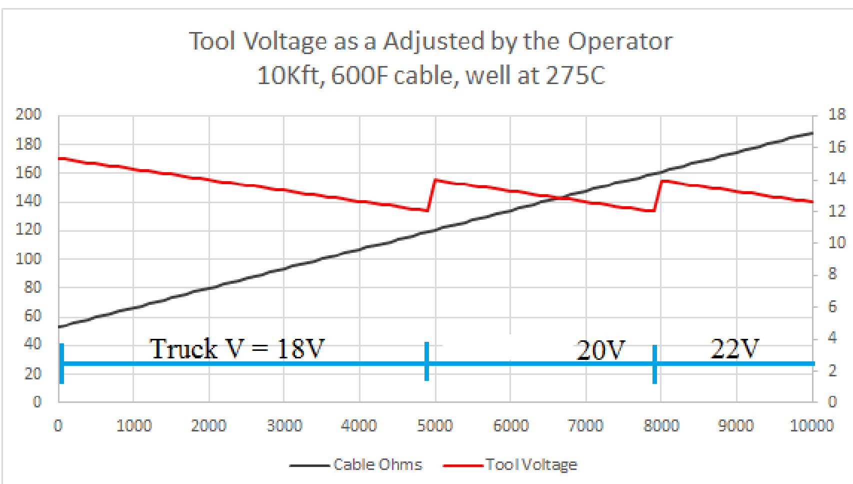
The Perma Works tool design has a maximum supply voltage rating of 20V DC or the electronics can be damaged. This is because of the lack of high-temperature components for 300°C operation at the time of the grant. The standard logging tool rated to only 150°C Perma Works sells can operate from 12V to 35V.

When the 300°C tool is first attached to the cable on a logging truck, the cable is rolled up on the drum and the armor is shorted, so when the tool is first placed on the cable with the cable still rolled up onto the truck, the only voltage drop is the center conductor. Also, at the well site, the ambient temperature could be well below 20°C on a cold winter's day, dropping the cable's resistance and voltage drop to the tool.

Below is a plot of the cable resistance in ohms on the left axis, increasing as the tool's supply voltage at the tool's cable head is dropping caused by increasing voltage drop. The supply voltage at the logging truck is a nominal 18V and falls to ~5V, which is well below the tool's minimum operating voltage.



In the plot below, when the cable head voltage falls to the tool's minimum operating voltage of 12V, the supply voltage at the truck is increased. This happens at the first depth ~4,900 ft. into the well. In short, at this point or before, the tool operator must manually increase the logging truck voltage to compensate for the voltage drop on the cable.



This is not easy because the actual well temperature or the well temperature gradient is not known.

Still looking at the plot to the left, the blue line shows the increases in supply voltage at the surface conducted by the operator to keep the tool working. In order to protect the tool from having its supply voltage at the cable head exceed its maximum 20V rating, the operator must also reduce the logging truck's supply voltage as the tool is returned to the surface. This over-voltage condition on the return trip actually occurred to a logging demonstration with the 300°C tool.

Digital Transmission on High Temperature Geothermal Logging Cable

Digital transmission of 1s and 0s allows for near zero error in the transmission of data. The Perma Works digital tool uses frequency skip key (FSK) transmission. FSK is a standard in the logging tool industry. The transmission rate is a function of the band pass of the logging cable. As might be guessed, the band pass of the logging cable is a function of the cable's temperature.

In electronics, cables are described by their resistance per unit measure, capacitance per unit of measure, and characteristic impedance, which is simply referenced as ohms for a cable matching impedance.

However, manufacturers of logging cables only provide resistance per unit measure and capacitance per unit measure. For the 600°F Rochester cable, the capacitance per foot is 58pF/ft.

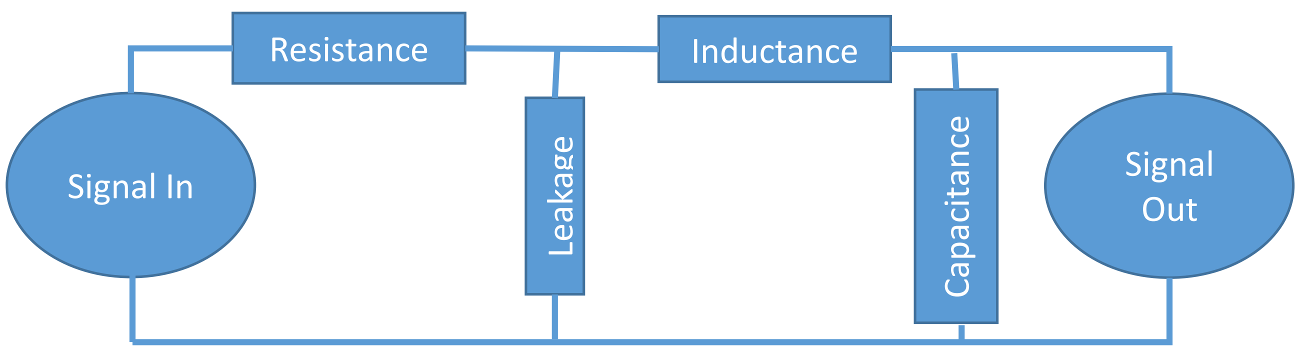
Under the grant, Perma Works received 75 ft. of 600°F cable. Using this cable, the character impedance was measured. The characteristic impedance (Z_0) is equal to the square root of inductance (L) over capacitance (C), as shown below.

$$Z_0 = \sqrt{\frac{L}{C}}$$

The inductance is measured using an inductance meter with the other end of the cable-shorted armor to the center conductor and then divided by the cable's length. The capacitance is measured with the other end of the cable's open circuit.

The measured Z_0 is about 46 ohms. This is the best matching impedance needed by the tool's cable driver and the surface receiver's signal amplifiers. This value doesn't have any appreciable dependence on the cable temperature. The cable's signal loss is tied to the cable's resistance. Just like the voltage drop loss for tool power, there is a signal amplitude loss as the signal moves up the cable.

In general, the lossy signal model of an electrical cable is as below, where all values are distributed values as resistance per foot of cable.



In the above cable loss model, the signal is subjected to a low pass filter. In short, the higher frequencies are attenuated more than low frequencies. The longer the cable, the more high frequency the attenuation. For geothermal well logging trucks, it generally assumed that the cable is 20,000 ft. long.

The leakage loss is normally very, very small compared to the other elements, so it is normally simply assumed to be zero. The cable inductance and capacitance have very little dependence on cable temperature. However, the resistance has been shown to double with cable temperatures near 275°C. The equation below assumes lumped values for a distributed cable system. This is only for illustration purposes of this type of RCL low pass filter approximating a cable as signal frequencies are increased.

$$\text{Signal Out} = \text{Signal In} \times \left(\frac{1}{1+2\pi fRC+(2\pi f)^2\,LC}\right)\text{ ; f = frequency of the digital signal}$$

For the equation above, the squared term of frequency (10^4) would normally dominate; however, the distributed capacitance (10^{-12}) and inductance (10^{-9}) values are much smaller, so it's common to drop that term.

$$\text{Signal Out} = \text{Signal In} \times \left(\frac{1}{1+2\pi fRC}\right) \text{; f = frequency of the digital signal}$$

In short, the frequency band pass of the cable will be significantly reduced at geothermal temperatures as the cable resistance (R) is doubled. Unfortunately, the story does not end here. There is another factor reducing the band pass of the cable, called the *skin effect*. The skin effect is outside of the scope of this report. It will only be mentioned that the skin effect occurs with increasing signal frequency, which drives the signal current to the outer edges of the center conductor. For 600°F logging cable, the copper-clad wire is where the higher impedance nickel metal is located. Depending on the signal frequency, the impedance will actually be higher at elevated temperatures than our simple x2 assumption above.

For the Perma Works digital tool, a conservative approach to digital communication is taken using a very old method called frequency skip key (FSK).

DIGITAL DATA TRANSMISSION USING FSK

For the Perma Works digital tool, past experience has been a good teacher. The upper signal frequency of 20 KHz is normally passable on a 20,000-ft. logging cable. At this point, some discussion on FSK digital data transmission is useful.

FSK uses two discrete frequencies. For the Perma Work digital tool, a frequency of 18 KHz represents a binary 0. A frequency of 9 KHz (1/2 the 18 KHz) represents a binary 1. It is very simple for the Honeywell 8051 microprocessor to generate a short burst of pulses at a known frequency. A high-temperature Honeywell transistor amplifies the microprocessor output and drives the signal onto the same logging cable providing DC power to the tool.

In a true FSK receiver, the receiver detects each frequency using two independent circuits. The 18 KHz detector has a logic 1 output if there is a strong 18 KHz signal on the cable; otherwise, the output is a logic 0. The same is true for the 9 KHz detector detecting a 9 KHz signal. The receiver microprocessor uses the truth table for the two frequencies to recreate the tool's binary data.

Tool		Receiver		
Binary Data	**Cable Freq.**	**9KHz Detector**	**18KHz Detector**	**Received Data**
0	18KHz	0	1	0
1	9KHz	1	0	1

This allows for significant noise rejection. If the 9 KHz and 18 KHz detectors are both logic 1 or both 0, the receiver microprocessor rejects those signals as noise. Such might be the case for a failing AC generator on the logging truck. The FSK requires both detection and lack of detection for successful data transmission.

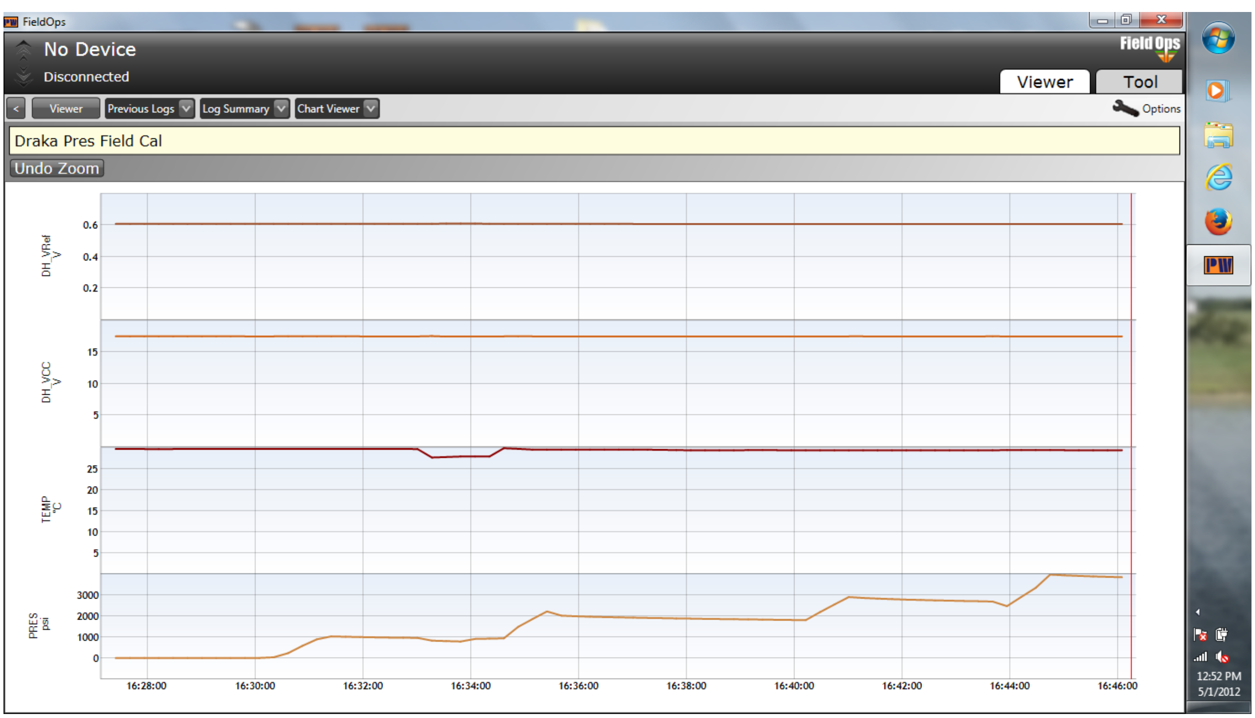
The cable is a low pass filter, so the FKS data rate is limited by the cable's upper operating frequency and the time it takes for the receiver to detect a signal frequency. At Perma Works, we used 10 clocks at 18 KHz to transmit a logic 0 and 8 clocks at 9 KHz to transmit a logic 1. The digital tool can communicate at 1200 baud.

SURFACE RECEIVER

Under this grant, three versions of the surface receiver supporting the analog and digital tools were designed. At the time of this report, the surface receiver is still undergoing future development to meet the needs of EGS development.

The surface receiver works like most. The surface receiver has an internal clock to track measurement time with tool depth. Depth is supplied by any number of commercial depth encoders. The PW software takes whatever the depth encoder ASCII file out is and messes it with the tool readings based on synchronized clocks. A PC is connected to the surface receiver to provide visual data readings both as number values of the last reading and a scrolling plot providing historical readings. The PC is used to provide user input to the tool and to the receiver. The PC is also storing the tool data in an LAS format, which is standard for well log data used in the geothermal industry.

The Perma Works software is called Field Ops.



As the surface receiver is a standalone system with an option of real time data displayed on a PC or storing data internally for downloading later. This standalone design is needed so the receiver can be easily removed from the truck to simply log the well over periods of months or years as needed. The surface receiver can operate from 12 VDC, 120 Vac @ 60Hz, or 240 Vac @ 50Hz. The receiver can be powered by a 12V solar cell and a battery for truly remote locations. The data is time-stamped and stored in electronic flash memory. This requires the operator to travel to the site to download the data about once a month.

The receiver also has extra measurement channels for measuring well head temperature, well head pressure, and a third channel for well flow. The reason for this is to identify if changes in the reservoir seen by the well monitoring tool deep in the well are the result of changes in the surface flow. The surface receiver is the gray box attached to the pole in the photograph. Above is a screenshot taken of the Field Ops software showing a pressure test of the 300°C analog tool using a hand pump.

THE EVOLUTION OF RECEVIER DESIGN

The first two versions of receivers were based solely on an 8015 microprocessor with a 24Bit A/D. The 8051 used in the receiver was part number C8051F350 from Silicon Labs. This device can be referred to as a system on a chip (SOC). The program memory, eight-channel 24Bit A/D, data memory, and communication (UART, SPI) are all on the C8051F350 device. Only the real-time clock and data long-term data storage are located off the chip.

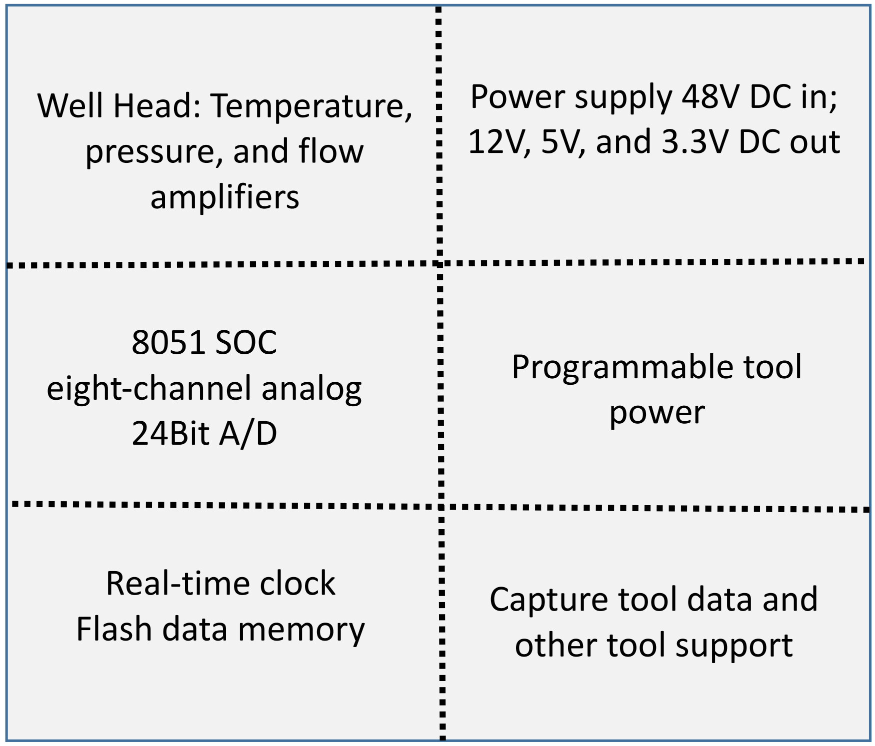
This design makes for a very low-power system, ideal for remote operation from a solar cell. In the photo below, the receiver is located inside the gray box mounted on the pole holding the solar cell. A small deep cycle 12 voltage is located inside with the receiver electronics.

With a PC connected to the surface, receiver data can be displayed in real time. The Field Ops software is unique, allowing the operator to change calibration as needed.

Also, there are simple measurement filters available to the user. These filters are simple moving averages and median point filters (3 or 5 points) or combinations as a median filter followed by averaging.

Unfortunately, this first-generation surface receiver's electronics had too much noise on the circuit board's ground circuit. The block diagram to the right shows the basic circuit board layout of the first generation surface receiver. Having the power supply and the programmable tool power on the same board as the 24Bit A/D was at the heart of the noise issue. The second generation surface receiver broke the circuit board in two pieces right down the middle.

It was this second-generation surface receiver that was used in New Zealand and Australia.



Surface Receiver First Generation Electronics

The demonstrations run in New Zealand and Australia provided a wealth of real-world required changes needed to support EGS power development. These issue have been discussed in prior sections of this report. The impact on the surface received will be detailed here to support the third-generation surface receiver electronics. There were two objectives coming out of demonstrations requiring changes to the surface receiver: computer control of tool voltage using tool data and better digital filtering.

Tool Voltage

As was shown in the Understanding High Temperature Cables section of this report, the tool's voltage at the surface must be adjusted as the tool is lowered or removed from the well. In the first two generation surface receivers, the 8051 would change the tool supply voltage based on commands from the user via a connected PC. This process is just too slow and dependent on an active observer.

Digital Filtering

The tool was designed with a minimum number of electronic components. This includes capacitors that are normally used to reduce electronics noise in measurement circuits. The general thought was that well monitoring electronics are working with very slow changing values. The tool readings could be averaged over a long period. However, this was not true in Australia. They needed to track changes in the well over a period of minutes. The analog's tool readings were coming out as one set of readings every 15 seconds. Most of the time the tool is simply changing data channels. The 8051 SOC could make a 24Bit reading approximately two readings a second. In short, the receiver was collecting two readings per analog channel every 15 seconds. This resulted in ~8 readings per minute per channel. The simple filtering provided to the user under Field Ops was not enough.

The third-generation surface receiver is still under development. In the previous versions, the 8051 was simply overtaxed. Its on-board program memory was full. It was too full to add automatic correction of the tool's downhole voltage. Also, the eight-bit processor was maxed out, handling 24-bit data for both tool and well head measurements while storing the data in memory and continuously monitoring for potential input from the user.

A second 32-Bit ARM processor based on the Raspberry PI operating system has been added to the receiver. This 32-Bit processor will handle data storage, track the tools voltage, and adjust as needed, handling all communications between the operator and the downhole tool. The smaller 8051 microprocessor handles only the A/D for tool and well head data readings. The C8051F350 is replaced with a C8051F300 with a 16bit A/D. This still provides high resolution (1 part in 65536). This greatly increases the A/D speed by more than 100 times, allowing for better digital signal processing.

The ARM processor provides a host of user interfaces in the form of four USB sockets and HDMI video output. Plans at Perma Works hope to include a very easy operating system for the end user. This operating system will be easy enough to operate that university students will be able to reprogram the receiver for their own use.

CONCLUSIONS

This paper discusses the development of a 300°C analog tool designed for supporting EGS development and general purpose geothermal well monitoring. The initial concept was to start with a Sandia National Labs conceptual analog well monitoring tool built back in 2006. Expectations were high as Honeywell had significantly improved their HT SOI amplifier over the older HT1104 amplifier. Their new HTOP01 amplifier has improved the DC offset performance needed for making pressure and temperature readings.

Sandia had tested many of the HT SOI components to 300°C, but not complete tool assemblies, including circuit boards and solders. The complete tool was only tested to 250°C. Although the components function to 300°C and above, as a complete assembly, issues were discovered. Perma Works reinvestigated complete circuit designs as constant current, voltage-controlled oscillator, and multi-wire.

- **Constant current:** Here, the circuit draws a fixed supply current of 4mA while the sensor amplifier draws additional current based on sensor value. So, a cable drawing 10.542mA on a 4-40mA circuit would be a signal of 6.542mA. Calibrations for temperature and pressure are C/mA and PSI/mA, respectfully.

- **Conclusion, CC:** HT SOI electronics are new to the market. As such, most are general purpose in nature, focusing on high-temperature operation and reliability over low-power performance. At 275°C and above, the fixed supply currents of the tested circuit approached 40mA. This made these circuits draw maximum power at all tool temperatures, which lowers reliability and functionality. This idea was dropped.

- **Voltage-controlled oscillator:** 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, 1 KHz might mean 0°C and 1.3 KHz might mean 300°C for a temperature measurement calibrated C/Hz.

- **Conclusion, VCO:** This is one of the best means for communicating sensor information to the surface. However, even as most of the HT SOI devices continued to function up to 300°C, as a VCO, none of the circuits held calibration. (Note: As of this report, X-Rel has started marketing HT SOI frequency devices that may work. Perma Works is planning to test these new devices.)

- **Multi-wire:** Here each sensor amplifier located in the downhole tool has a wire leading to the surface. For a pressure and temperature tool, four wires are required: two signal wires plus power and ground. This is the easiest to design for but increases the cost of the cable.

- **Conclusion, multi-wire:** Given that future EGS wells might be 5K ft. to 30K ft. deep, cable costs quickly become a major cost factor.

The end result is a set of analog tool electronics that operate as a constant current type of circuit; only the Perma Works software adjusts the tool's baseline current for increasing temperature to the tool's pressure and temperature measurements. Now the tool's electronics are self-compensating over the operating temperature range. This solution should also work for correcting long-term electronic drift of the tool's electronics.

As electronic circuits become hotter, the electronic noise levels increase. The initial Perma Works analog tool used a minimum of capacitors and the smallest capacitor values. This was done to maximize the long-term operating life of the tool at geothermal temperatures. However, working with the geothermal industry exposed the need for this tool to operate both as a well monitoring tool and a logging tool.

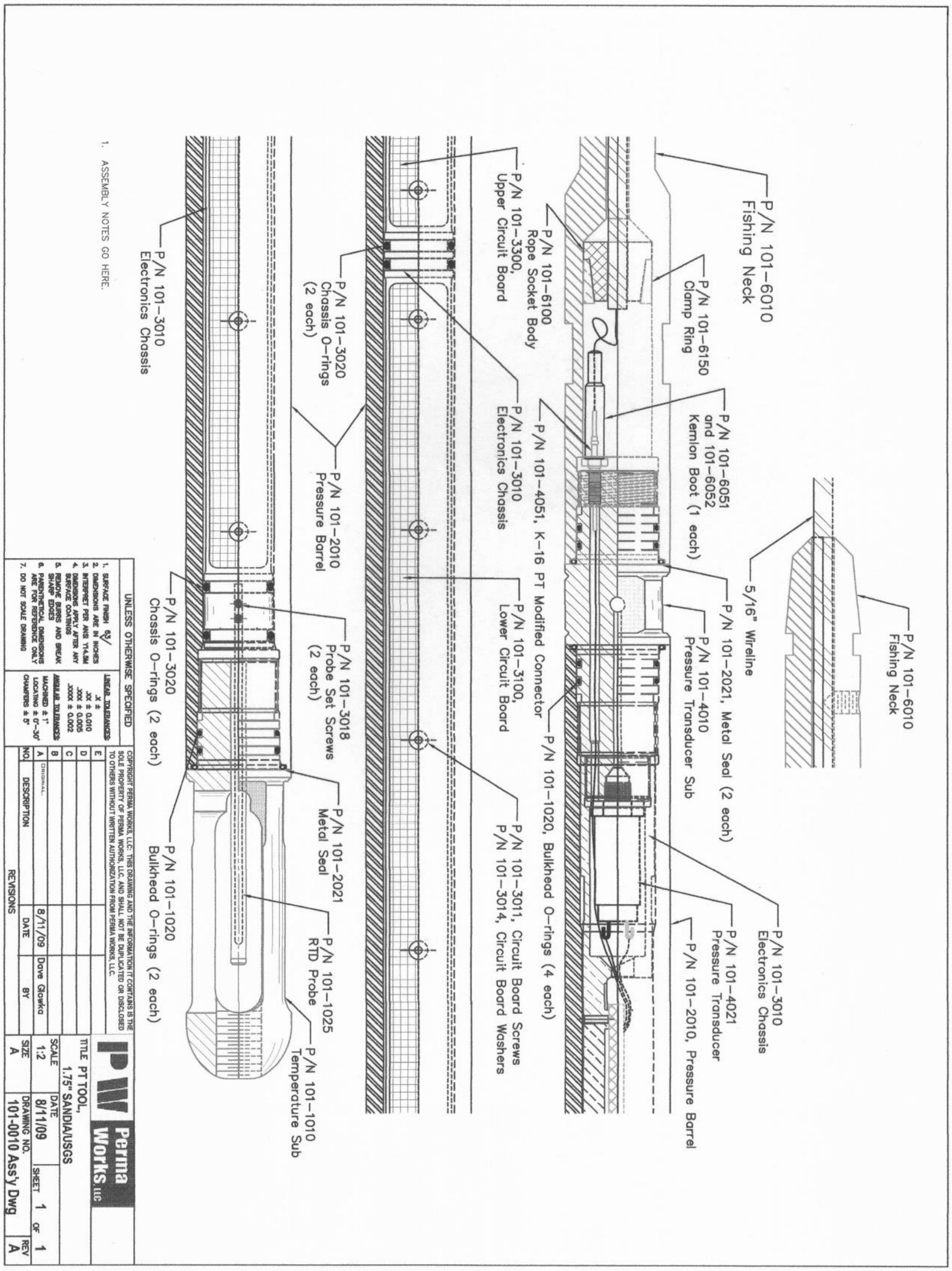
To improve the number of applications for this technology requires significant changes in the surface receiver. The surface receiver is currently being enhanced to better control power to the tool as the cable moves on or off the logging truck's drum. This required adding a second microprocessor to the receiver. Another change to the surface receiver was to increase the signal filtering to better reduce noise. The new receiver design has a multi-pole low pass filter at 1 Hz.

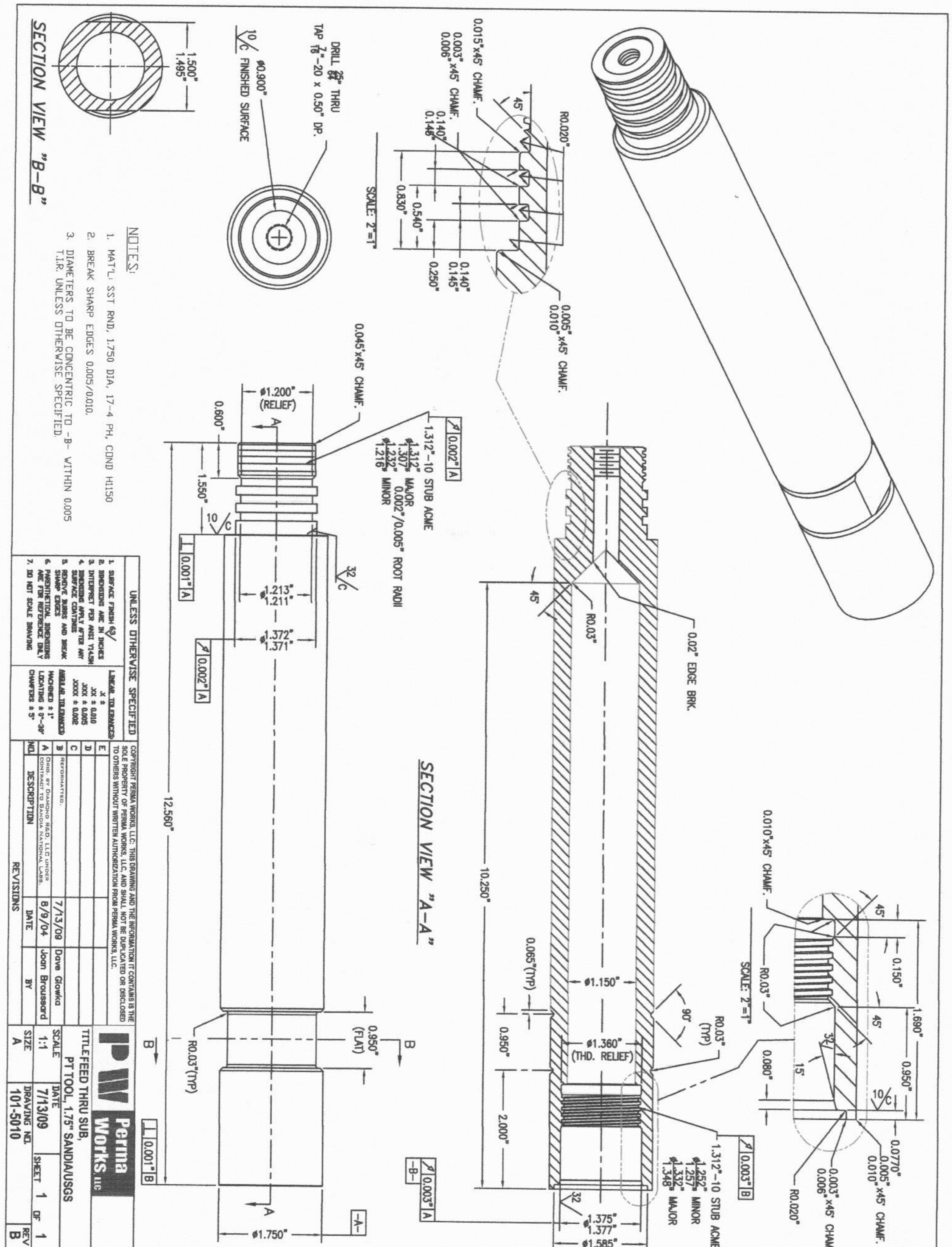
All in all, the Perma Works analog 300°C tool is working well up to 280°C, with capability of near 300°C for short durations. The main limitation on temperature is covered under a report on 300°C solder development. After field testing, the total system has been improved for use in well logging, well monitoring, and supporting EGS well stimulation and production testing.

Attachments

Tool Mechanical Drawings

Field Test Report "Report on Perma Work's Results at Habanero 4"


P/N 101-6010 Fishing Neck
P/N 101-6150 Clamp Ring
P/N 101-6100 Rope Socket Body
P/N 101-3300, Upper Circuit Board
P/N 101-6051 and 101-6052 Kemlon Boot (1 each)
P/N 101-4051, K-16 PT Modified Connector
P/N 101-3010 Electronics Chassis
P/N 101-3020 Chassis O-rings (2 each)
P/N 101-2010 Pressure Barrel
P/N 101-3010 Electronics Chassis
1. ASSEMBLY NOTES GO HERE.
P/N 101-6010 Fishing Neck
5/16" Wireline
P/N 101-2021, Metal Seal (2 each)
P/N 101-4010 Pressure Transducer Sub
P/N 101-1020, Bulkhead O-rings (4 each)
P/N 101-3100, Lower Circuit Board
P/N 101-3018 Probe Set Screws (2 each)
P/N 101-3020 Chassis O-rings (2 each)
P/N 101-3010 Electronics Chassis
P/N 101-4021 Pressure Transducer
P/N 101-2010, Pressure Barrel
P/N 101-3011, Circuit Board Screws
P/N 101-3014, Circuit Board Washers
P/N 101-2021 Metal Seal
P/N 101-1025 RTD Probe
P/N 101-1020 Bulkhead O-rings (2 each)
P/N 101-1010 Temperature Sub
UNLESS OTHERWISE SPECIFIED
REVISIONS
NO. DESCRIPTION DATE BY
A ORIGINAL 8/11/09 Dave Glowka
PW Perma Works LLC
TITLE PT TOOL, 1.75" SANDIA/USGS
SCALE 1:2
DATE 8/11/09
SIZE A
DRAWING NO. 101-0010 Ass'y Dwg
SHEET 1 OF 1
REV A



SECTION VIEW "A-A"
SECTION VIEW "B-B"
SCALE: 2"=1"
0.015"x45° CHAMF.
0.003"x45° CHAMF.
0.006"
R0.020"
0.005"x45° CHAMF.
0.010"
0.02" EDGE BRK.
R0.03"
0.010"x45° CHAMF.
1.312"-10 STUB ACME
0.002"/0.005" ROOT RADII
MAJOR
MINOR
0.045"x45° CHAMF.
ϕ1.200" (RELIEF)
ϕ1.150"
ϕ1.360" (THD. RELIEF)
ϕ1.585"
ϕ1.750"
0.950" (FLAT)
R0.03"(TYP)
0.065"(TYP)
12.560"
10.250"
2.000"
1.550"
0.600"
1.500"
1.495"
DRILL 25/64" THRU
TAP 7/16"-20 x 0.50" DP.
ϕ0.900"
FINISHED SURFACE
NOTES:
1. MAT'L: SST RND, 1.750 DIA, 17-4 PH, COND H1150
2. BREAK SHARP EDGES 0.005/0.010.
3. DIAMETERS TO BE CONCENTRIC TO -B- WITHIN 0.005 T.I.R. UNLESS OTHERWISE SPECIFIED.
UNLESS OTHERWISE SPECIFIED
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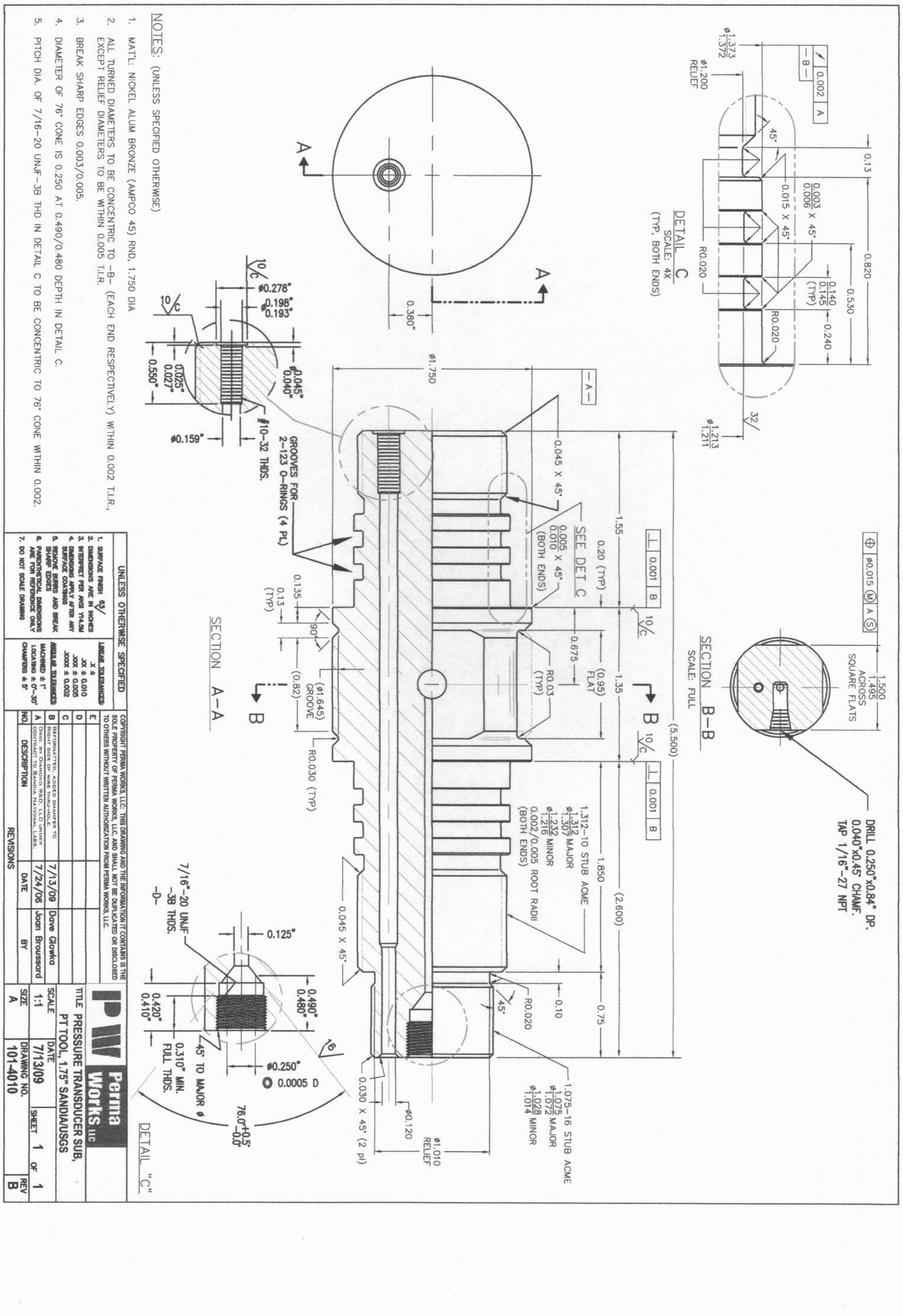
B REFORMATTED. 7/13/09 Dave Glowka
A 8/9/04 Joan Broussard
NO. DESCRIPTION DATE BY
REVISIONS
Perma Works LLC
TITLE FEED THRU SUB, PT TOOL, 1.75" SANDIA/USGS
SCALE 1:1
DATE 7/13/09
SIZE A
DRAWING NO. 101-5010
SHEET 1 OF 1
REV B



NOTES: (UNLESS SPECIFIED OTHERWISE)
1. MAT'L: NICKEL ALUM BRONZE (AMPCO 45) RND, 1.750 DIA
2. ALL TURNED DIAMETERS TO BE CONCENTRIC TO –B– (EACH END RESPECTIVELY) WITHIN 0.002 T.I.R. EXCEPT RELIEF DIAMETERS TO BE WITHIN 0.005 T.I.R.
3. BREAK SHARP EDGES 0.003/0.005.
4. DIAMETER OF 76° CONE IS 0.250 AT 0.490/0.480 DEPTH IN DETAIL C.
5. PITCH DIA. OF 7/16–20 UNJF–3B THD IN DETAIL C TO BE CONCENTRIC TO 76° CONE WITHIN 0.002.
DETAIL C
SCALE: 4X
(TYP, BOTH ENDS)
SECTION B–B
SCALE: FULL
SECTION A–A
DETAIL "C"
DRILL 0.250"x0.84" DP.
0.040"x0.45° CHAMF.
TAP 1/16"-27 NPT
GROOVES FOR 2-123 O-RINGS (4 PL)
SEE DET C
#10–32 THDS.
1.312–10 STUB ACME
1.075–16 STUB ACME
7/16"–20 UNJF –3B THDS. –D–
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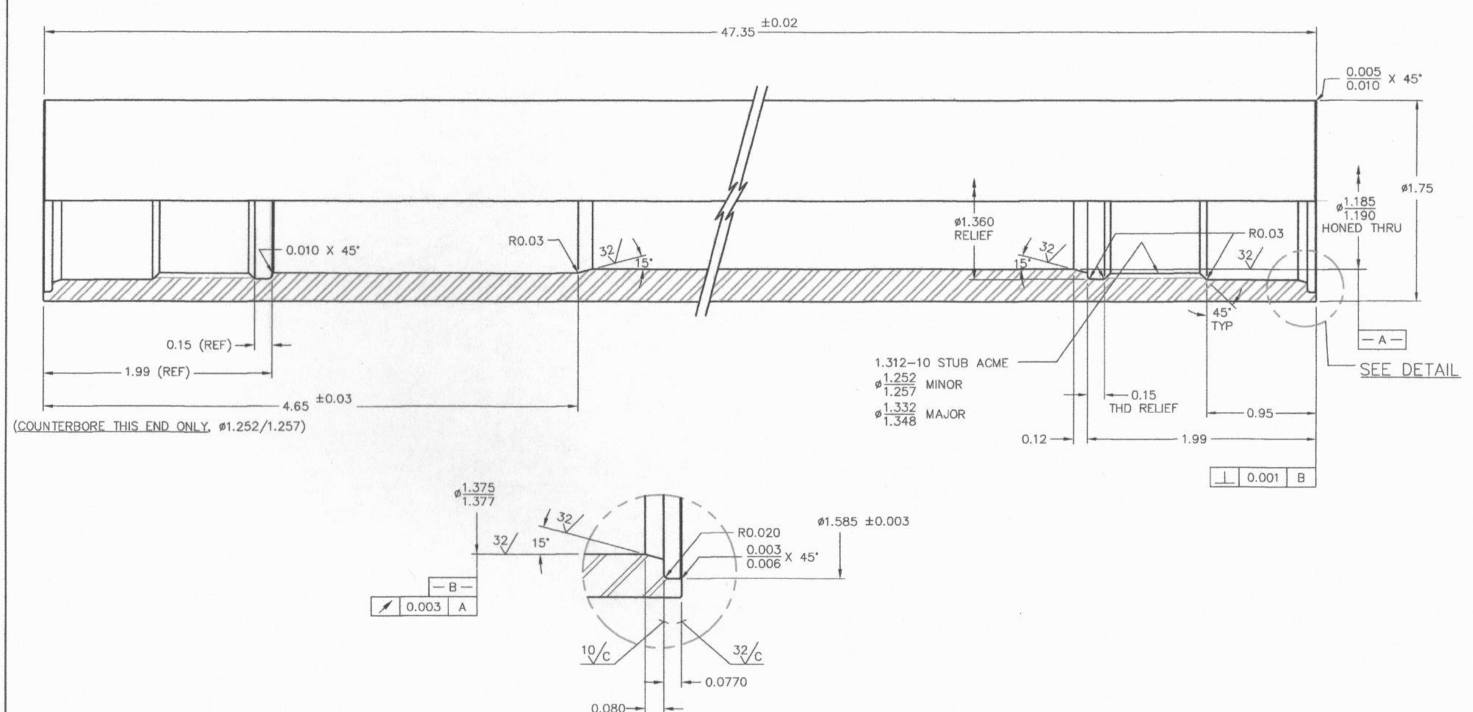
PW Perma Works LLC
TITLE PRESSURE TRANSDUCER SUB, PT TOOL, 1.75" SANDIA/USGS
SCALE 1:1
DATE 7/13/09
SIZE A
DRAWING NO. 101-4010
SHEET 1 OF 1
REV B
B 7/13/09 Dave Glowka
A 7/24/08 Joan Broussard
NO DESCRIPTION DATE BY
REVISIONS



NOTES:

1. MATERIAL: SST RND, 2.000 DIA, 17–4PH, CONDITION H1150
2. END DETAILS ARE TYPICAL BOTH ENDS, EXCEPT FOR THE COUNTERBORE IN THE LEFT END ONLY, AS SHOWN.
3. END DETAIL DIAMETERS ARE TO BE CONCENTRIC TO –B– (EACH END RESPECTIVELY) WITHIN 0.002 T.I.R., EXCEPT THE O.D. (AT THE ENDS) AND THE THREAD RELIEF DIAMETERS, WHICH ARE TO BE CONCENTRIC TO –A– WITHIN 0.005 T.I.R.

UNLESS OTHERWISE SPECIFIED

1. SURFACE FINISH 63
2. DIMENSIONS ARE IN INCHES
3. INTERPRET PER ANSI Y14.5M
4. DIMENSIONS APPLY AFTER ANY SURFACE COATINGS
5. REMOVE BURRS AND BREAK SHARP EDGES
6. PARENTHETICAL DIMENSIONS ARE FOR REFERENCE ONLY
7. DO NOT SCALE DRAWING

LINEAR TOLERANCES:
.X ±
.XX ± 0.010
.XXX ± 0.005
.XXXX ± 0.002

ANGULAR TOLERANCES:
MACHINED ± 1°
LOCATING ± 0°–30'
CHAMFERS ± 5°

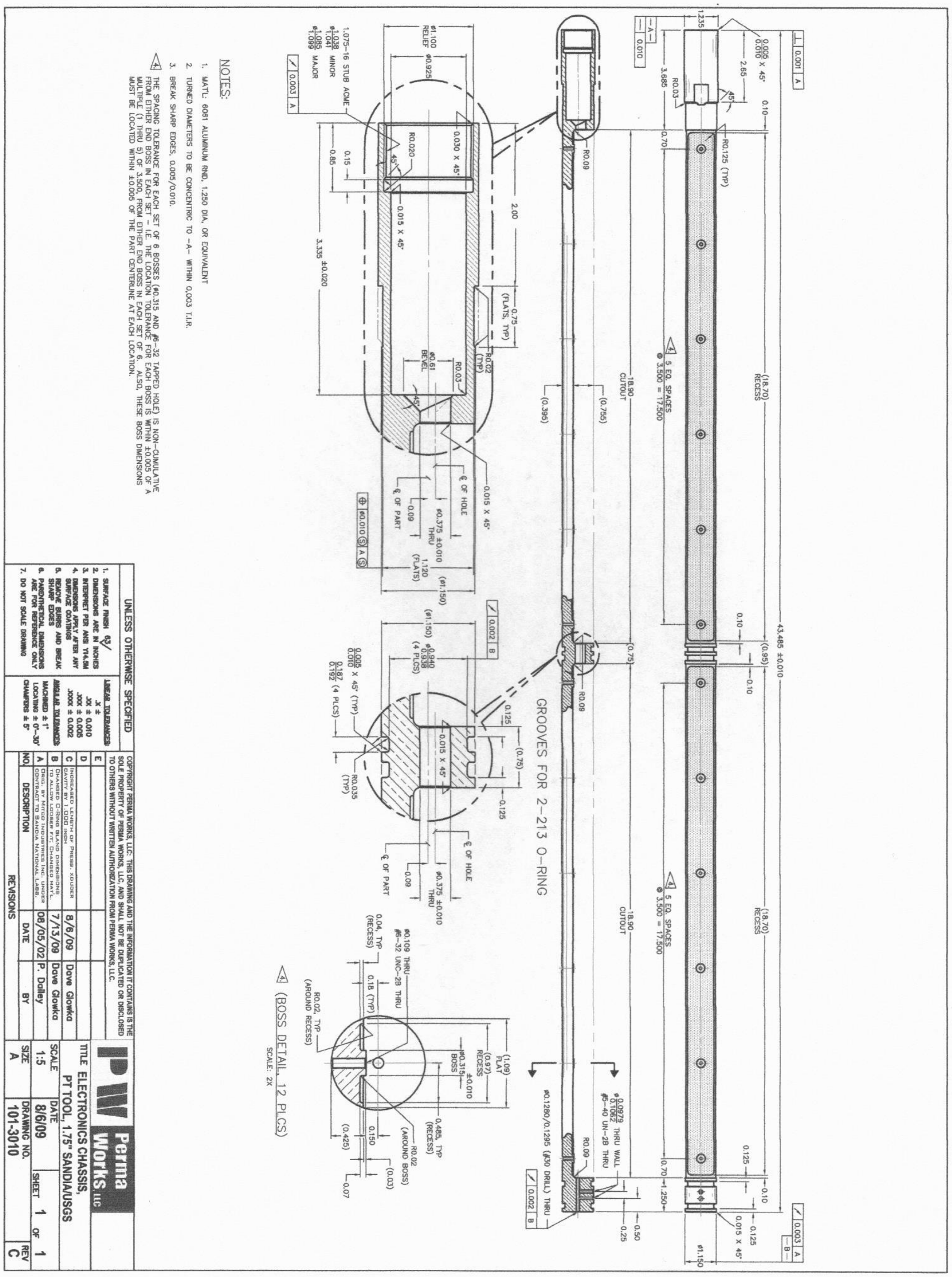
REVISIONS

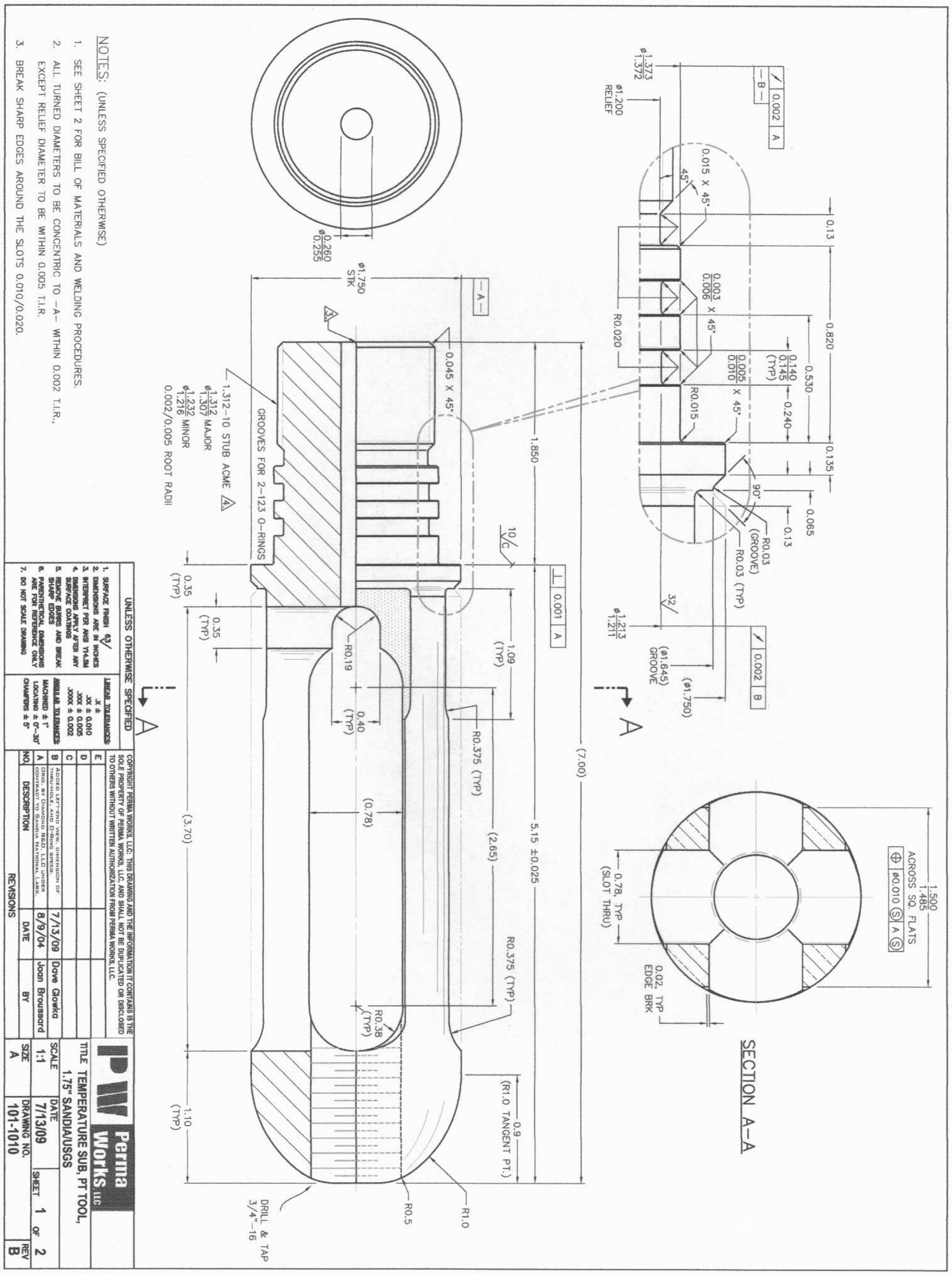
NO.	DESCRIPTION	DATE	BY
E			
D			
C	INCREASED LENGTH BY 1.00 INCHES TO ACCOMMODATE LONGER PRESS. XDUCER.	8/6/09	Dave Glowka
B	REFORMATTED.	7/13/09	Dave Glowka
A	ORIG. BY MITCO INDUSTRIES INC. UNDER CONTRACT TO SANDIA NATIONAL LABS.	8/1/02	P. Dailey

PW Perma Works, LLC

TITLE PRESSURE BARREL, PT TOOL, 1.75" SANDIA/USGS

SCALE	DATE	SHEET	SIZE	DRAWING NO.	REV
NONE	8/6/09	1 OF 1	A	101-2010	C


NOTES:
1. MAT'L: 6061 ALUMINUM RND, 1.250 DIA, OR EQUIVALENT
2. TURNED DIAMETERS TO BE CONCENTRIC TO -A- WITHIN 0.003 T.I.R.
3. BREAK SHARP EDGES, 0.005/0.010.
4. THE SPACING TOLERANCE FOR EACH SET OF 6 BOSSES (⌀0.315 AND #6-32 TAPPED HOLE) IS NON-CUMULATIVE FROM EITHER END BOSS IN EACH SET - I.E. THE LOCATION TOLERANCE FOR EACH BOSS IS WITHIN ±0.005 OF A MULTIPLE (1 THRU 5) OF 3.500, FROM EITHER END BOSS IN EACH SET OF 6. ALSO, THESE BOSS DIMENSIONS MUST BE LOCATED WITHIN ±0.005 OF THE PART CENTERLINE AT EACH LOCATION.
GROOVES FOR 2-213 O-RING
(BOSS DETAIL, 12 PLCS)
SCALE: 2X
UNLESS OTHERWISE SPECIFIED
REVISIONS
Perma Works LLC
TITLE ELECTRONICS CHASSIS, PT TOOL, 1.75" SANDIA/USGS
SCALE 1:5
DATE 8/6/09
SIZE A
DRAWING NO. 101-3010
SHEET 1 OF 1
REV C



NOTES: (UNLESS SPECIFIED OTHERWISE)
1. SEE SHEET 2 FOR BILL OF MATERIALS AND WELDING PROCEDURES.
2. ALL TURNED DIAMETERS TO BE CONCENTRIC TO -A- WITHIN 0.002 T.I.R., EXCEPT RELIEF DIAMETER TO BE WITHIN 0.005 T.I.R.
3. BREAK SHARP EDGES AROUND THE SLOTS 0.010/0.020.
SECTION A-A
1.312-10 STUB ACME
GROOVES FOR 2-123 O-RINGS
0.002/0.005 ROOT RADII
ACROSS SQ. FLATS
0.78, TYP (SLOT THRU)
0.02, TYP EDGE BRK
DRILL & TAP 3/4"-16
5.15 ±0.025
(7.00)
UNLESS OTHERWISE SPECIFIED
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Perma Works LLC
TITLE TEMPERATURE SUB, PT TOOL, 1.75" SANDIA/USGS
SCALE 1:1
DATE 7/13/09
SHEET 1 OF 2
SIZE A
DRAWING NO. 101-1010
REV B
B 7/13/09 Dave Glowka
A 8/9/04 Joan Broussard
NO. DESCRIPTION DATE BY
REVISIONS

Report on Perma Works' Results at Habanero 4

RANDY NORMANN, CTO

JAN 1, 2013

OVERVIEW

Habanero 4 is the fourth production well drilled by Geodynamics in the Cooper Basin, Australia. This is a true EGS 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.

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 in Cooper Basin.

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.

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.

FAST PRESSURE MODE:

The fast readings are 8 readings /sec. Here the last Zero pressure measurement is recorded in surface memory and only pressure data is transmitted. Because we are not switching between readings, the fast pressure mode provides very fast pressure readings. This mode was designed for capturing stimulation events deep in the well.

Testing in New Zealand

OBJECTIVE:

To demonstrate thePW-PT535A on a HT single conductor wireline for an extended period at 250°C.

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.

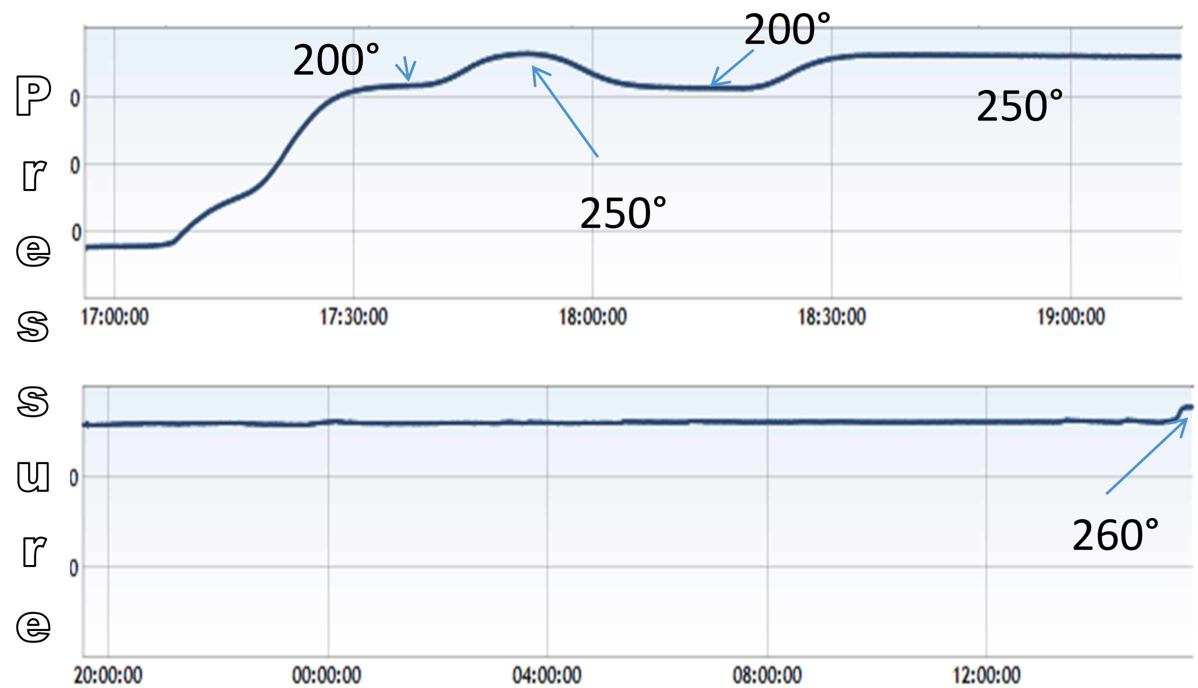
The tool worked in a 24 hr well monitoring test at ~250°C with a push down to ~260°C at the end of the 24 hrs prior to removing the tool. During the second logging run, all tool functionality was tested. The tool made pressure and temperature well monitoring measurements and switched to the high speed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



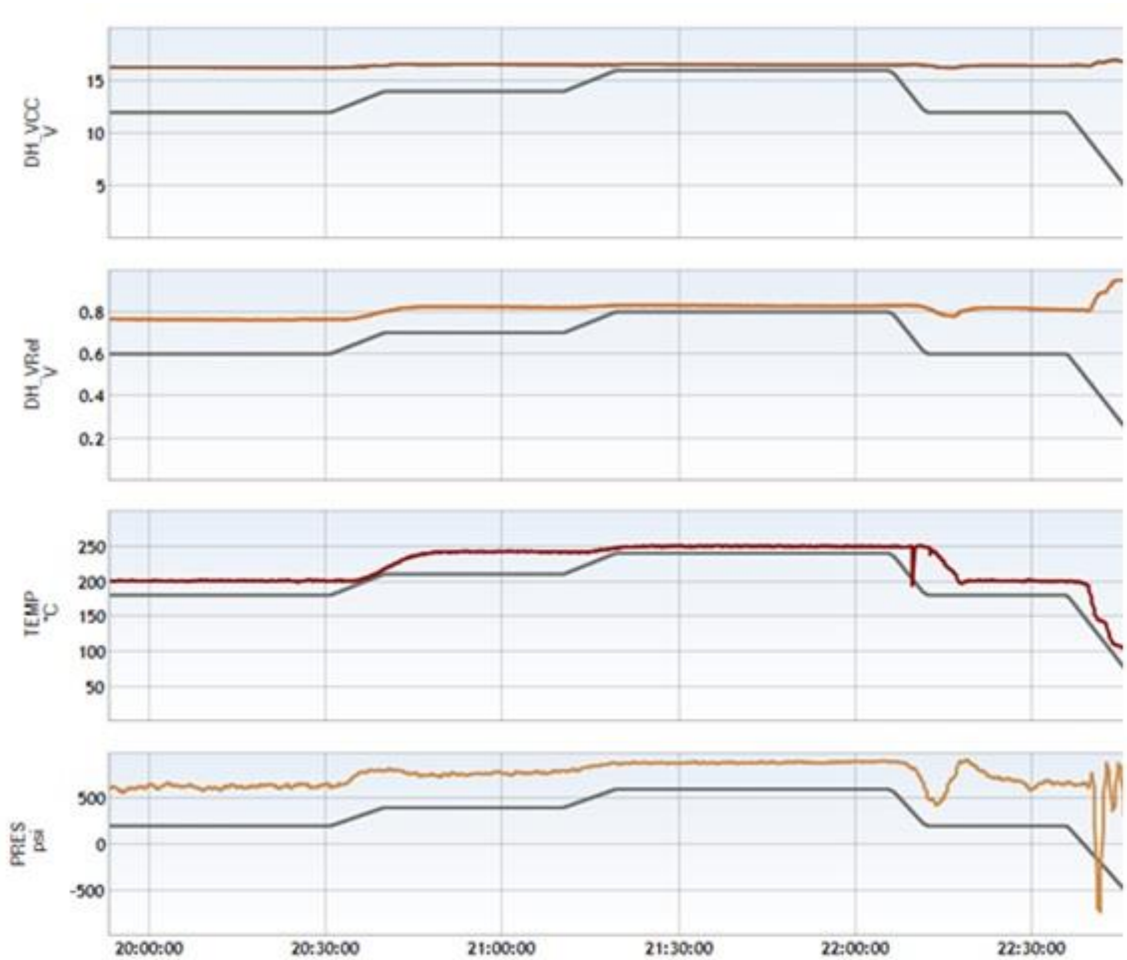
The downside to doing pressure only over such an extended time is that we do not have the corresponding temperature and P/T zero point data to help control drift or temperature related calibration changes.

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 tools pressure transducer amplifiers were increased.   Now, the pressure 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 grove 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 grove. A large chip was actually broken out of the steel next to the O-ring grove. To the right is the missing chip.

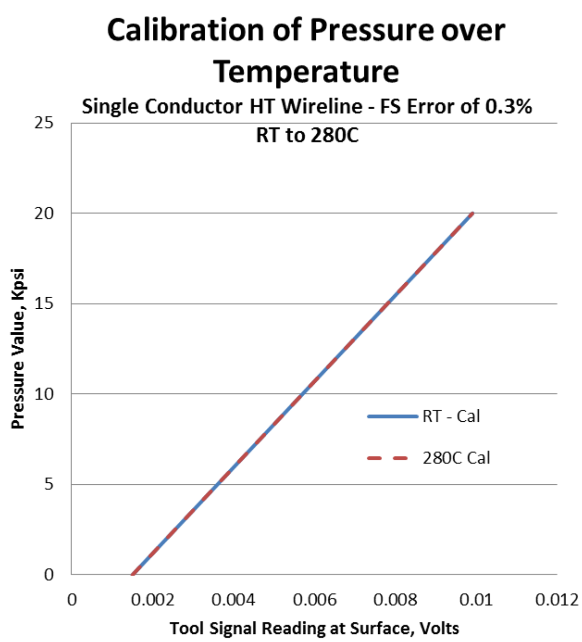
Habanero 4

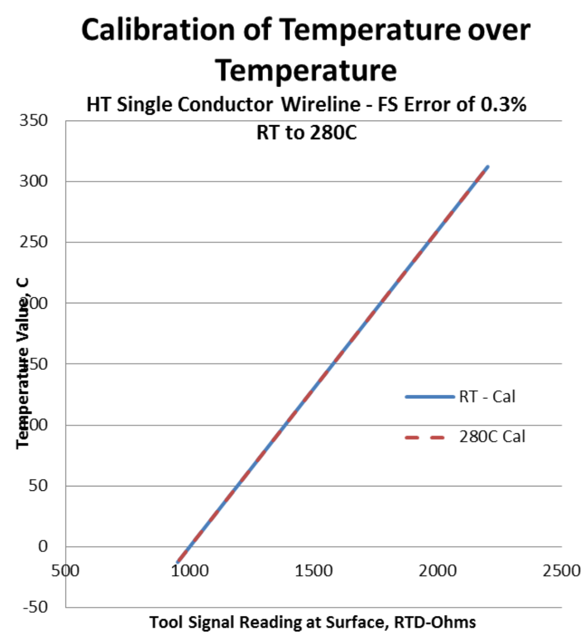
OBJECTIVE:

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.

CALIBRATION OF ELECTRONICS:

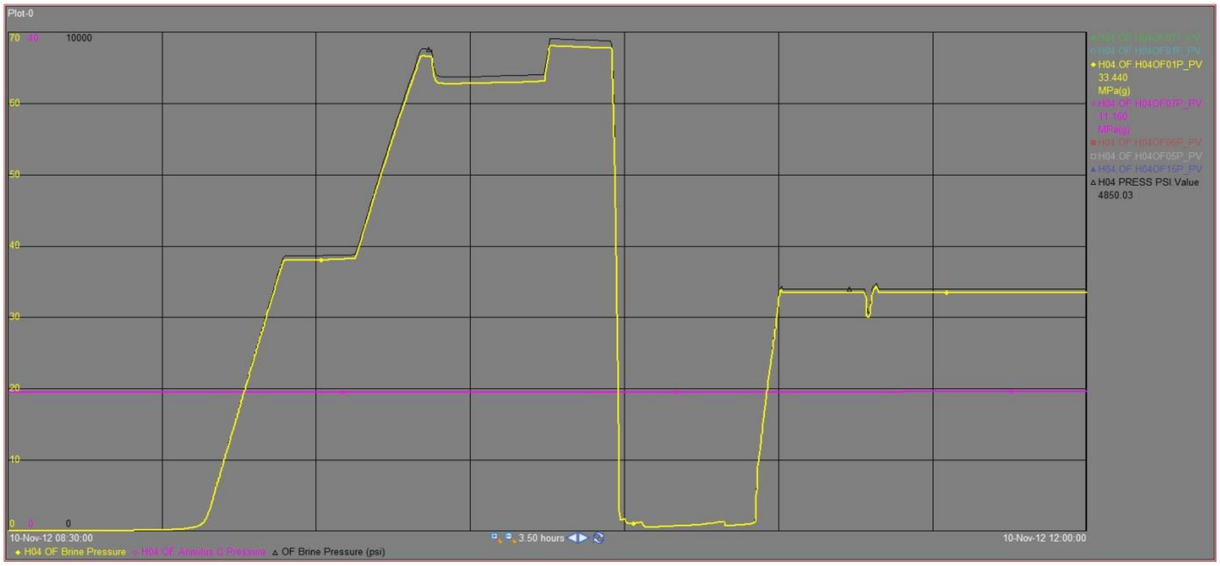
After the electronics were modified following the NZ test, they were mounted on a board carrier and placed in an oven and run using a cable simulator. The results below are from one of the first boards calibrated. The error from room temperature to 280°C is extremely small because of our on-board compensation for electronic drift. For permanent well monitoring, the electronics cannot be removed from the well for calibration so Perma Works uses a means to compensate for electronic drift over time. A major side benefit is greatly reduced electronic drift versus changes in temperature as can be seen here for both Temperature and Pressure measurements. Also, note calibration takes >18hrs.



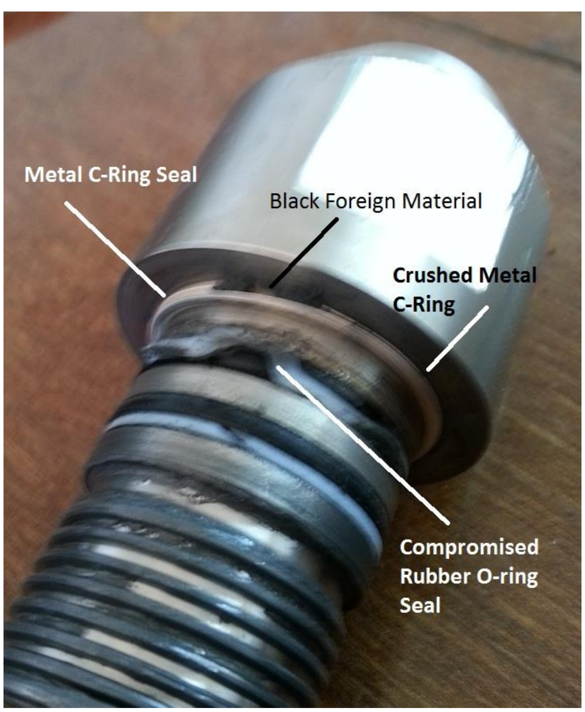


RESULTS AT HABANERO 4:

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. 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.

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 tools 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 voltage-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.

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 pack-off 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 (CONCLUSION)

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. A new HT tool design incorporating better signal filtering options and wider operating voltage range (learned in New Zealand) has already be completed.
4. 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. However, it has not been built. At this point, we need to reevaluate this design for increased weight and build it.

Otherwise this experience has provided invaluable insight to the reservoir engineer needs and highlighted a number of operational issues.