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Design Considerations for Geothermal Logging Tools

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ABSTRACT

The extreme downhole conditions in a geothermal well combine to make it one of the most challenging design environments encountered by modern technology. Complicating the design of logging tools and other hardware intended for deployment in geothermal wells are the high temperatures, high pressures, shock and vibration, corrosive fluids, inaccessibility, difficulty in testing, and even a limited ability to communicate and know what is actually going on downhole.

This paper describes the design parameters that must be considered when developing a downhole tool for geothermal wells. These parameters can be grouped into several categories related to the integrated design process of the tool: 1) design of the measurement method and technique, to ensure that the data that will be obtained is of the type and quality needed for well or resource evaluation; 2) design of the electronic circuits and components to provide whatever level of downhole data acquisition, processing, storage, and telemetry is needed; and 3) design of the mechanical packaging to carry the transducers and electronics and provide whatever level of protection is necessary against high temperatures, high pressures, shock, vibration, and corrosion.

Tool Deployment Method

As shown in Table I, the method of deploying a logging tool has a major impact on its design specifications. A tool that is deployed on the end of a single- or multi-conductor wireline or wired metal alloy tubing can receive power from and communicate with the surface more easily than a tool that is deployed on a slick-line or in the drillstring while drilling. The drilling environment imposes extreme shock and vibration on electronics and mechanical housings, but even logging tools designed for non-drilling conditions are subjected to significant dynamic stresses during transportation and deployment. Electronics can be shielded from high temperatures for a limited time downhole with vacuum-Dewar pressure barrels, but long-term deployment requires the use of high-temperature components using SOI (Silicon-On-Insulator) and other specialized chip technologies [1].

The Role of Modeling in Downhole Tool Design

Successful logging tool development, particularly for new tools, requires extensive use of modeling. The need for engineering

Table 1. Geothermal Logging Tool Design Specifications for Various Deployment Methods.

Deployment Method:	**Single- or Multi-Conductor Wireline**	**Wired Metal Tubing**	**Slickline / Non-drilling**	**Drill Collar**
Power Supply:	Surface	Surface	Battery	Battery/ Downhole generator
Comm. with Surface:	Via wireline	Via wireline	None	Mudpulse or EM telemetry
Data Storage:	Downhole or surface	Downhole or surface	Downhole	Downhole
Maximum Vibration:	10 g @ 50-800 Hz	10 g @ 50-800 Hz	10 g @ 50-800 Hz	30 g @ 50-800 Hz
Maximum Shock:	200 g @ 0.05 ms impulse	200 g @ 0.05 ms impulse	200 g @ 0.05 ms impulse	2000 g @ 0.05 ms impulse
Maximum Electronics Temp., Dewar:	150°C in 10 hours (in300°C wellbore)	150°C in 10 hours (in 300°C wellbore)	150°C in 10 hours (in 300°C wellbore)	150°C indef. (in 150°C wellbore)
Maximum Electronics Temp., Unshielded	300°C (in 300°C wellbore)	300°C (in 300°C wellbore)	300°C (in 300°C wellbore)	300°C (in 150°C wellbore)
Maximum Pressure:	1350 atm (20 kpsi)	1350 atm (20 kpsi)	1350 atm (20 kpsi)	1350 atm (20 kpsi)
External Material Requirements:	High-strength, corrosion resistance	High-strength, corrosion resistance	High-strength, corrosion resistance	Same plus erosion resistance

modeling inherent to the rigorous design of circuitry and hardware is somewhat obvious. Not so obvious is the need for modeling the very process that is being measured. At least a rudimentary understanding of how a tool both affects and is affected by the process it measures, is sometimes necessary to prove the validity of the measurements.

An example of such modeling, which was conducted for the development of a downhole flowmeter, is shown in Figures 1 and 2. This tool, under development as an alternative to the problematic spinner for long-term geothermal wellbore monitoring, needs to operate without obstructing the flow or sealing against the wellbore wall. With the concept shown, an open flow tube through the center of the tool carries a small, but repeatable and quantifiable percentage of the total flow that is passing up the wellbore. Sensors placed in the annular space between the inner flow tube and the outer diameter of the tool are used to measure the inner flow velocities, which are then used to extrapolate the wellbore's total flow rate.

A flow model was developed that calculates the pressure drops around and through the tool. It uses these results to predict the flow distribution and, ultimately, the flow velocities through the tool. The typical results shown in Figure 2 are the flow velocities through the tool plotted as a function of the inner tube diameter and the borehole diameter, with a total wellbore flow rate of 100 gpm.

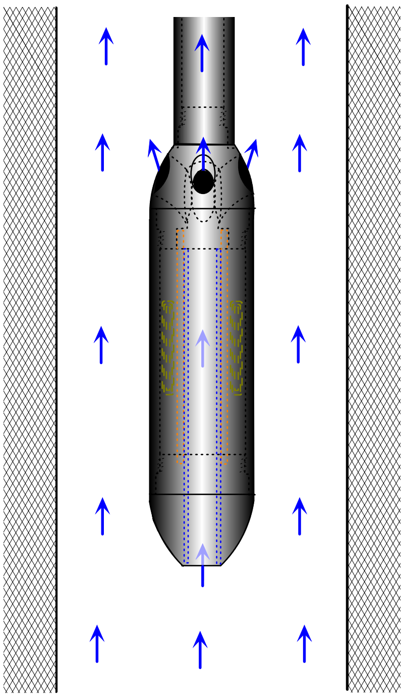

Figure 1. Schematic of downhole flowmeter under development for geothermal wellbore monitoring applications.

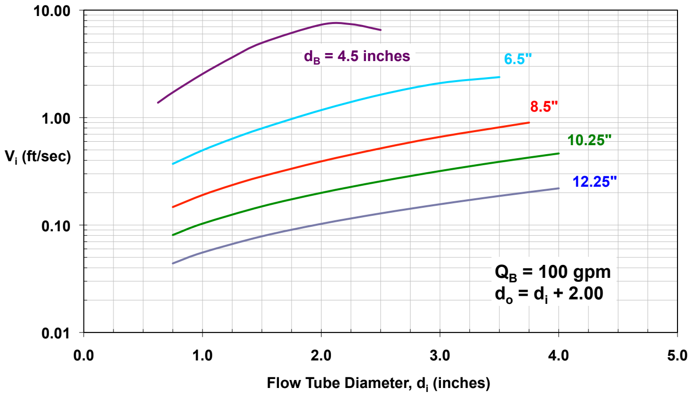

Figure 2. Predicted flow velocities through the downhole flowmeter as a function of the flow tube and wellbore diameters.

In general, flow velocities need to be at or above 0.1 ft/sec for accurate measurement with either magnetic or acoustic doppler sensors. The predictions indicate that such velocities can be attained with reasonable tool diameters in all size wellbores, although more than one tool size may be necessary to cover the full range of wellbore diameters from 4-1/2 to 12-1/4 inches. These results are guiding the development of the downhole flowmeter.

High-Temperature Logging Circuitry

Even with process variables that are ostensibly easy to measure, like temperature or pressure, it is necessary for the electronics to accurately make those measurements and communicate them to on-board or remote memory. Long before making electronic components inoperable, high temperatures cause drift and erratic behavior in component performance. It is often necessary to incorporate sophisticated sensors and circuitry to compensate for this drift.

Advances in high-temperature components have both extended the upper unshielded operating temperature and reduced temperature drift at the circuit level. An example is shown in Figure 3, which shows the offset accuracy of a new high-temperature amplifier. Even at an operating temperature of 300ºC, the error in offset voltage for a signal ranging from 0.3V to 3.3V is only 25

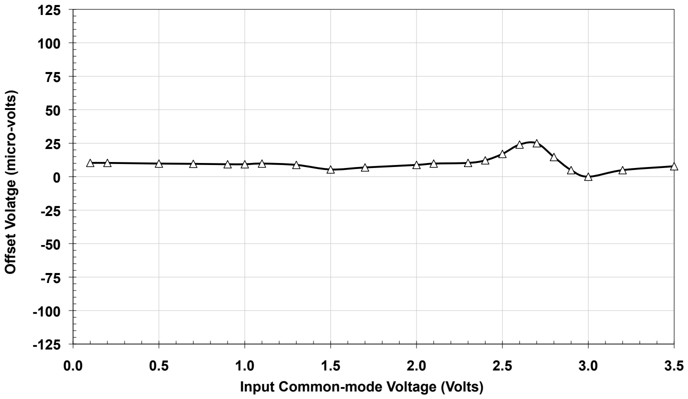

Figure 3. Input offset voltage for new high-temperature amplifier after operating at 300ºC for 438 hours.

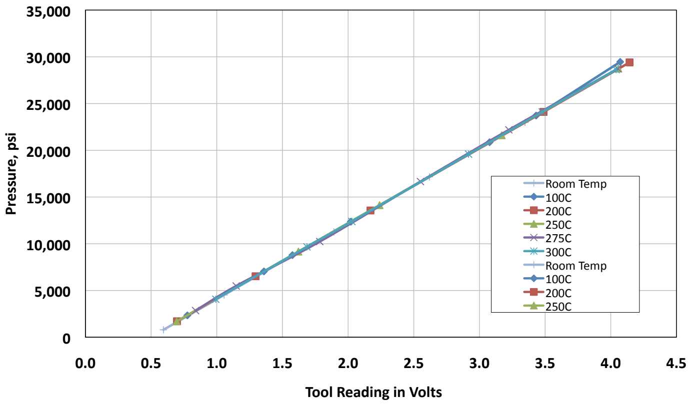

Figure 4. Measured pressure signals from 300ºC-PT tool (uncorrected) operating at various laboratory test temperatures.

ppm. Moreover, calibration will correct about 90% of that error. This accuracy represents a 250-fold improvement over previous high-temperature downhole amplifiers.

Additional results such as those seen in Figure 4 illustrate the advantages of building circuits with components having superior thermal stability. Seen here are output signals from a recently commercialized 300ºC (unshielded) pressure-temperature (PT) tool. The signal from the pressure sensing circuitry is shown without temperature compensation of any sort.

In developing the second-generation analog PT tool, we included the capability for the tool to operate on single-conductor wirelines in either one of two communication modes: direct measurement or pulse amplitude modulation (PAM). The direct measurement mode is suitable for shallow wells or wells where a multi-conductor wireline is available. The PAM option transmits a series of pulses to communicate signal amplitudes as well as calibration signals. Each measured signal is thereby compared with a calibration signal. This improves the tool's ability to operate over a broad temperature range.

Digital tools operating at high temperatures present additional challenges. The limited availability of high-temperature components for digital circuits has always held back digital tools in this environment; but availability is continually improving. The original high-temperature digital PT tool developed by Sandia was developed without the availability of high-temperature microprocessor program memory. The tool had to boot up on the surface and receive its program as a download. If at any time the tool lost power (even for a few milliseconds) the tool would lose its program. Perma Works is working with Honeywell toward commercial fabrication of high-temperature silicon-on-insulator (HT SOI) versions of the electrically erasable memory so commonly found in most electronic devices. Also, improved A/D converters are now available that enable much faster data processing and communication at high temperatures.

Another temperature limiting device in high-temperature digital tool circuitry has been the digital clock needed by the microprocessor. Perma Works is currently working with Frequency Management Inc. to develop a 300°C digital clock.

The availability of new high-temperature batteries delivers the capability for the digital tool to operate from a slick-line. The high-temperature battery is being developed by Electrochemical Systems Inc under an existing DOE grant. The battery will be a rechargeable; however, it will not operate at temperatures *below* 125C.

Any downhole tool that operates under battery power must be designed with power consumption in mind. Power management circuits are necessary that strategically power and de-power circuits when not in use.

The long, slender geometry inherent to downhole electronics requires that care be taken in locating signal and power wires and traces in a circuit board. Wires and traces carrying analog transducer signals should be located as far from other wiring and components as possible to minimize noise on the signal lines. To the extent possible, circuits for processing transducer signals should therefore be located near the end of the circuit board that is closest to the transducer.

Electronic components used in high-temperature applications should be "burned-in." This is a process whereby the components are operated at the required operating temperature for some period of time to eliminate the components that fail early. The failure rate of electronic components at elevated temperatures, even those rated for such temperatures, is relatively high; and it is best to weed out the early failures before they go downhole.

As suggested above, a significant aspect of our effort at Perma Works has been the creation of second-generation designs using commercial processes, most of which have required developing external suppliers. These suppliers are now available to other tool designers and users in the industry. Examples of these resources include:

Wired Metal Tubing Wireline: Sandia hand-built a wired metal tubing cable for 300°C by pulling HT wire through ¼-inch tubing. Working with Draka Cableteq, Perma Works now has the option to buy such cable at any length and with a 350°C rating.

Wire Connection: Sandia used hand wiring and laser welding to interconnect the circuit components. This has almost unlimited temperature operation. Working with Electronic Working Standard (EWS), Perma Works now has a supplier capable for working with high-temperature solder up to 300°C.

Pressure Sensor: Sandia worked with Paine Electronics on an experimental 600°F pressure sensor. Perma Works has continued to work with this supplier by providing feedback on their now commercial version of the experimental pressure sensor.

Commercialization: Perma Works is currently offering 300°C analog PT tools to industry as engineering units. Perma Works is conducting talks with US and overseas service providers. Service providers will be trained in tool installation and operation.

High-Temperature Circuit Boards

Circuit boards can be a limiting factor for unshielded electronics. Delamination of most board materials at high temperatures limits the ability to fabricate reliable multi-layer circuit boards. Perma Works has worked to convert to commercial practice a new circuit-board technology demonstrated at Sandia back in 2001. Here, a patent-pending metal-spray process impacts metal onto a ceramic substrate. This process has a major advantage over the existing co-firing process, which is firing of green ceramic with conductive traces of metal particles. These metal particles are held in an organic binder which is silk screened onto the green ceramic. As the ceramic is fired, the organic binder is burned off and the metal particles melt, sintering them onto the ceramic. This process is limited to 3- to 4-inch ceramic circuit boards because shrinkage of green ceramic is ~30% in the firing process. Logging tools, however, require long and slender circuit boards, commonly 12 to 18 inches long.

The metal-spray process works with already-fired ceramic and can be used on a circuit board of any practical length. An image of a board fabricated with this technique is shown in Figure 5. This close-up is of solder joints after exposure to five temperature cycles to 250°C. In laboratory testing, technicians were able to solder and unsolder connections four times at ~320°C before the failure of a circuit pad. This is unheard of with other circuit board technologies, even at much lower temperatures.

We are currently working with other suppliers to make this process commercially viable. In addition to geothermal logging, these circuit boards may find use in automotive and aerospace applications as well.

Figure 5. Photograph of solder joints in a metal-spray trace on a ceramic circuit board (after 5 temperature cycles to 250°C).

Ceramic Circuit Board Mounting System

Ceramic circuit boards and high-temperature electronic components combine to make for a relatively heavy electronic package. This package must be secured within the tool in a manner that does not place undue stress on the circuit boards in the presence of the vibration and shock associated with transportation and deployment of the tool. Furthermore, the differential thermal expansion between a ceramic circuit board and the metal chassis on which the board is mounted must be accommodated in a manner that does not place the board under tensile stress.

Accordingly, a new system for mounting a heavy circuit board subjected to differential thermal expansion has been developed. The mounting system employs a clamp at the lower end of the circuit board that fixes the board relative to the electronics chassis; and sliding mounts at selected intervals along the circuit board, from the bottom up. The clamp is designed to hold the circuit board by friction, which prevents relative movement between the board and the chassis in the presence of the significant dynamic forces resulting from vibration and shock on the tool. The sliding mounts are designed to prevent lateral movement of the circuit board while allowing longitudinal movement along the board's length due to differential thermal expansion between the board and the chassis. This prevents the board from developing unnecessary mounting stresses at high temperatures.

Designing for Thermal Dissipation

Many electronic components generate heat through the consumption of electrical power. The *minimum* temperature of any electronic component is the ambient fluid temperature, whether it is that of the hot wellbore fluid or the cooler temperatures inside a Dewar pressure barrel. The temperature rise due to internal heat generation is additive on top of the ambient temperature. It is, therefore, generally advantageous to reduce the heat generation and improve the heat dissipation from each component to the extent possible.

In a Dewar pressure barrel, there is no way to dissipate heat from each component without eventually increasing the ambient temperature inside the vessel. Shielded tools must therefore be designed with an extreme goal of minimal onboard power consumption.

In unshielded tools, heat generation is also important, perhaps more so since the minimum starting temperature of each component is so much higher with the hotter ambient sink. In this case, however, heat dissipation achieves much greater importance. It is better with an unshielded tool to simply embrace the ambient temperature as the minimum and work to dissipate the generated heat as quickly as possible. This can be done by attaching heat sinks to the components that help dissipate heat to the outer tool body and into the wellbore fluid. In extreme cases, eutectic (phase-change) materials could be used as they are in Dewar vessels to extend the operating time; however, eutectic materials would only buy time over a short period and would probably be useful only in unshielded applications where periodic cooling occurs, such as in drilling tools.

Pressure Barrel Design

The pressure barrel is the cornerstone of the basic mechanical envelope employed in most geothermal logging tools. The minimum wall thickness is either in the sealing areas or at the roots of the threads used to screw the bulkheads on the ends of the pressure barrel. To determine the strength requirements for the pressure barrel, it is necessary to calculate its triaxial stress field (tangential, radial, and longitudinal) under downhole conditions.

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

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

where

σ_t = tangential stress;
p_i = internal pressure;
p_o = external (borehole) pressure;
a = one-half cylinder ID;
b = one-half cylinder OD; and
r = radial position between a and b where stress is to be calculated.

The radial stress, σ_r, in the cylinder wall is

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

and the axial stress, σ_a, is

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

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

These three stresses represent the tri-axial stress state at any radial location in the pressure barrel. 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:

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

This quantity is then compared with the yield strength to determine when failure of the material is likely [2].

Equations 1-4 are plotted in Figure 6, showing the stress distribution over the thickness of the pressure barrel wall with a wellbore pressure of 10,000 psi. These curves show that the highest combined stress in the pressure barrel cross-section is at the inner wall. This maximum Von Mises stress is plotted in Figure 7 as a function of the borehole pressure and the pressure barrel outer diameter. A material yield strength of 150 kpsi is shown for reference because materials having this strength (e.g., 17 PH stainless steel) are commercially available and are suitable for this purpose. The figure shows that pressure barrels can be designed using modern alloys and reasonable wall thicknesses to cover the entire practical range of borehole pressures that may be encountered in a geothermal well.

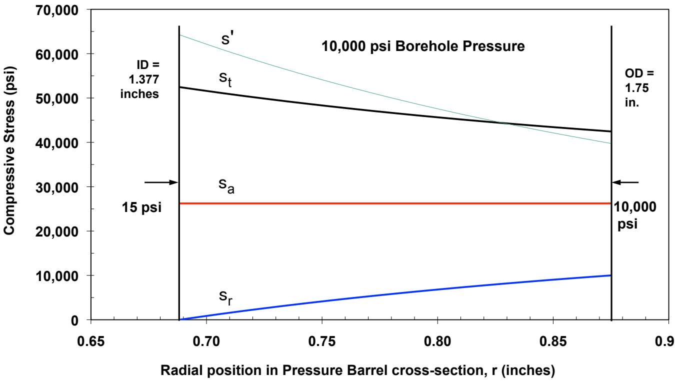

Figure 6. Calculated triaxial and Von Mises stresses in a pressure barrel at 10,000 psi wellbore pressure.

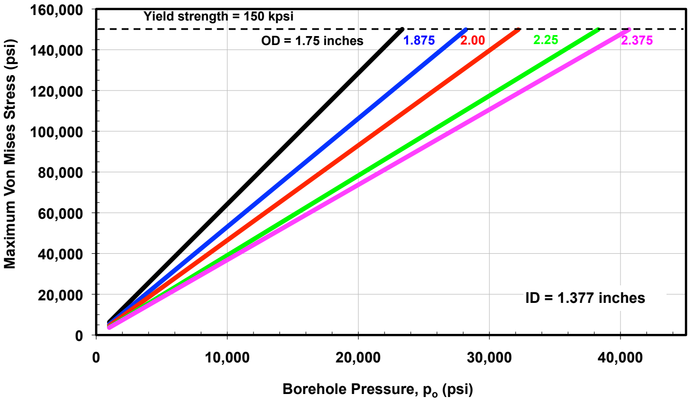

Figure 7. Maximum Von Mises stresses at the pressure barrel ID for various outer diameters.

In addition to wall thickness, the methods of attaching and sealing a bulkhead on each end of the pressure barrel are important design considerations. Because of the thin walls typically used, stub Acme threads are usually the best choice for the bulkhead connection. Shown in Figure 8 are the thread heights for Acme, Stub Acme, and Modified Form 2 Stub Acme threads cut according to the listed specifications. A thread count of 10-16 threads/inch is generally used on logging tools 1-4 inches in diameter. As the figure shows, this results in the threads taking up only a very small fraction of the pressure barrel diameter.

The importance of using thread lubricant to prevent seizing of the threads cannot be overstated. Bulkheads and pressure barrels are generally made of different materials, so galling should not usually be a problem. If the design allows wellbore fluid to flood the thread, however, other problems that cause seizure of the threads can appear (see below). Suitable thread lubricants can be found that cover most temperature ranges encountered in geothermal wells.

Except at very high temperatures, double radial O-ring seals are generally a very effective means for sealing the bulkhead within the pressure barrel. Seals can be placed either inboard or outboard of the threads. This means the threads are either flooded or sealed from the wellbore fluid. In general, it is better to protect the threads from the fluid by placing them inboard of the seals; however, a thinner wellbore wall can be used if the seal is placed closer to the minimum ID of the pressure barrel. As with many things in life, there are trade-offs that must be considered for any given application. Wireline-deployed logging tools used in wellbore production may not need protected seals. On the other hand, drilling mud inside thread passageways can bake at high temperatures into a type of ceramic wonder material, making joints difficult to un-thread.

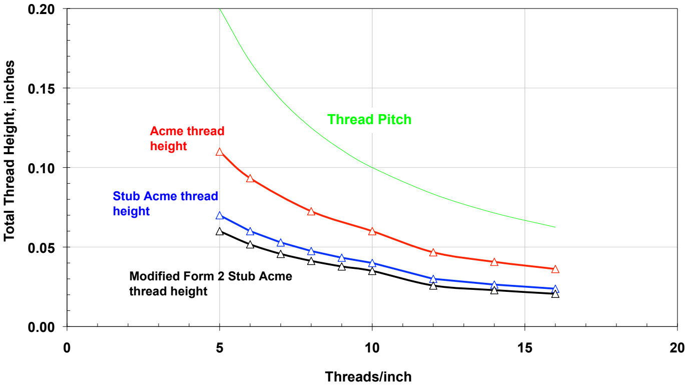

Figure 8. Thread height specifications for Acme, Stub Acme, and Modified Stub Acme threads per ASME 1.5-1997 and ASME/ANSI 1.8-1988.

At temperatures above 250ºC, O-ring seals can become problematic. Although the materials may sometimes continue to seal if left undisturbed, it is often deemed too risky to return a tool downhole until the seals are replaced. This can be an expensive, time-consuming task. Metal c-ring and e-ring seals are available that can seal to much higher temperatures (>250ºC) and pressures (>20,000 psi). These seals are relatively expensive, and as metal face seals, they do not offer the flexibility in design that is inherent to radial seals. They are reliable, however, and obviate the need for replacement on every run.

Materials

An entire paper could (and probably should) be written on the selection of materials for the mechanical envelope of geothermal logging tools. The high-temperature, high-pressure, high-corrosion environment is a challenge for many alloys. The spotty availability, material cost, and difficulty of machining suitable high-strength alloys makes it worthwhile to conduct a detailed examination of the exact environment and required life of any given tool. One-of-a-kind research tools that will not be used for many runs or actually spend that much time downhole can sometimes be made from lower cost materials without adverse consequences. It is important for the tool designer to carefully match materials procured for downhole tool parts with the exact expected environment.

Shock Mounting

The main design strategies for preventing shock damage to electronics are to:

1) mount them solidly so that there is as little unconfined movement as possible between the circuit boards and the pressure barrel; and
2) emplace shock-absorbing materials at strategic points in the fixtures that attach the electronics to the rest of the tool.

The first requirement conflicts with a desire to design for ease of assembly. The tighter the electronics chassis slides into the pressure barrel, the less likely it will suffer damage from shock and vibration; but the harder it becomes to assemble and disassemble the module. Greases used to lubricate O-ring-type stabilizers may disappear at high temperature, making it difficult to later remove the electronics from the pressure barrel.

The long, slender nature of downhole electronics makes it imperative to stabilize each electronics chassis at frequent intervals along its length. Regardless of the strength of a given chassis, if a long enough section is left unstabilized, a harmonic frequency can be excited by external impacts and vibrations that will subject the electronics to extreme shock levels. O-ring-type stabilizers are effective if placed frequently enough along the chassis length; and provided they are designed with the proper amount of O-ring squeeze to make assembly possible.

Axial shock isolation of the electronics chassis is possible through the use of shock mounts that incorporate rubber pads to attenuate the shocks before they reach the chassis. Such mounts are not generally necessary for non-drilling applications, but any tool designed for drilling needs them. The choice of elastomers to use in the shock mounts becomes an issue at high temperatures, and frequent replacement may be necessary if the shock mounts are expected to maintain their functionality.

Re-Use of Mechanical Envelope Designs

A good mechanical envelope design can be used and re-used in many different logging tools. In order to reduce the development time and costs of new tools, Perma Works is continually perfecting a standard mechanical envelope that can be used in most tools. This does not necessarily mean that a single tool size must be adopted. Many of the design features in the mechanical envelope can be scaled up or down in size to accommodate a large range in tool diameters.

Where possible, it is advantageous to use standard machined parts that are now commercially available for downhole logging tools. Entire mechanical envelopes for non-extreme wellbore conditions can be purchased in pieces, from the wireline cablehead to pressure barrels and bulkheads. The requirements of any given tool environment may mean that certain parts of the mechanical envelope need to be upgraded to a more robust material type, different thickness, etc. Existing suppliers are often eager to work with the tool developer in modifying their standard parts to accommodate the needs of a new tool.

Summary

Many factors go into the development of a successful geothermal logging tool. Although the general guidelines discussed in this paper can be used as a starting point to design a downhole tool, each aspect of the design needs to be critically evaluated for the intended environment of the tool. It is not necessary to incorporate all the costly remedies that are possible if they are not needed in any given application. Critical attention should be paid, however, to every aspect of design mentioned in this paper, and more. Up-front engineering time is generally more cost-effective than the costs of re-worked parts, project delays, and additional engineering time on the back end.

The integrated design approach undertaken by Perma Works has strived to identify and assist where possible any commercial vendor providing critical hardware, design, or fabrication services that can be utilized in geothermal logging tool development. There are an incredible number of parts that go into any downhole logging tool, and many of these require specialized suppliers because they are slightly out of the ordinary. This is especially true for logging tools intended for geothermal environments. The ready acceptance and utilization of these suppliers as integral partners in the development of any tool can mean the difference between development periods measured in months and those measured in years.

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