# International Partnership for Geothermal Technology

# High Temperature Downhole Tools

## Recommendations for Enhanced and Supercritical Geothermal Systems

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## INTRODUCTION

Geothermal energy for power production is extracted through wells. These wells address the geothermal resource directly and provide the primary information on the resource characteristics. Enhanced geothermal drilling and fracturing requires ever more detailed formation analyses to allow correct assumptions on fracturing and monitoring of enhancement activities. Geothermal wells are getting hotter and deeper, with attempts at drilling into supercritical fluids already carried out in Iceland (however still not successful) and being considered in New Zealand. The downhole measurements require increased tolerance, both short and long-term, at gradually harsher well conditions. This demand is expected to rise significantly in coming years, in particular if enhanced or supercritical wells will become economically exploitable.

Development of new instrumentation and methods, in preparation for unconventional high temperature geothermal exploration and utilization, will benefit the current geothermal industry, which is now beginning to extract televiewer data at 300°C and data from electronic temperature and pressure gauges functioning up to 400°C. More high temperature formation tools are however required and at least the pressure and temperature sensing options need to be available up to 600°C and 1000 bar.

Definitions: In the context of this White Paper, high temperature wireline instruments (having live readout at surface) are tools that should function at 300°C, while high temperature slick-line tools (data stored in memory) should reach 400°C in conventional wells and 600°C in 'supercritical wells'.

| | | | | |
|---|---|---|---|---|
| **150°C** | **250°C** | **300°C** | **400°C** | **600°C** |
| **302°F** | **482°F** | **572°F** | **752°F** | **1,112°F** |

## GENERAL COMMENTS ABOUT EXISTING GEOTHERMAL TOOLS

Today most geothermal tools use conventional oil patch electronics operating in a heat shield or Dewar flask. These instruments have electronics that are generally limited to 150°C. The heat shields used in geothermal tools are highly specialized and relatively expensive. In a few words, heat-shields are large metal thermos bottles with a vacuum between the double wall pressure housing. The current limit of heat shielded temperature and pressure sensors (the most urgent sensing parameters in geothermal development) is 400°C.

To place this technique in perspective, conventional electronics in a Dewar flask can be expected to deliver between 4 and 12 hrs of operating time at 300°C in a geothermal well, primarily ruled by the time it takes for the internal heat loss from the shielded electronics to reach their own tolerance limit. An example of such high temperature instrument (300°C) is a televiewer developed by ALT in Luxembourg, now applied commercially in New Zealand high temperature wells.

Heat shields for extreme temperatures are very difficult to design and build. The amount of leakage through conductive path ways must be controlled. The best designs have time limitations from structural leakage but also from internal heat generation. Eutectic materials or thermal absorbing mass inside the tool buys a greater operating time. These energy absorbing materials are merely energy absorbers that use phase change or energy absorption to store energy due to leakage or internal heat generation into the electronics cavity.

Current technology does not lend itself to any long term "monitoring logs" because of the time limit of conventional oil patch electronics operating inside a heat-shield. Instruments that have sensors or electronics that cannot be flasked are also very limited in terms of geothermal applications.

## DESCRIPTION OF HIGH TEMEPERATURE TOOL NEEDS

There are two main applications for high temperature tools: 1) For exploration of enhanced geothermal wells, obtained as part of an Enhanced Geothermal System (EGS) and 2) For exploration of wells drilled into high temperature (or 'volcanic' geothermal systems), some of which can be expected to reach supercritical fluid temperatures within the next few years (supercritical means beyond 374°C for pure water and pressure greater than 22 MPa). The need for new EGS technology evolves around formation characterization to determine the generation and placement of the reservoir, the stimulation (even creation) of the reservoir itself and the maintenance of the reservoir once production is started. In high temperature geothermal fields, the need is primarily for higher temperature and pressure readout tolerance and secondly for improved temperature tolerance of existing formation evaluation tools. For both EGS and volcanic systems, casing inspection during cementing and later monitoring is becoming more relevant at elevated temperatures.

## 1. FORMATION CHARACTERIZATION

Characterization is needed to locate the best possible region in the well for EGS activities and to analyze fractures in volcanic systems. This might mean looking at formations or rock structure while the well is being drilled. In most cases, characterization will take place after the well has been drilled. Characterization is needed because a well will penetrate a number of rock formations with differing characteristics. Identifying the formation with the best properties for EGS activities is extremely important as stimulation is an expensive activity. In many EGS projects, a hot granite formation represents a high value target for faster investment returns. In volcanic systems, the size and orientation of the main inflow fractures needs to be known, along with the overall rock mechanical properties of the high temperature site.

Characterization information needs are, in arbitrary order:

- ❖ Formation intersection in the well
  - ➢ Acoustic instruments (high and low frequency)
  - ➢ Resistivity probes, including microelectrical formation imaging
  - ➢ Natural gamma ray detectors
- ❖ Measurement While Drilling (MWD) tools
  - ➢ Logging While Drilling (LWD) tools for pressure while drilling
- ❖ Formation ambient temperature
  - ➢ Temperature tools
- ❖ Type of rock: thermal conductivity, chemical and other geophysical properties
  - ➢ Temperature gradient tools
  - ➢ Fluid samplers
  - ➢ Rock density gauges: gamma and sonic

    - pH indicators
- Natural stress and the direction of the stress in the formation
    - Acoustic tools
- Orientation of natural fractures
    - Acoustic tools, including televiewers, seismic sensors on surface and vertical seismic profiling
    - Micro Electrical Imaging Tools
- Size of natural fractures along with material filling the fractures

There are a limited number of instruments in these categories that have been engineered for operation at 300°C. A televiewer with a stackable spectral gamma tool from ALT has been demonstrated at 300°C and Schlumberger can provide a 238°C tolerant vertical seismic profiling instrument. In addition, Sandia National Laboratories are developing a seismic tool lasting at 210°C with improved data transmission rates, using fiber optic wirelines exceeding 1 Mbit/s . These tools are useful in the analysis of induced fracturing and microseismicity studies. In addition, a dual laterolog resistivity tool has been designed for 300°C operation but not demonstrated yet.

During drilling, conventional techniques can be used if the wells are sufficiently cooled down, as currently required with available drilling instrumentation. However, when the wells recover to their natural states, it becomes of high importance to measure temperature, pressure and sometimes chemical conditions at the subsurface location of the main supercritical inflow zones. It is foreseen that future EGS formation tools (such as resistivity, natural gamma and televiewer) can be used within cooled zones on wireline connection to 300°C, but well recovery and monitoring will require instrumentation tolerance beyond the current 400°C limit (at present only possible in memory-tools, not accessed during measurements from surface).

Perma Works has suggested adding a heat shield to existing 300°C instruments to reach beyond 500°C tolerance. In order to access live readings at such very high temperatures, wireline temperature tolerance will need to improve beyond the existing 300°C tolerance.

Directional drilling and MWD or steering tools both serve the same purpose, but the MWD is much more convenient. A new area of interest is managed pressure drilling, where the measurement of interest is pressure at the bit. These Pressure While Drilling tools are important where underbalanced drilling is being used. Underbalanced drilling helps protecting the geothermal production zone and could also influence the conductivity of fractures by inducing additional secondary compressive stresses. Under-balance drilling is common in hydrothermal or EGS development and directional drilling could become more feasible to increase injectivity since the borehole orientation affects shear fracturing and dilation.

Inclination and azimuth are the critical measurements for directional drilling. The introduction of the Electronic Yaw Equipment (EYE by Scientific) and the introduction of the DynaDril by Smith International improved directional drilling dramatically. Offshore platform drilling was very difficult and time consuming to manage before the combination of the EYE tool and DynaDril.

A big first step would be a 300°C EYE tool (Sperry Sun Boss tool was also developed and used). The EYE tool only measured inclination (pendulum) and azimuth (magnetometers) and maintained the high side of the tool. This permitted real time steering of the downhole motor drilling assembly.

A number of innovations have been developed from that beginning. Automatic steering tools that either maintain verticality or proceed in a specified path are now available from more than one service company. But none of them are capable of temperatures above 175°C.

Imaging of the formation can identify natural fracturing, a means to measure natural formation stresses and some rock properties. Acoustic imaging tools exist for most geothermal applications.

Total count gamma detectors are temperature tolerant up to 225-300°C and can be used to locate formation boundaries. The range of measurement may be much lower than for oil and gas. However, spectral gamma provides a significantly improved sensitivity in formation identification. All known spectral gamma systems have been built in Dewars and some use carbon dioxide to cool down the detector crystals prior to deployment in the wells.

Neutron density tools are commonly used in oil and gas to measure rock density and porosity. Can a high temperature version (not heat shielded, but bare electronics) be developed? This question has relevance in that the Dewar flasked tools are mandrel type tools and generally give inferior measurements to the pad type tools, where the electronics and detectors are exposed to well bore conditions.

A fluid sampler has been developed to last at 300°C (Japanese NEDO project) and the New Zealand company Geokem can sample deep borehole fluids at high temperature. A fluid sampler for supercritical geothermal fluids has been proposed but not funded.

## 2. STIMULATION TOOLS

Stimulation of the well is most commonly done with hydraulic pressure to fracture the rock in the chosen formation. Shear dilation can also occur at lower pressures when the rock is under a shear stress, potentially permitting the rock to displace and develop permeability. Thermal shock treatments (cooling water and natural heating) can also induce fractures.

This operation requires well packers to localize the hydraulic pressure at the point the chosen formation intersects the well. As the rock is fractured, a number of secondary activities occur that require renewed fracture mapping.
Fracture recording or mapping is done by seismic sensors on the surface. These fractures are very small so very sensitive seismic sensors are needed. Seismic sensors inside the geothermal well would greatly benefit facture mapping, and would enable Vertical Seismic Profiling (VSP) in the individual wells and between wells (cross-borehole).

Along with the seismic fracture mapping, pressure inside the well is recorded. Monitoring wellbore pressures while pumping will provide valuable information on the tectonic stress regimes and fracture pressures. Along with pressure measured pressure peak, the fall off of pressure as fluid moves into the new fracture is recorded to provide data on the size and extent of the fracture network.

Stimulation information needs are:

- ❖ Packers or other concepts for formation zonal isolation
    - ➢ Removable or permanent isolation systems rated for geothermal temperatures
- ❖ Seismic sensors in the well to improve fracture mapping
    - ➢ Removable high-temperature seismic sensors
- ❖ Pressure sensors to record brake points and fluid loss

- Tilt meters to record dislocations in the well bore
- Flow measurements could better define fluid loss
  - Non-moving part flow sensor
- Fracture imaging to measure the new fractures intersecting the well
  - Acoustic imaging (televiewer)
  - Micro Electrical Formation Imaging
  - Multi-arm caliper
- Tracking fluid flow through formation fractures
  - Chemical Tracers and associated sensors
  - Other new technologies

Flow measurements in geothermal wells are currently made by mechanical spinners. These provide only a velocity measurement, not mass flow. Also, spinners are easily fouled. As such, spinners are currently not used in stimulation monitoring.
Reservoir flow models can be obtained with high temperature tolerant tracers, with organic naphthalene disulfonate tracers already demonstrated in a magmatic reservoir. Additional neutral density and chemically inert tracers need to be identified and applied to supercritical reservoirs.

A downhole fluorimeter is in development at the University of Utah (EGI) for tracer detection at high temperature (current design limitation is 150°C). If successful, such instruments could prove very valuable to monitor stimulation effects on individual fractures and should therefore be developed for even higher temperatures to accurately determine flow paths.

## 3. MAINTENANCE TOOLS

Maintenance of future EGS wells will require ‘smart’ well technology similar to those used in the oil industry. Also, EGS wells will require higher operating temperatures and controlling much larger flow rates. Downhole pumps will be required for certain EGS applications and development towards functionality of such pumps beyond 200°C is ongoing. For the high temperature systems, i.e. beyond 300°C, improved casing inspection instrumentation is needed, since recent experience proves that very high temperature wells (e.g. the IDDP-1 well with 405°C at wellhead) are subject to more critical damages, often linked to annulus water entrapments and rapid temperature effects.

Types of instruments that need to be developed for EGS and high temperature reservoirs include:

- Installed well sensors to track well changes
  - Temperature
  - Pressure
  - Flow
  - Distributed temperature profiles (fiber optic)
- Controls if well starts losing fluid
  - Downhole well valves
  - Motors or other mechanisms to operate the valves
- Sensors for tracking fluid flow in the formation away from the well
- Casing inspection tools
  - Casing thickness measurements
  - Casing caliper

- Downhole cameras
- Cement bond logging

Only sensor systems developed for operating without a heat-shield can be used for long-term well monitoring. Perma Works is currently working to develop temperature, pressure and flow systems for permanently monitoring geothermal wells. The commercial technology was established at the national laboratories, primarily Sandia National Laboratory.

As the conventional high temperature fields become older, the demand for casing monitoring surveys has risen. Casing thickness measurements have been achieved commercially using televiewer acoustics at temperatures up to 150 °C and in prototype testing to 200 °C. Casing metal mass can be qualitatively measured with magnetic tools and casing thickness inferred at temperatures up to 300 °C. . Improvement of the magnetic detection method is needed for quantitative thickness and corrosion measurements and a method to measure casing thickness acoustically at high temperature in any water phase needs to become available. The Kinley calipers (from Expro) currently have the best temperature performance (300°C) of commercial calipers but these are not rated in a geothermal environment long-term and the tolerance will need to go even higher. Similarly, downhole cameras for those conditions also need to be developed. Cement bond logging is normally performed below 300°C, but as the casings in new wells sometimes reach into 300°C reservoirs, such tools need to manage that temperature. Distributed temperature sensing (fiber optic Raman scattering) has been proven to be valuable in geothermal applications both in Iceland and New Zealand, rated up to 300°C, but the fiber can be blinded by hydrogen ingression and degrade due to e.g. temperature induced dopant migration and mechanical stresses.

## FURTHER UTILIZATION OF NEW HIGH TEMPERATURE INSTRUMENTATION

It has been estimated that a 5-10 fold increase can be realized from a single well if it would be drilled deeper into volcanic systems, with bottom depths close to large magma chambers. Recent experience in Iceland has also kindled ideas on exploiting smaller magma bodies, that have on two occasions been accidentally struck during both conventional drilling and while drilling one of the deep wells in the Iceland Deep Drilling Project (IDDP), a project designed to research these exploitation possibilities.

The smaller magma bodies could be located and mapped using seismic techniques (e.g. vertical seismic profiling) and relatively shallow wells could be designed to harness the heat from these bodies. The realization of such engineered wells will require improved steering of drillbits, using seismic instrumentation with fast communication to surface, as the oil and gas industry has recently been able to perform using wired drill pipes (drill strings with electrical communication to surface). Adaption of these techniques to high temperature drilling and volcanic formations would require collaboration with leading seismic-while-drilling developers and introduce novelties from companies such as Novatek (IntelliPipe), NOV-IntelliServ and Tempress. Existing electric field transmission rates (E-Field MWD) can also be improved through high temperature formations.

A review of the ANSI/NACE MR0175/ISO corrosion standard used by the fossil energy industry for use with hardware development in the geothermal industry has been conducted. The NACE standards do not address geothermal environments exceeding 230°C. However, the NACE standard addresses common problems with chloride (HCl) and sulfur ($H_2S$) for normal well bores in the oil and natural gas industry. As such, the NACE standard could be considered as a minimum standard for EGS projects.

Future supercritical geothermal wells and instrumentation will require the development of new standards for material corrosion. A reasonable case can be made for creating a geothermal-centric program for corrosion evaluation of materials used in all types of geothermal wells and instruments. This effort would support geothermal producers and tool manufacturers to choose the correct materials (saving cost) for the fluid type and temperature. Also, as new materials are introduced within the industry, a standard set of testing profiles would speed up the adaption of new materials into the industry. Already, several companies have acquired experience in material corrosion and scaling in the geothermal environment, which could contribute to such a program.

## POTENTIAL APPROACH TO TECHNOLOGY DEVELOPMENT

The major issue holding back private investment in technology needed for EGS is the lack of a market. EGS is in its infancy and the concept of supercritical resource exploitation is unproven. Fossil energy based solutions simply lack performance at geothermal temperature or simply don’t exist.

Two approaches towards further technology development in geothermal instrumentation can be envisaged.

a) One is to create a consortium of strong instrument developers, directed by a scientific vision and driven into a potential new market with possible rich returns. Geothermal stakeholders, operators and drilling companies preferably need to be involved. For technical transfer the consortium needs to include partners from different but required fields, e.g. space research, electronics industry and research institutions. This approach is risky in the sense that the geothermal market may not reach the required size to support such development expenses, but is an example of a large-scale effort if combined with real nationwide or global ambitions to harness geothermal power.

b) Another approach is crossing EGS technology needs over to those of other industries, looking beyond the fossil energy industry and towards e.g. automotive and aircraft industries (see discussion below). The fossil energy needs for higher temperature downhole tools are, however, still increasing as the oil and gas industry is drilling deeper into hotter formations to continue the search for and production of fossil fuels, but their upper temperature limits will always be lower than required for future geothermal utilization. This hydrocarbon exploitation limit is currently estimated at 220°C. However, heavy oil can be extracted using steam exceeding 300°C - Cyclic Steam Stimulation - but at those conditions the oil industry would only require currently available PTS tools (pressure/temperature/spinner).

Geothermal is a very small market, but it’s ready and able to accept new technology in high-temperature electronics and fiber optic systems. These same basic systems are also needed by the aircraft, power grid and automotive industries. However, the aircraft and automotive industries have very long lead times before they can accept new technology. Geothermal is technology development friendly.

In the aircraft industry, the lead time for new technology is 7 to 15 years. Years of testing are needed to qualify a new control system on commercial aircraft engines.

The automotive industry requires cost effective solutions. In short, they need high-temperature electronic parts to be cost competitive with low temperature electronics. This may never happen. Also automotive temperatures are low, 125-145°C compared to geothermal applications.

Our best matches for partnering industries are oil and gas ‘smart’ well and the power grid applications. The smart well industry is also a very small market with only moderate temperatures, <200°C. The power grid is a very large market, potentially larger than the automotive market.

One of the best matches for secondary applications for high-temperature electronics are found in the power grid. When we increase the operating temperature of electronics, we also increase the operating life. Grid applications require power electronics (‘power’ is another word for high-temperature) which operate with grid life times, ~30 years. The power companies hate repairing systems because of the cost of maintaining so many systems and customers demand continuous service. So, grid companies will pay more for longer operating life times and higher temperatures.

In general, two years in a 250°C well is equal to eight years at 175°C. Where else can a company find test data on electronic components with eight years of reliability testing? Geothermal should not underestimate this benefit. In the world of low temperature electronics, devices are redesigned every six years on average. In short, if you’re an engineer for the power grid or aircraft industry, you’re working with electronics which will be replaced before you can get them qualified.

The truth is, geothermal is a great venue for the development of new high-temperature electronics because we can offer very high-temperatures and the opportunity for very long life testing in a real world application.

In comparison, path b) presented above can be realized on the existing high temperature electronics market, creating synergies with geothermal. Path a) requires a global political level effort, shifting even oil & gas existing infrastructure and pushing that industry into geothermal utilization. Decision makers need to agree on what path geothermal development is on.

## APPENDIX

The following list contains contributors to this final version of the White Paper, which has been circulated within the IPGT community and outside it for almost a year. The contributors are in arbitrary order.

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