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HIGH TEMPERATURE GEOTHERMAL LOGGING FOR TEMPERATURE AND PRESSURE

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ABSTRACT

In Iceland, efforts to drill High Temperature and High Pressure wells have proved very successful in recent years. In 2001, only two HT wells were completed, whereas 27 wells were completed, in 2007 and a similar amount will be drilled in 2008. High accuracy and reliability of data from deep high temperature wells has been the main driving factor for Iceland GeoSurvey to implement the latest electronic instruments (Dewar flask tools), from Kuster Co., California, the so-called K10 (Strain tool). As a consequence the classical mechanical Amarada and Kuster tools were retired to back-up tools. Though the mechanical tool are sturdier tools the data quality and resolution is not up to date with respect to client requests. An introduction of new drilling technology, mainly for environmental reasons and in order to intersect fractures perpendicularly, meant a shift from drilling near vertical wells to deviating around 90% of the wells. As a direct result of this shift Iceland GeoSurvey is the logging contractor in the world logging most intensively in deviated wells. In logging, the first concern is to obtain data from the entire length of any given well i.e. getting successfully down the well and retrieving the tool. A few problems have occurred during the past four years: extremely corrosive geothermal fluid (Reykjanes area) causing brittle failure on the slick-line; highly inclined wells (~40-60° from vertical), means that the tool might stop on its way downhole; extensive wear on Dewar flask as the tool rubs against wall-rock constantly while logging, which calls for centralizers and further; lack of experienced personnel (Iceland GeoSurvey logging department has expanded its personnel over 3 years from 6 to 22 people); extreme high well head pressures (128 bar recorded), which can strain the well head to the breaking point, also extreme high downhole temperatures (385°C recorded) calls for vigilance, due to limited downhole lifetime of the electronics. Iceland GeoSurvey has solved many of afore mentioned problems with great success, bearing in mind that solutions need to be revised regularly, as new obstacles occur.

Though the K10 tools are generally more fragile than the older sturdier mechanical tools experience has shown that denser and more reliable data sets are obtained spending less time and money. High resolution and quality of datasets also give greater knowledge and improves interpretation and modelling. Planning, safety and good communicating between clients and contractor play very important roles in ensuring good quality of the end-product and all are parts of the success criteria.

1. INTRODUCTION

Robert Wilhelm Bunsen obtained the very first downhole temperature readings in Iceland, during a two week field trip in 1847. He and his college Albert Des Cloizeaux took several readings, between eruptions, down the vent of the famous Geysir in South Iceland (Figure 1). The readings were taken from a depth of 19,5m and up to the surface. The maximum temperature was 127, 5°C. In 1869, William Thomson (later Lord Kelvin) obtained temperature readings in a 117 m deep well by using a thermocouple. In following years, several scientists carried out further measurements and geothermal logging was born! In Iceland, geothermal drilling was initialized in 1928 and in the beginning only artesian wells (self flowing) were exploited. In 1964 much higher production rates were achieved by the installation of the first deep well pumps. Substantial downhole logging was carried out from the early stages of geothermal exploitation in Iceland.

FIGURE 1: Geysir Steam eruption from Geysir in Haukadal, Iceland. The picture was taken by Guðmundur Pálmason in 1982. The eruptions last for 5-10 min. and the steam column height has been estimated to be in the order of 30 – 60 meters for at least a couple of centuries (Pálmason, G. 2005).

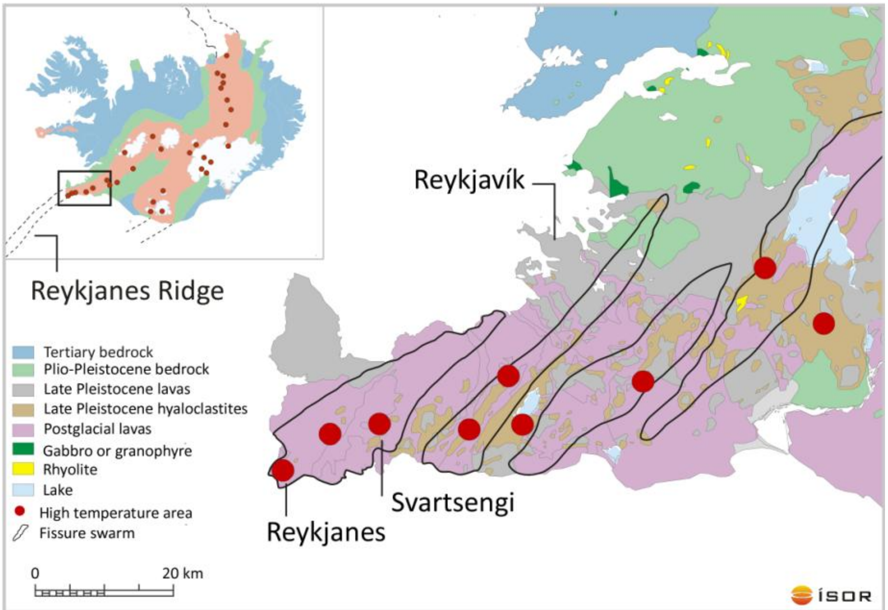

FIGURE 2: A map of Iceland is situated in the top left corner showing the high temperature areas that aligns with the active volcanic zone. The Reykjanes geothermal field is located on the tip of the Reykjanes peninsula in southwest Iceland. Here several geothermal fields are aligned en-echelon due to fracturing out onto the Mid-Ocean Ridge.

The first "high temperature" geothermal logging was carried out in 1959, on the outskirts of Reykjavik, to a depth of 408 m (Figure 2). That year more than 7 km of high temperature wells were logged. In comparison, 330 times more has been logged in high temperature wells, in 2008 alone (ultimo October), or a total of 2.316 km (Figure 3). It should be noted that direct use of geothermal resources was one of the major factors in Iceland's transition from a third world country into a thriving developed country in the 20th century.

The accuracy, simplicity and cost of downhole PT (Pressure and Temperature) measurements have changed considerably in the past 40 to 50 years. Until the 1960´s, temperatures were usually obtained by maximum readings on thermometers or clock driven (Amarada or Kuster) recorders, which were also used to obtain pressure readings. The accuracy and resolution, in terms of depth vs. readings, were limited. In addition, their use in un-equilibrated wells soon after drilling stop further degraded their scientific value (Blackwell and Spafford, 1987).

The development of electric-line tools, with an electrical connection to the surface, provided much better accuracy and precision of both temperature and depth. With these tools, it was now possible to make essentially continuous temperature versus depth logs within a relatively short time frame and at affordable costs, with a precision of ±0,001°C (Roy et al., 1968; Sass et al., 1968; Blackwell and Spafford, 1987). The main limiting factors became the cable temperature limit of ≈150-250°C and to some degree the cost of cables (>1km length).

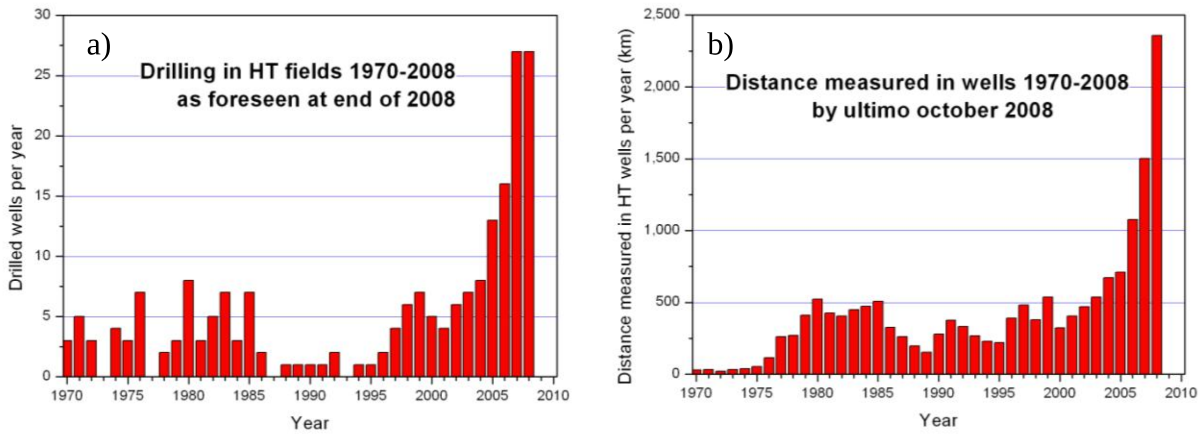

FIGURE 3: a) Shows the number of drilled wells per year, from 1970 to 2008.
b) Shows the distance measured in wells under both low- and high-temperature conditions, for the same period. All data is from the Iceland GeoSurvey database.

Memory tools were developed in the late 1980's. These tools are self-contained, battery powered, computer and sensor packages that are lowered into a well on a solid wire (slick-line). The sensor and computer can be housed in a Dewar flask assembly (double-walled vacuum flask; invented by Sir James Dewar in 1892), adjusted to HT (High Temperature) environments. This allows operation at temperatures in the order of 400°C for up to half a day. Further advantages are that the cost of the slick-line is a fraction of the cost of the electric-line previously used, and it can be packed off more efficiently, using a stuffing box (the slick-line is threaded through a narrow hole just wide enough for the slick-line itself and through a section a bit wider, stuffed with HT Teflon sealing, at the top end of the lubricator) on the well head for pressure build-up tests.

Efforts to drill deviated High Temperature and High Pressure (HP) wells have been proven very successful in recent years, in Iceland. The almost exponential increase in wells drilled per year since 2001, mirrors the increased demand for HT measurements. In year 2001, only two HT wells were completed, whereas 27 wells were completed, in 2007. High accuracy and reliability of data from deep high temperature wells have been the main driving factor for Iceland GeoSurvey to implement the latest electronic instruments in HT logging. Iceland GeoSurvey made an early start in 2004; four years after the launch of the first line of electronic HT pressure and temperature instruments, from Kuster Co., California, the so-called K10 (Strain tool).

Besides the scientific reason for getting improved quality and much denser datasets, a number of relatively new problems arose with HT logging from being implemented in only near vertical wells, to circumstances where around 90% of the wells were deviated. The shift is directly related to new drilling techniques brought to Iceland, mainly due to environmental reason and the realisation that with directional drilling one can reach geothermal zones of interest and targeted fractures, hitherto out of reach. Since the main source of geothermal fluid flow, in Icelandic rocks, originates in fractures, targeting of these are very important. In several of the geothermal fields, fractures are near vertical and it has proven easier to intersect the fractures with deviated drilling. This addition in new technology has place Iceland as the top country in number of deviated wells drilled per year, and therefore Iceland GeoSurvey is the logging contractor who is logging most intensively in deviated wells worldwide.

2. HT INSTRUMENTS

2.1 Mechanical TP tools

Mechanical Amarada and Kuster T and P tools are a well-established part of geothermal logging. The tools were developed early in the last century. They have been in use since the late fifties, in Iceland, and have proven their value. They are still in use today, though moreover for application in extremely demanding situations or simply as back up for more advanced tools.

Mechanical tools are well known within the geothermal community and therefore they are only briefly mentioned here. Mechanical tools are one-sensor tools that measure either temperature or pressure. The tools work by a simple array of components, i.e. in order to measure, one need to "load" the tools and set the clock. In short, the steps are: change O-ring, insertion of carbon chart in to the sledge, making a baseline, wind and attach clock (which pushes the sledge down), and enable a needle (scratching the carbon chart with increased T or P). Logging is done by stopping at intervals of 50-100 m, the T sensor is rather slow in response time and one can expect the reading to be of a duration of 10-15 min. where drastic T changes takes place and never to be less than 5 min. The P sensor is somewhat faster and usually 3-5 min. will allow for a reading. This procedure is clearly rather time-consuming and the resolution of data points is relatively poor. The resolution does not improve when measuring with time, as for pump tests, and valuable data can be lost.

2.2 Electronic TP tools

Electronic TP Kuster memory tools entered geothermal logging, in Iceland just four years ago. Since then they have almost completely taken over from the mechanical tools, in Iceland. Today a wide range of electronic Dewar flask tools is available but in this article focus is on the experience that Iceland GeoSurvey has had with the Kuster Co. tools.

2.3 The Kuster K10 tool

The electronic Kuster tool (hereafter referred to as K10) measures T and P simultaneously. This gives the benefit that no station to station stops are needed while logging and sample rates can be as dense as 1 reading/sec. For the tool to operate one need to program it from a computer, change the O-rings and C-rings and connect a battery that will immediately indicate the status on both the programming of the tool and the lifetime of the battery itself. Due to the Dewar flask the tools can withstand temperatures of 250°C for about 9 hours and up to a maximum of 400°C for two hours (pers. com. John Jacobson, general manager of Kuster Co.).

One of the most recent additions to the Kuster Co. electronic products, the K10 Quartz XT (designed on request for Iceland GeoSurvey) arrived ultimo October, 2008, in Iceland. Since the quartz sensor response time is much faster and more accurate than the strain sensor, the K10 Quartz tool is bringing data collection and quality to the next level, especially when it comes to injection tests while drilling.

2.4 Wear on the logging tools

Logging in HT wells is very demanding on the logging tools. The tools will, of course, have to endure very high temperatures and pressures for extensive periods of time. Furthermore there is a significant mechanical wear from running the tools down and up wells, even if they are supplied with liner and more so when logging takes place in a barefooted hole. Since the beginning of deviated drilling, in Iceland, extensive wear on the housing has been an issue of concern and the necessity to fit centralisers, springs and wheels on the tools, have become apparent.

3. MECHANICAL VS. ELECTRONIC INSTRUMENTS

3.1 Logging hardware

Most operators in HT logging have firsthand experience with clock driven (Amarada or Kuster) recorders, since they have been around for well over half a century and they come relatively cheap. These tools are very sturdy and reliable, fairly easy to use (Table 1) and in fact most geothermal logging service groups are able to calibrate and repair almost any part of the tool. When preparing mechanical tools for logging several procedures have to be kept in mind, and they are simple per se, there are no indicators telling you if you have forgotten an important step.

TABLE 1: Schematic comparison of the most apparent differences between the mechanical Amarada and Kuster tools and the electronic Kuster Co. K10 tools. Red indicates superior tool qualities.

K10	Properties	Mechanical
Small (especially in deviated well)	**Robustness**	Very good
To short experience to tell	**Lifespan**	Very long
Essential	**Computer**	Not essential
Very good (1/2m. Interval at 30m/min.) (1sec. In pump-tests)	**Data resolution**	Poor (normally measurements are taken every 100m)
Easy -> guided through ->> less likely to fail	**Tool preparation**	Easy -> NOT guided through ->> more likely to fail
Easy and fast	**Data handling**	Easy but time consuming
2km well: ~9 quarter 3km well: ~14 quarter	**Measuring time down and up**	2km well: ~12+6 quarter 3km well: ~18+9 quarter
2 (both T and P)	**Number of sensors**	1 (either T or P)
~3 weeks (at 5sec. sampling interval)	**Longest measuring time**	48 hours (120 hours clocks available)
~$250	**Cost per run**	~$20
30	**Maximum speed (m/min.)**	~100
0-400	**T range (°C)**	0-470
$25.000	**Price; one tool all incl.**	$7-8.000
6,2 runs (-> 12.400m)	**Turn a profit (based on a 2km well)**	3,8 runs (-> 7.600m) 3,8 runs (-> 7.600m)

Electronic memory tools are not yet widespread, since they only appeared on the marked a few decades ago and are approximately 4 times more expensive, than the mechanical tools, or $25.000 a piece vs. $7-8.000 (Table 1). One should, though, bear in mind that the K10 logs T and P simultaneously while mechanical tool log either T or P and one would need two mechanical tools to log both parameters; one could thus argue that the electronic tools are only twice the cost. The K10 (and other Dewar flask tools) are, however, much more fragile and should be handled with care. Normally logs with mechanical tools would be done at around 100 m/min. down and up while the K10 runs no faster than 30 m/min., especially in deviated wells. A run in a 2000 m well would take the K10 around 2 hours down and up, while it would take the mechanical T tool around 3 hours and the P tool around 2 hours (Table 1). Although logging speed has decreased with the introduction of electronic tools, much time is none the less saved, meaning that it is feasible to log two wells a day instead of one, thus limiting the cost for both manpower and equipment, cutting the budget and increasing the profit. The K10 is equipped with four memory chips and need to be programmed before running in a well (Kuster Co, 2008). This of course means that more advanced equipment is needed than for the mechanical tools. Programming a K10 and consequently affirming that everything is ready for logging is pretty straightforward and it is easily noticed if the tool is not ready for logging.

After logging many sensitive components, although in working order, are all routinely replaced to ensure optimum performance on subsequent logging jobs, high temperatures are particularly wearing on seals, like O- and C-rings.

A readily accessible calibration bath and dead weight tester is situated in the basement facilities at Iceland GeoSurvey. With regards to the HT equipment it is mainly used for regular calibration controls on the K10 tools, being that all tools are calibrated for both P and T at the Kuster Co. facilities and thus arrive fully operable upon purchase.

3.2 Continuous improvement of tools

The on hand experience, at Iceland GeoSurvey, with K10 tools might shed some light on their strengths and weaknesses, for others to benefits from. The major issue from the early beginning has been software bugs. Bug feedback is very important and Kuster Co. has been readily responding to comments. Computer software can be a real pain and time consuming if it does not work properly but Iceland GeoSurvey have never lost a single data string from a tool retrieved from a well. The cost of running a log with the electronic tools is quite steep, since three seals (O- and C-rings at approx. $200) need to be changed for each run, special HT tape is needed to seal off wiring inside the instrument, and the battery keeping the tool powered up amounts to $250 alone. Iceland GeoSurvey has experienced that the logging speed recommended (50 m/min.) by Kuster Co., apply only to vertical wells, and have adjusted this to a maximum of 30 m/min. for extensive logging in deviated wells. The results of too high logging speeds, down and up hole, have lead to the tools being bent internally (Figure 4) and thus needing repair but still data has been retrievable on site.

There is always room for improvement and this is why Iceland GeoSurvey tries to keep an open honest dialogue with Kuster Co. so as to promote on-edge development and enhanced durability, reliability and user friendliness of the TP tools and related products. We aim to give candid feedback and in return get good service and assistance, and hopefully help to evolve specialized quality TP products for the benefit of logging.

FIGURE 4: On the figure a dent on the capillary tube can be seen. This part of the tool is shielded from heat, pressure and geothermal fluid when logging is ongoing. The damage occurred due to too high speed. Though the tool did not stop abruptly on an obstruction in this case, speeds above ~35m/min. are enough, in deviated well, to do this kind of damage.

3.3 Data quality

When comparing logs from mechanical and electronic tools in the same well, it is clear that the higher resolution, improved quality and precise data from the electronic tools gives information (Figure 5) previously not registered by the mechanical tools.

In well SV-09 in the Svartsengi field (Figure 5a) the superior resolution of the electronic K10 tool clearly shows the pulses down the well, in the pressure measurement. Pulses are very clearly seen down to about 400m depth but can in fact be followed all the way to the bottom of the well. This may come as no surprise since the pulses are readily observed from the free flowing well itself but no indication of pulsating in the well are seen on measurements carried out with mechanical tools. On Figure 5b, four temperature measurements are shown, obtained from a shut-in well in the Hellisheiði geothermal field (well HE-08). The two latest measurements are carried out with the electronic K10 tool and at least four aquifers are clearly seen on the graph. These were not evident from the measurements carried out with mechanical tools.

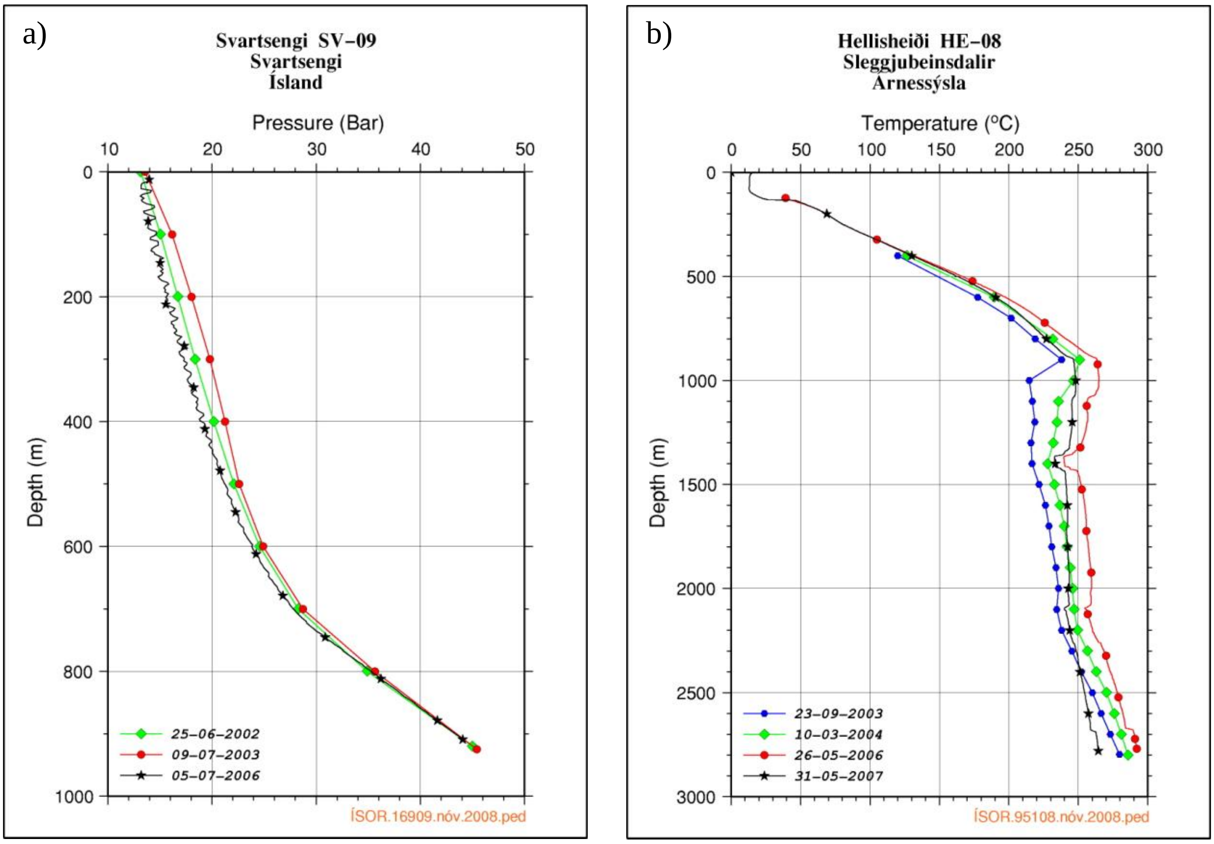

FIGURE 5: a) Three pressure measurements from a flowing well (SV-09) in the Svartsengi geothermal field (Figure 2). The latest measurements (black stars) are carried out with an electronic K10 tool and the two older measurements are done with mechanical tools. The well was clearly pulsating while all three measurements were done but only the K10 tool shows the pulsating in the well itself. b) Four temperature measurements, from a shut in well (HE-08) in the Hellisheiði geothermal field, are shown. The two latest measurements (black stars and red rings) are done with the electronic K10 tool, while the two older measurements are done with mechanical tools. Several aquifers can be seen on the graphs from the K10 measurements that do not show up on the other measurements. Counting up the aquifers, they are clearly situated at ~1100, ~1350, ~2100 and 2650m depths. This data is published with permission of the Hitaveita Suðurnesja (SV-09) and Reykjavik Energy Company (HE-08).

4. HT LOGGING SERVICES

Monitoring temperature and pressure conditions of HT wells is an integrated part of the logging services that Iceland GeoSurvey performs. For a large part logging services are fairly standardised, though clients might have slightly different approaches (Gudmundsson, Á. 2005). Essentially all wells go through the same steps before being connected to the power plant or on standby. Firstly, warm-up measurements are taken after drilling, often within short time intervals. This is done to evaluate when the pressure conditions have reached equilibrium (pivot point) and also to estimate rock formation temperature.

During discharge tests, a multi flow rate step-testing of the well is carried out, in order to evaluate production outcome, sometimes with a steam separator connected. Following this the well will either be connected to the power plant after a relatively short period of time. In the case of a standby or monitoring well, measurements will be carried out on a regular basis. Long-term monitoring will give information on pressure drawdown in the geothermal field, due to production, and cooling, if for instance too much fluid is re-injected into the field.

4.1 Slick-line units

At the moment Iceland GeoSurvey has three slick-line trucks in operation (Figure 6). The “fleet” of HT logging trucks are:

- A roughly 10 years old small both slick-(0,052”) and e-(3/16”) line truck (Ford Econoline), with a capacity of approximately 5000 m slick-line,
- A 2 year old small slick-line truck (Mantra; Mercedes), with a capacity of approximately 6100 m slick-line and
- A brand-new big slick-line truck (Scania), with two winches, was added to the fleet this autumn Each winch has a capacity of approximately 7600 m slick-line.

The logging equipment of the Ford truck is almost 100% homemade. The Mantra is equipped with a removable slick-line unit from DynaWinch Industries Ltd. in Calgary, Canada while the cabin interior is designed and made in Iceland. Both slick-line unit and cabin on the Scania are made by DynaWinch but designed after Iceland GeoSurvey specifications.

Figure 6: The “fleet” of three slick-line logging trucks, in action, that Iceland GeoSurvey currently operate. a) The 1997 Ford Econoline, double winch slick-line and e-line truck, b) the 2006 Mantra slick-line truck and c) the 2008 Scania double winch slick-line truck.

4.2 Slick-line wire

The year 2004 was a turning point in many aspects for Iceland GeoSurvey. This was the year where the K10 was introduced and also the year where a new field (Reykjanes) was added to the Iceland GeoSurvey logging programme. The latter turned out be somewhat of a headache because of slick-line failure. Until then loggers had used only regular black steel wire for logging. It became clear, after a few “lost in hole”, that the problem was connected to the fluid chemistry of the Reykjanes geothermal field. The field is situated on the tip of the Reykjanes peninsula in southwest Iceland (Figure 2), an hour’s drive from Reykjavik. In contrary to most other geothermal fields in Iceland, its geothermal fluid is hydrothermally altered seawater (with seawater salinity). The brine is very corrosive and gives rise to brittle fracturing in regular steel wire in the wells and SS-316 wire fractures when it has cooled down, even after being in only 200°C (though specifications stipulates this should not happen below 300°C). Trying out a special Sandvik alloy (Sanicro 36Mo) did not solve this problem. The only known solution so far is to use the wire only once and then dispose it. This is of course rather expensive for the client and extra work for the loggers.

At the moment Iceland GeoSurvey is trying, together with the company Elgiloy, Speciality Metals in Illinois, to find a better alternative. We are now looking into several alloys; C-276, MP-35n and a special Elgiloy alloy; one of these hopefully meets the critical limits for brittle fracturing and corrosion resistance, for the fluid chemistry of this particularly field. After preliminary discussions with Elgiloy, it can be stated that C-276 seems to apply better to the very aggressive fluids at the Reykjanes peninsula. Additionally the C-276 is sold at a much more favourable price.

4.3 Safety

Besides taking care of the tools and making the right choices of wire-line, ample training of employees and safety is very important and awareness has increased during recent years. Confidence and safety of employees, saves not only time and money, for both clients and contractor but more importantly it secures that people return safely to their home and families, after long days in the field.

Safety as a stand-alone factor is a success criteria and has to be recognised as such. Furthermore planning ahead is part of the success criteria and must not be underestimated. This means keeping close contact with clients, both verbally and through internet based project interfaces, enhancing information about well head conditions, weather conditions and whether wells are free flowing (gas/ice/visibility). The elements of the success criteria also apply to HPHT (High Temperature and High Pressure) jobs performed in other parts of the world; here especially early consultation with the operator is essential. All aspects must be addressed i.e. requirements, solutions, capabilities and limitations of the tools.

4.4 Contingency plans

Contingency plans in case of tool malfunction, “lost-in-hole” (i.e. tool lost in well due to slick-line failure) in well or other obstacles interfering with logging must be documented. Due to the relatively short lifetime of the electronic parts of the K10 tools in HT wells, it is usually not feasible to fish and retrieve tools. Furthermore fishing in pressurised well is almost impossible. The main issue is to ensure the well is left as tidy as possible. When possible attempts are made to shoot the tools out but our experience has shown that it is more difficult to succeed when the tools are lost in deviated wells.

5. CONCLUSIONS

A comparison between mechanical and electronic tools, clearly show an improved data quality and more reliable data, together with reduced time on site this will lower costs significantly for the client and the contractor, thus advocating the electronic tools. Interpretation is less time consuming due to more readily accessible and precise data. Higher resolution and quality of the obtained data, in turn, improve on the quality of data interpretation, leading to better understanding of the geothermal field. The greater fragility of the electronic tools does not seem to be of great importance, however it is necessary to adapt to the new conditions and handle the tools carefully.

Pushing the tool limits in the field and communicating the operation experience to the supplier, as for instance Kuster Co., Elgiloy or similar companies is a very important role for the logging service companies to undertake, in order to improve the reliability, user friendliness and endurance of the end-product, i.e. logging tool components, their related software and wire line material, as all of these are critical parts in what is necessary for a successful logging of a well.

Planning operation ahead and safety measures are both very important factors in a successful outcome of any logging trip. Any project interface or verbal contact enhancing information flow between clients and contractor is a part of the success criteria.

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