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Improving the Performance of Geothermal Pressure, Temperature and Spinner (PTS) Tools used in Down-Hole Measurements

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ABSTRACT

Pressure, Temperature and Spinner (PTS) probes/tools are commonly used in the characterization of geothermal wells during drilling, completion testing, and monitoring throughout the life of the well. These well tests include static formation temperature testing, water loss surveys, injection fall-off tests, drawdown build-up tests, warm-up surveys, flowing surveys, and other tests. The challenge when using these tools is to ensure that the electronic components of the different sensors, signal processing, and memory are not affected by the heat generated from the tool's internal energy use, internal supply (battery), and from the high temperatures inside the well. This buildup of heat limits the working time available for the tool down the geothermal well and can affect/limit the acquisition and quality of the data.

A survey was conducted on the current state of electronics and electronic packaging for the use in geothermal, and oil and gas probes/tools. Techniques for high temperature performance were reviewed including the use of Dewar flasks for the thermal insulation of electronic components of the PTS tool and the use of electronics for operation at higher temperatures. An in-depth analysis of the performance of the widely used commercial PTS tool developed by MB Century Ltd. was completed using SolidWorks™ thermal simulation software. The model was optimized and compared to PTS probe test data taken from five different test cases. The calibrated model was used to evaluate several different heat sink materials, with results showing that the current tool design cannot be easily optimized further. However, predictions based on the calibrated model showed an alternative operating procedure that can provide an increase in the operating down-hole time of the tool.

1. Introduction

PTS probes are used to help characterize the performance of geothermal, oil, and gas wells. The probe is lowered in the well and Temperature Pressure and Flow Rate (determined with the spinner) are measured at different depths as the probe is moved up and down the well. The information is used to help determine depth of inflow or outflow, and contributes to the determination of the overall mass flow rate and energy from the well. This information helps determine the actual thermal power available from the well at the present time and can help reservoir engineers learn more about how the well will perform in the future. Ultimately the results of testing with PTS probes help determine the overall economic benefit of the well itself and its response to changes. The data obtained is considerably more useful if obtained over long periods of time, and therefore for a PTS probe it is always desirable to be able to remain inside the hole/well as long as possible. This can be a problem in geothermal wells due to the high temperatures at depth. However, such high temperatures are more beneficial due to the increase in power output, and therefore the incentive in the industry is to utilize ever hotter wells. Many reservoirs are being analyzed to determine the economic gain of increasing well depths and aiming for temperatures at or above 300 ºC, or even 350 ºC. For these reasons there is a strong need for development of probes that can continue to operate for long periods of time in high temperature environments.

2. Temperature limit: the electronics

Most PTS probes include a data acquisition circuit that obtains information from the different pressure, temperature, and spinner sensors. The acquisition circuit either stores that information in memory or transmits that information to the surface through a wireline. While the sensors themselves may be robust and able to survive in high temperatures, the acquisition circuitry itself is usually based on more commonly available Standard-Electronics, due to the large variety and availability of circuit components in that family, allowing the designer many options and methods to develop the circuit. High-Temperature (HT) electronics is a growing family of devices based on Silicon-on-Insulator substrates (Honeywell). These devices can perform at higher temperatures, but to gain the benefit of the greater temperature performance from these devices, the entire support structure of the electronics must also be able to perform at higher temperature. Many necessary items such as mounting substrates, solder, discrete components (e.g. resistors capacitors and inductors), and interconnect components, must also be upgraded to the performance level of HT devices. The need for all components to be up to the same high temperature capability, limits the designer to a much smaller set of components and a limited number of suppliers. Table 1 below gives a comparison of high temperature thermal performance of the two families.

Table 1. Comparison of temperature performance of the two electronics families

	Max. die Temp.	Max. op. Temp.	Main market	Suppliers
Standard Electronics	125 °C	90 °C	Numerous	Numerous
HT Electronics	250 °C	210-240 °C	Oil/Gas, Avionics	Honeywell, Ti, Analog Devices

Definitions:
Max die Temp.: Maximum temperature for connection point of IC (the die) to the substrate. If the device is subjected to temperatures above this, the die may separate from the substrate causing failure.
Max op. Temp.: Maximum Operational temperature. The maximum temperature where output from the device will remain within specification. If the device is operated over this temperature, information may be inaccurate, (Honeywell; Texas Instruments; Watson and Castro, 2012).

While standard electronics are used everywhere and in very high volumes, high temperature electronics are limited to a very small market space. The application in the Oil/Gas industry is indeed for down-hole probes, but the bulk of their need is under 300 ºC. One growing market is avionics, where sensors are placed in hot environments and close-by to the sensor devices such as A to D converters or OpAmps are used to tailor the signal. The main data acquisition circuit often can be located a short distance away from the actual heated area in a much cooler environment, thus the current avionics marketplace may not necessarily fuel a need for increased temperature performance for the whole range of devices such as in the standard electronics marketplace. Processors and memory components that can perform at extreme temperatures may not see much use in avionics until their price and availability is more favorable. Development of the HT family of devices is proceeding, but very slowly. Most of the discrete components of the standard electronics family have not been qualified to 250 ºC or above (Sandia, 1998), however some of these support components are becoming available. High temperature substrate fabrication is available from Quartzdyne and Honeywell (Quartzdyne, 2014 and Honeywell), and HT discrete devices are found from Presidio Components (Presidio Components). A full PTS probe based on HT devices from Texas Instruments has been made available from Permaworks, with funding from the U.S. Department of Energy. Their product has been used for continuous operation at temperatures of 250 ºC (Vandermeer, 2013).

3. Protection beyond 250 ºC: Dewar flasks

For repeated use above 250 ºC, devices from the HT family will be at their temperature limit and also must be protected. Dewar flasks are incorporated to isolate the sensitive electronics from the hot external environment. There is a design tradeoff associated with the use of such a flask that drives the overall physical size and shape of the completed device. For best heat performance, a flask should be small in diameter, as this decreases the outside surface area subjected to the hot environment. Any electronic circuit design inside must therefore be developed long and thin to fit inside a small diameter tube. With high quality Dewar flasks, temperature encroachment across the main cylinder area can be very low. Temperature encroachment occurs at the ends of the cylinder, and the tube should be longer in length than the circuit itself, to keep the warming ends of the tube away from the sensitive electronics inside. Therefore the tube may be long and thin, and design becomes a balance between best-practice thermal design and maintaining sufficient pressure performance. Flasks themselves can fail due to pressure. Rough handling or denting of the flask is a major cause for concern. The largest user of probes is the oil and gas industry, which does not normally experience down-hole temperatures as hot as those encountered in geothermal wells. Though flasks are designed to handle the pressure at depth, the industry is still learning about methods of failure. In operation, a flask on a probe must be kept safe from harm as much as possible. Dents, cuts, or bumps to the flask may contribute to flask failure, and therefore such devices are handled with extreme care. Nevertheless the thermal isolation possible with a flask is a very useful feature, and helps allow for an improvement in working time.

4. Evaluation of the MBCentury PTS probe.

A detailed study of a specific PTS probe design was undertaken with support from MB Century New Zealand, Ltd (Willson and Gould, 1989). Mechanical drawings and design information as well as results of five separate tool test cases were obtained, and the probe was modeled with a 3D modeling software. A thermal simulation model was created and applied to the 3D model, and results compared to the supplied test data. The five sets of data are from probes of the same mechanical design but different serial numbers. Parameters in the thermal model were adjusted to simulate the supplied field performance data and a best-fit match is presented below. Figure 1 below shows the mechanical design of the 3D model.

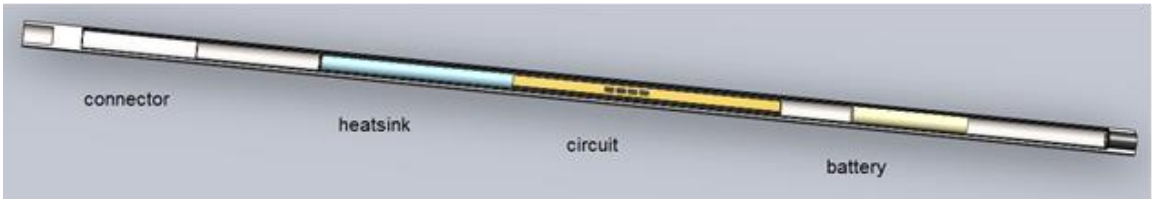

Figure 1: 3D Model of MB Century Probe showing the main components, the heat is generated in the middle (circuit).

Material properties for the various components in the model are chosen based on specifications on the design drawings. The thermal model includes air for the open spaces between items, with a suitable choice of thermal conductivity, specific heat, and density for the vacuum that is present between the walls of the Dewar flask. The model performs thermal heat transfer calculations based on thermal conduction from one material to another, with the performance of air and vacuum modeled accordingly.

Heat flow in a cylindrical coordinate system is governed by the heat equation below:

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial z^2}\right) + \frac{q'}{\rho C_p} \quad (1)$$

where:

T	Temperature (ºC)
t	time (sec)
r	radius (m)
θ	angle in cylindrical coordinate system (degrees)
z	flask length (m)
q	heat generation rate (W/m^3)
$\propto$	thermal diffusivity (K/ρ Cp)
K	thermal conductivity (W/m.K)
ρ	density (kg/m^3)
Cp	specific heat (J/kg.K)

Since the internal components such as the circuit and substrate do not conform to a simple radial coordinate solution, the model performs a finite element analysis using a finite grid system. The grid is variable in size, allowing detailed analysis of small distances such as the vacuum in the Dewar flask, while allowing larger grid blocks for larger same-material volumes such as the cylindrical portion of the heat sink. A portion of the grid is shown in Figure 2 below.

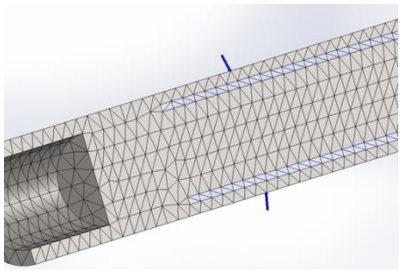

Figure 2: Finite element grid detail of the model

Details of the thermal performance of the actual substrate between the circuit and the connection point to the heat sink are not known. Different materials for the substrate were tested in the model to allow the model to best-match probe test data. Iterations of thermal conductivity and specific heat for the vacuum in the Dewar flask and the surrounding air inside the flask were performed, to create a suitable model. These values could vary from one probe to another. Figure 3 shows the thermal models prediction of temperature encroachment through the flask due to external heat. Heat encroachment from the ends can be seen as well as a lesser amount across the vacuum of the flask itself.

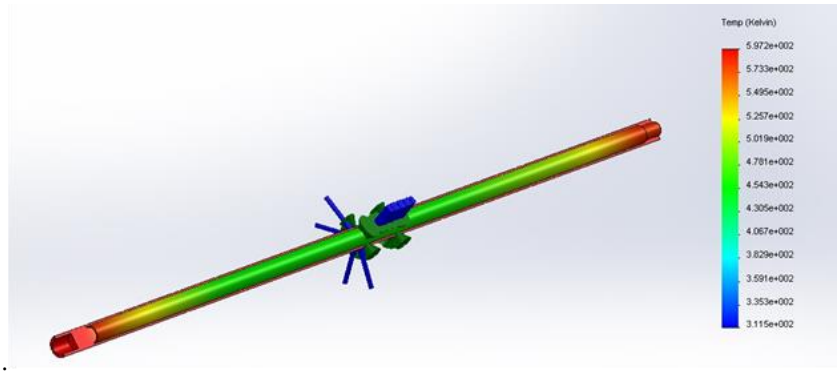

Figure 3: Heat encroachment from the ends of the flask toward the center.

Tool test data taken from five different cases was provided by MB Century and is summarized in the Table 2 below. The test data includes detailed readings taken at multiple times per second. The test data sets include time taken for insertion and extraction. The exposure time in each test is also summarized in the table where the probe was kept at a constant pressure and temperature.

Table 2. PTS tool test data used in the model calibration.

Test	Initial temp. (°C)	Insertion time (minutes)	Dwell press. (bar abs.)	Dwell Time (minutes)	Ext. Temp. (°C)	Extraction time (minutes)	Total Time (minutes)
92--37	37	Start at temp.	40	41	92	finish at temp.	41
184--23	23	11.3	11	49.7	184	finish at temp.	61
205--51	51	4.5	55	84	204	88.5	89
248--39	39	Start at temp.	59	63.8	248	finish at temp.	63.8
324--21	21	19	129.8	150	324	169	185.3

A final model was created and compared to the field data after adjusting the model for thermal lag, and taking into account the difference between wireline operation and memory mode operation. The results of the models thermal performance is plotted against the actual probe test data as shown in Figure 4.

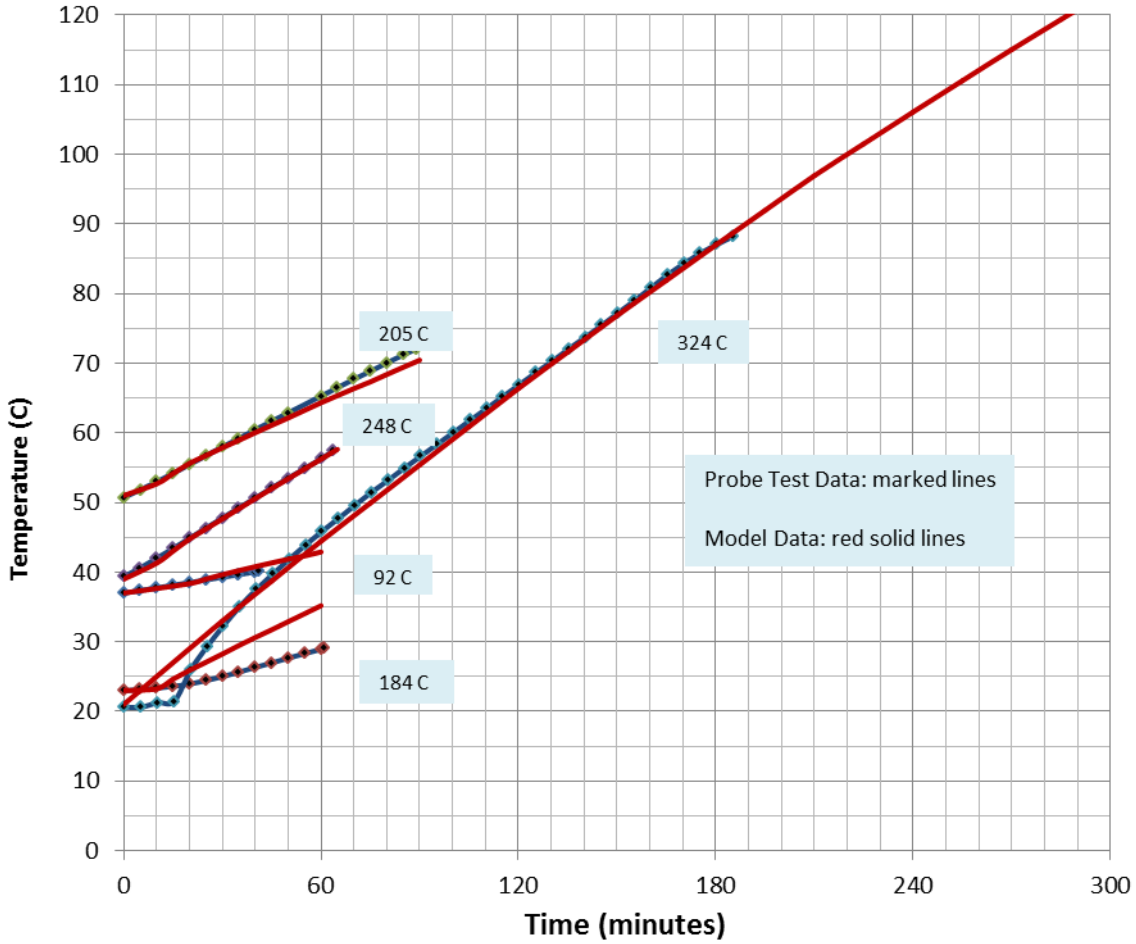

Figure 4: Comparison of final model to field data

The model appears to be a close match to the test data at 248°C. The model shows slightly lower temperature rise per exposure time compared to the test data at 205°C and a slightly higher temperature rise per exposure time compared to the test data at 92°C and 324°C. The model gave a poor match the test data at 184°C. The differences in performance of the model depend on small changes in the values of thermal conductivity and specific heat of the vacuum and substrate material. With adjustments to these parameters in separate models, a close match could be obtained for each set of field data independently. But a generic thermal model was maintained which is not specific to one probe that would provide more useful predictions of performance for the entire probe family.

The increase of internal temperature with time (the slope of the plotted lines) shows the expected increase accordingly. Since the probe circuits can be damaged at 125°C, and may supply incorrect readings at 90°C and above, it is prudent to be certain they can be removed from the hot environment before damage or inaccurate results occur. For this reason the test plan for the probe is to

begin the extraction process when the probes internal temperature approaches 80°C. This is seen in the test data from the highest temperature test, at 324°C, though the thermal model was allowed to continue until higher internal temperature were reached. With the model defined as shown above, evaluations of various materials for the heat sink were undertaken to discover possible changes that can increase down-hole working time. The model was run with an external temperature of 324°C, as is seen in the test data at 324°C. This data set is most useful as it includes information from a longer period of time as well as from the hottest environment. Different heat sink materials were evaluated in the model, and performance projected over five hours. The probe currently uses stainless steel as heat sink material, and after analysis this proves to be a very good balance between the three factors that affect thermal performance: thermal conductivity, specific heat, and density. Table 3 below gives a comparison of thermal properties of the materials evaluated in the model.

Table 3: Thermal properties of the materials evaluated in the model

Material	**Thermal Conductivity (K)**	**Specific heat (Cp)**	**Density**	**Cp × Density**
	W/(m.K)	**J/(kg.K)**	**kg/m³**	**J/(m³.K)**
316 Stainless Steel Rod	16.3	500	8000	4000000
Aluminum Oxide	18	880	3690	3247200
Boron Nitride	30	1610	1900	3059000
Copper	390	390	8900	3471000
Grey Cast Iron	45	510	7200	3672000

The heat sink is a cylindrical structure and equation (1) can be a close approximation of its performance. It can be seen from equation 1 that the important parameter for the material itself is not specific heat alone, but specific heat times density, or Specific Heat Capacity. Some of the materials investigated have higher specific heat than stainless steel but lower density, and the actual Specific Heat Capacity is not greater than that of the stainless steel currently used. All of the materials evaluated did not show a significant improvement in down-hole working time. A suitable material with a higher Specific Heat Capacity and suitable thermal conductivity would have to be used in order to obtain a significant performance improvement from a change in heat sink material alone. Such materials may be possible with composite structures, and could be evaluated with this model in future studies.

A theoretical phase-change material was also investigated. Such materials can exhibit a high specific heat at their melting temperature, but have a relatively low specific heat when in the solid or liquid phase. Results of initial tests were inconclusive, possibly due to the time-step used during evaluation. The time taken for the model to complete an iteration increases when calculating a material with a variable performance such as is seen in phase change materials. Investigation had to stop also due to time constraints.

5. Performance improvement from a change in procedure

Other possible changes were explored with little gain in down-hole working time found during investigation of different materials for the heat sink. Analysis of the test data at 324°C test case shows that the rise in internal temperature is approximately 25°C per hour. If the same rate of temperature rise applies when the internal components in the flask begin at a lower initial temperature, the time required to reach the temperature of removal should be extended. Several model runs were conducted with an external temperature of 324°C and the components of the probe given an initial temperature of around 21°C. The model was run again with the initial temperature of 1°C for all its components including the outside flask, with the possibility of the overall probe being cooled before use. Figure 5 shows the results with the probe components having an initial temperature of 1°C compared to an initial temperature of 21°C.

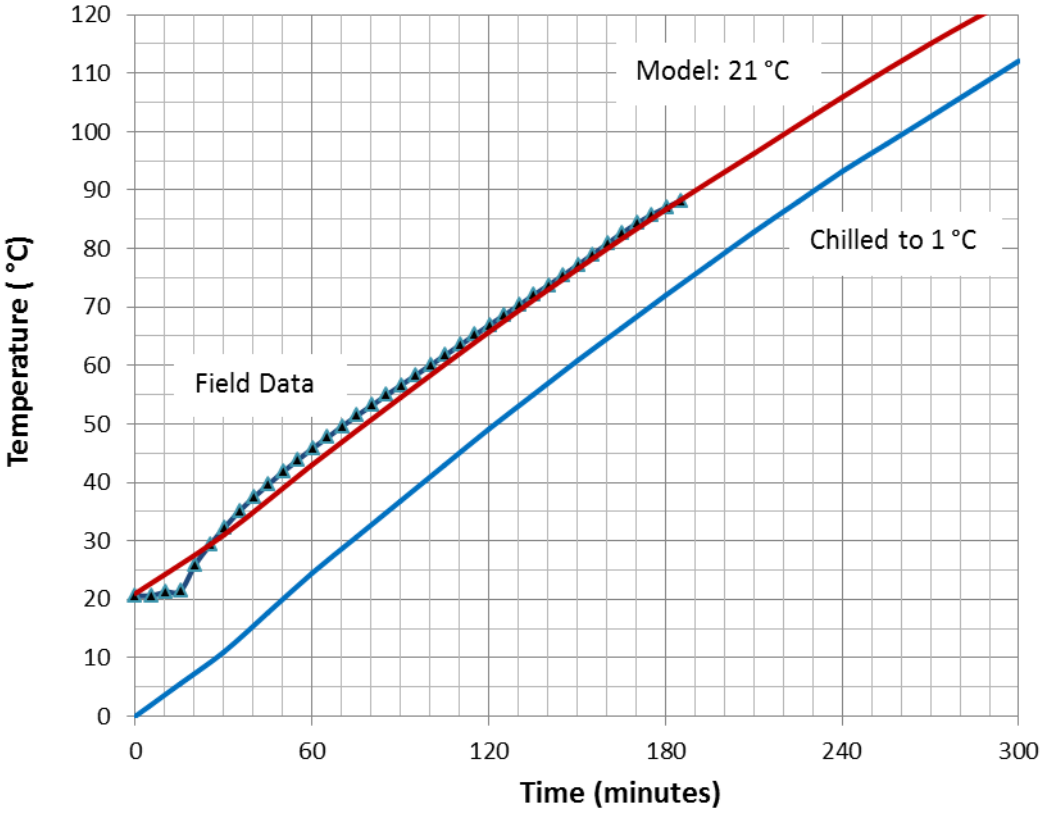

Figure 5: Probe initial temperature of 1 °C, compared to initial temperature of 21 °C

If the probe is chilled to 1°C before use, the model predicts there will be a gain in down-hole time of around 43 minutes. This is approximately two minutes for each 1°C drop in initial probe temperature before the temperature of the electronics reaches 80°C. This is considered a significant improvement. Much of the standard electronics family can perform at temperatures as low as -5°C (Watson and Castro, 2012; Presidio). Chilling the probe before use allows the test operation to take advantage of a larger portion of the operating temperature range available from the standard electronics family.

In fact, chilling portions of the probe (such as the heat sink) to temperatures colder than the overall 1°C as seen in Figure 5 can add additional working time. Figure 6 is a graph of results with the probe components having an initial temperature of 1°C, and with the heat sink only chilled to -40°C.

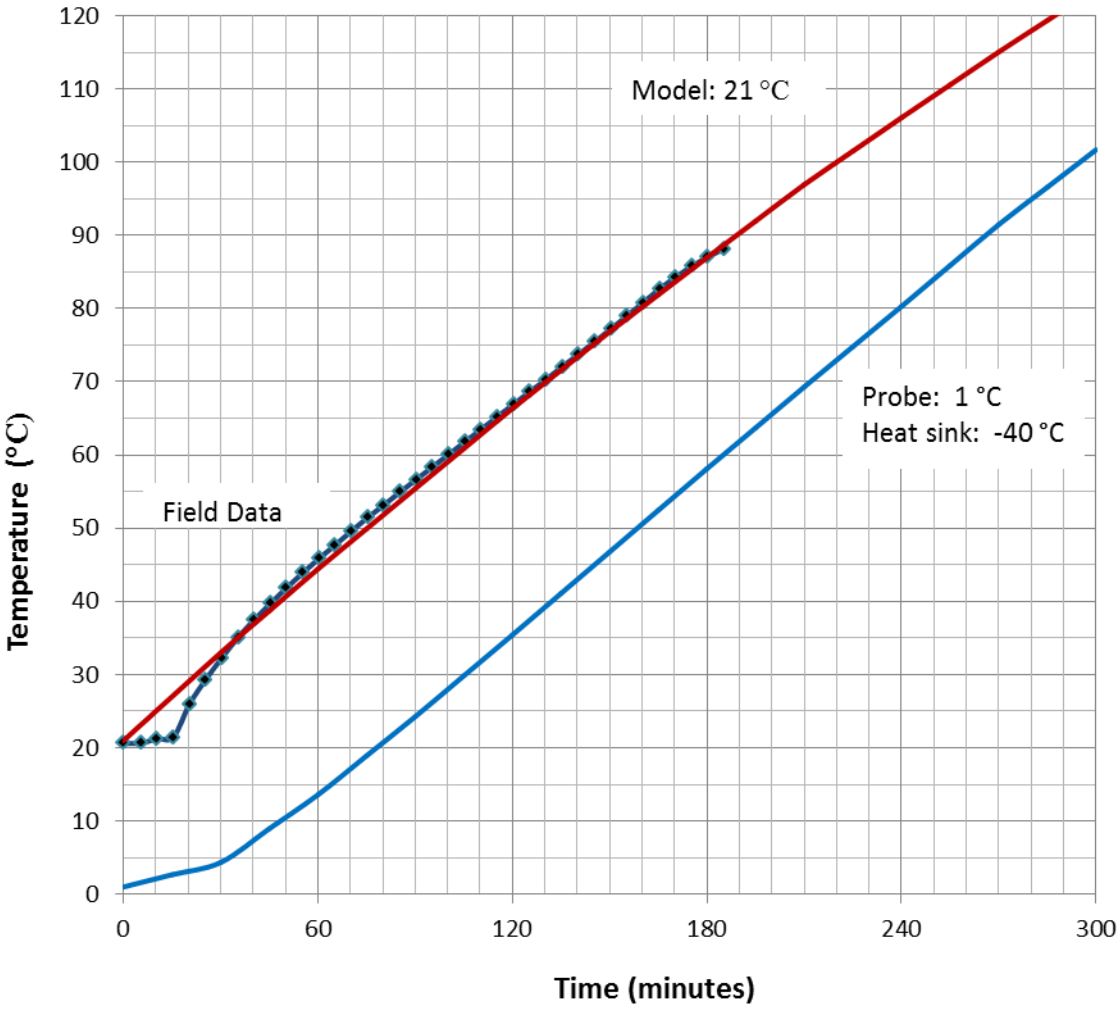

Figure 6: Probe initial temperature of 1 °C, heat sink only cooled to -40 °C

This finding shows that cooling the heat sink to -40°C increases down-hole working time by about 32 minutes compared to an overall probe initial temperature of 1°C. This translates to an overall increase in working time of around 75 minutes compared to a probe with an initial temperature of 21°C.

6. Practical aspects of a probe in use.

The concept of chilling the overall probe or its components before use may provide an increase in down-hole working time, yet it is important to see how much time may be required to chill a probe in this manner. Figure 7 shows the models prediction of temperature decrease over time, evaluated at a location on the circuit substrate near the circuit itself. The model case is for a probe initially at 21°C being cooled to 1°C and subjecting the outside surface of its Dewar flask to a 1°C temperature.

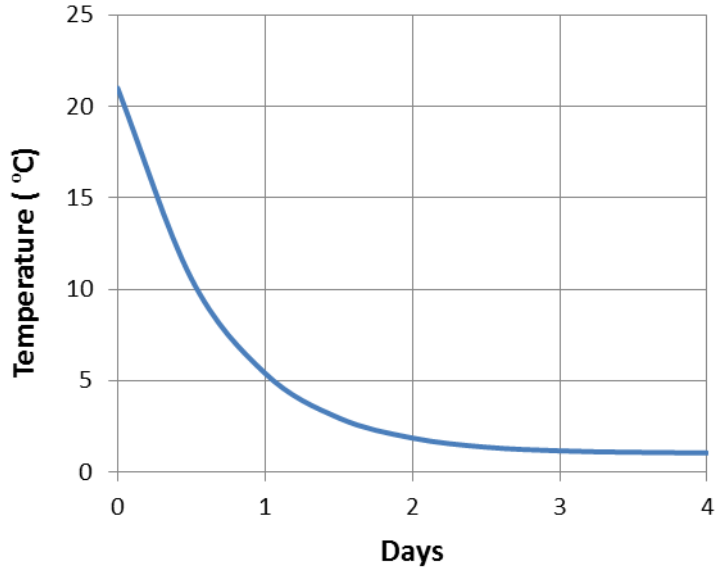

Figure 7 Temperature decrease with time, chilling probe from 21 °C to 1 °C

Figure 7 shows that cooling the internal components of the probe by means of subjecting the outside of the Dewar flask to 1°C may take up to four days, though the bulk of the cooling occurs in the first two days. If instead the components inside the Dewar flask are disassembled to the outside of the flask and allowed to cool separately, cooling time would be much reduced. This requires a change in procedure and planning, but could allow a longer working time in hot wells.

Before using the probe in the well, the probe must be conveyed to the site. If transportation is to take place in a 21°C ambient temperature, it is also useful to know how fast the temperature will increase on the components internal to the flask. Figure 8 shows the temperature increase over time, evaluated at the same location on the circuit substrate as used above, from 1°C to 21°C, as predicted by the model.

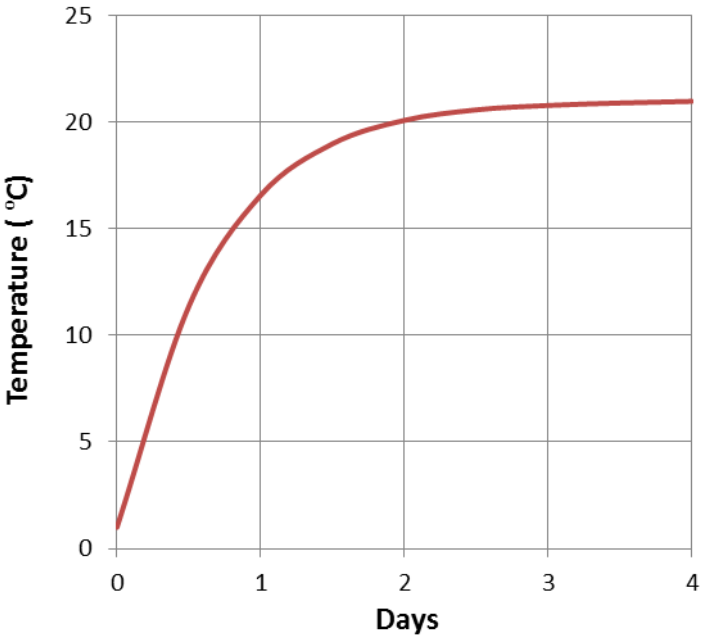

Figure 8: Temperature increase with time, warming probe from 1 °C to 21 °C

Figure 8 shows that approximately half of the temperature rise occurs in approximately one half of a day, so it may be useful to keep the probe chilled during transport.

7. Conclusions

A survey of the current state of HT electronics shows that the family is still in its infancy, yet development of circuits with this family of components has begun. Commercial down-hole tools have been developed based on these devices, with capability to work continuously in temperatures up to 250 °C. Above these temperatures, thermal protection for the circuit is still necessary, and Dewar flasks are being used. A thermal model has been developed using the commercial probe from MB Century that appears to closely match performance from actual field data. Analysis shows the MB Century's design is performing very well compared to the other Dewar flasks designs. The model was used to predict results of simple changes to materials used for the internal heat sink, and none of the materials modeled showed a major improvement in down-hole exposure time compared to the material currently in use. However, a change in operational procedure shows a potential gain in down-hole exposure time of approximately 45 minutes by cooling the probe to 1°C before its utilization, and approximately 75 minutes overall if the heat sink is further chilled to -40 °C. Future work can be done with the model to analyze phase change materials for the heat sink, or other component changes as desired.

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