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TITLE: UPGRADES IN THERMAL PROTECTION FOR DOWNHOLE INSTRUMENTS

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UPGRADES IN THERMAL PROTECTION FOR DOWNHOLE INSTRUMENTS

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ABSTRACT

Measurement of geophysical parameters in progressively deeper and hotter wells has prompted design changes that improve the performance of downhole instruments and their associated thermal protection systems. This report provides a brief description of the mechanical and thermal loads to which these instruments and systems are subjected. Each design change made to the passive thermal protection system is described along with its resulting improvement. An outline of work being done to scope an active thermal protection system and the preliminary qualitative results are also described.

INTRODUCTION

The development of the geothermal energy resource depends in part on the success in developing accurate physical models, cost-effective techniques for creating and enlarging geothermal reservoirs, and workable methods for extracting the stored energy. Each of these endeavors requires extensive data about microseismic events, borehole fluid chemistry, flowrate, temperature, pressure, and their growth and associated changes. The sensors and downhole electronics used in instruments that measure these geophysical parameters must withstand the conditions in hot geothermal wellbores to which they are repeatedly subjected. The purpose of this paper is to describe several design improvements made to passive thermal protection systems thus far and to outline work being done to increase the temperatures and the residence times at which downhole instruments operate.

GEOTHERMAL ENVIRONMENT

Conditions in geothermal wells are generally more hostile than in commercial oil or gas wells. Typical geothermal gradients produce temperatures as high as 593°K at depths of 4600 m where the hydrostatic pressure is approximately 38.5 x 10-6 Pascals. Water or geofluid chemistry ranges from acidic salt brines to very alkaline solutions with suspended solids averaging 10,000 ppm. Wellbores in geothermal reservoirs are purposely inclined from the vertical and left uncased in their lower sections which are in naturally heated, unmelted crustal rock such as granite (Smith and Ponder, 1982).

These conditions require that instruments be packaged in a pressure vessel that withstands both high temperature and pressure and the severe handling caused by being dragged across hundreds of feet of rough, exposed granite. Electronics and sensors housed in the sonde must be thermally resistant or be thermally protected to survive exposure at elevated temperatures during experiments over extended periods in hot wells.

GEOPHYSICAL INSTRUMENT THERMAL PROTECTION

Geophysical instruments range in complexity from the purely mechanical tools to instruments with delicate electronics that can be divided into three broad categories, (a) purely mechanical tools, (b) tools with minimal electronics or temperature hardened sensors, (c) tools with extensive delicate electronics that require thermal protection during use in hot wells.

Cooling systems for geophysical instruments and tools vary from "none" to "sophisticated". The purely mechanical tools in the first category require no cooling at all. The tools in the second category do not have any specially designed or specifically intended "thermal protection system." They typically survive a single trip into and out of a hot well during which the thermal capacitance of the steel tool body provides the major proportion of the thermal protection for electric motors, reed switches, etc.

The third tool category is thermally protected using current technology passive cooling system consisting of a hot service dewar and a phase change material used as a heat absorber. A typical cooling system is arranged as shown in Fig. 1. The heat sink, filled with Wood's Metal, is protected by an insulating plug with a central hole that provides a pathway for the wiring to pass from the electronics through the heat sink and finally to the cablehead. The heat from the wellbore and heat generated by the electronics must move from the electronics compartment into the heatsink. Available paths include conduction through long, thin mounting

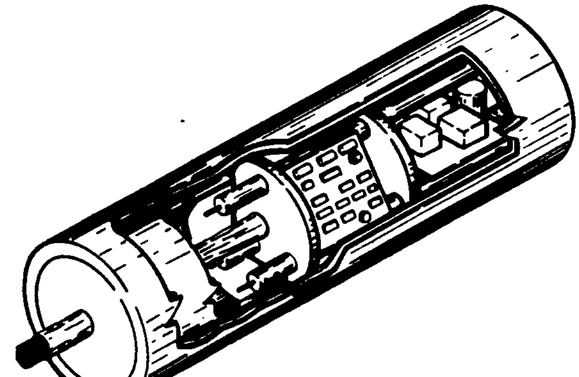

Figure 1. Passive thermal protection system components.

rods or conduction through air. It has been shown that the temperature gradient required to transfer heat from electronics to heat sink is too large to be practical or requires the compartment temperature to remain above its stated survival limit (Bennett and Sherman, 1983). One of the disadvantages inherent in the use of passive thermal systems is that their heat absorption capacity is volume limited and does not generally reach steady state when parked on station in a well.

Design Criteria

Tool shapes are restricted to small diameter, long cylinders in order to pass through wellhead hardware and still slide down into a well. Overall length is restricted by the available distance between wellhead hardware, packoffs, valves, etc. and the sheave over which the cable must pass. Tool diameter is restricted by the wellhead diameter or by the casing diameter, whichever is smaller.

Thermal Loads

The thermal protection system must withstand the mechanical and thermal loads imposed on it during transport to and from the well site, data logging during an experiment and storage while not in use.

There are no unusual thermal loads imposed during tool transport. The high temperatures in wellbores impose the largest heating load on the tool and its electronics and thermal protection system. The temperature boundary condition during a trip into the well is shown in Fig. 2 and the calculated heat flux at the tool body outer surface is shown in Fig. 3.

The conditions depicted in Figs. 2 and 3 represent some of the most severe thermal loads to which a thermally delicate instrument might be subjected. This geothermal gradient produces the

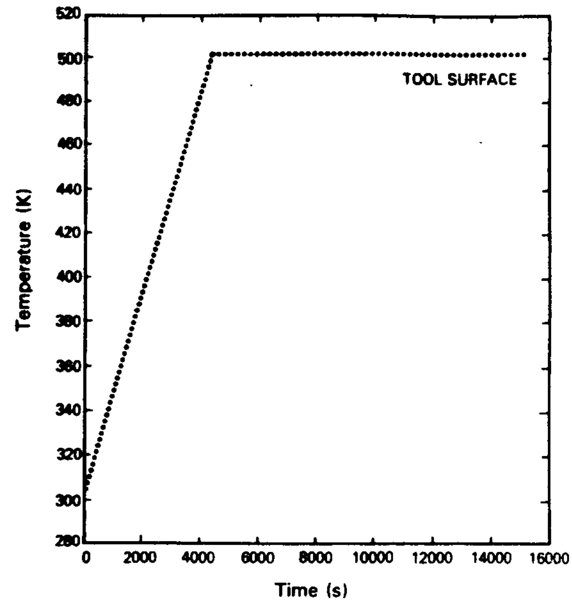

Figure 2. Boundary condition -- tool surface temperature.

large temperature differences between the wellbore and the cool interior of an instrument package. The heat flux shown in Fig. 3 is also relatively severe in that it provides a high heat transfer coefficient. Each parameter in the Colburn equation is near maximum -- the Reynolds number for a typical fast trip into a well at 0.76 m/sec and a high Prandtl number for water as opposed to gas or steam. The calculated flux crossing the dewar walls is approximately 36 W/sq-m indicating an average quality dewar. The heat reaching delicate instruments packaged with 0.20 sq-m exposed area is 8 W. This requires

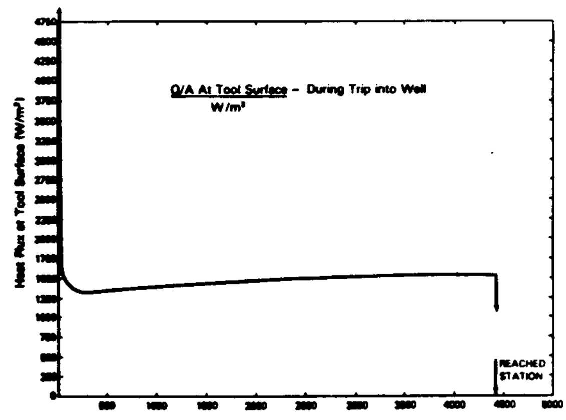

Figure 3. Heat flux at tool body outside surface.

that any thermal protection system be capable of removing 8 W plus self generated heat and then reject this sum to the heatsink or the wellbore.

The low temperature thermal loads are imposed during overnight storage outdoors during cold weather. Mechanical components must accommodate thermal expansions and contractions caused by temperature swings as large as 350°K in several hours.

Mechanical Loads

Mechanical loads imposed during transport consist mainly of vibration in the range of 10 to 400 Hz. Since tools are transported horizontally, radiation shields in dewars must be designed to resist shifting. Cushioning systems for mechanical components of an instrument inside the dewar must resist the horizontal vibration imposed during shipment as well as vibration imposed during vertical trips in and out of a well. Occasionally a tool is dropped or impacts an obstruction along the wall of the wellbore causing large momentary forces.

Summary of Imposed Conditions

Temperature	273°K <T <593°K
Pressure	0°Pa <P <82.7x10-6 Pa
pH	2 <pH <12
Suspended solids	>10,000 ppm
Vibration	10 <Hz <400
Impact Load	up to 15 G's
Heat flux	~1350 W/m^2

DESIGN IMPROVEMENTS

Several improvements were made to the passive thermal protection system that increased the downhole lifetime by a factor of 4. The improvements involved changing the basic way passive thermal protection systems are expected to operate. In conventional systems, the electronics compartment is intended to be the coolest part of the system. A previous thermal analysis for a LANL system containing a battery pack, electronics and a heat sink shows the temperature-time history illustrated in Fig. 4.

Even though the bulk temperature of the electronics is below that of the heatsink there are hot spots on the circuit boards where the local temperature is higher. This effect, as well as heat input through the dewar walls heats the air to a temperature above that of the heatsink, thus providing a potential to move heat from the electronics into the heat sink. But air provides an extremely low conductance path for moving heat into the heatsink.

The first major change involved replacing some of the brass mounting hardware with heat pipes in an effort to increase the conductance of the heat transfer path. The heat pipe body is

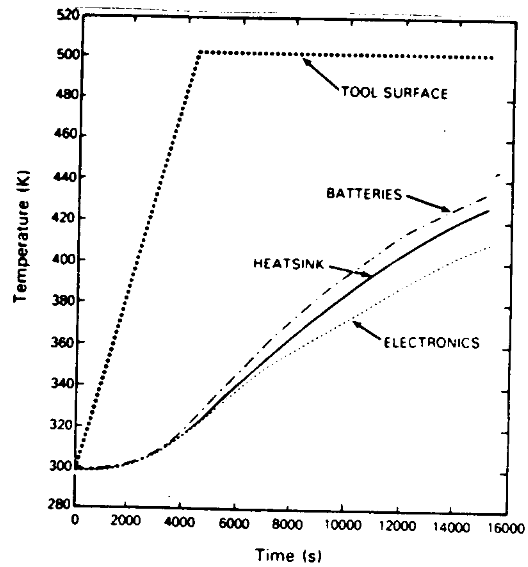

Figure 4. Temperature-time history of major sections inside dewar.

made of brass and uses methanol as the working fluid. For operation at 323°K, the axial heat flux is 4 x 10^4 W/m^2 which is twenty times larger than conduction down a long, thin rod and ten thousand times larger than conduction through air (Dunn and Ray, 1978).

By changing the heat sink material from the conventionally used Wood's Metal to ice, the total heat absortion capacity was increased by a factor of 1.6. This improvement was strictly the result of the incresase in the enthalpy change and the latent heat absorption capability for the same volumes of available heat sink material.

This change also moved the heat sink melting temperature from 343°K to 273°K so the thermal potential between the electronics and heatsink allows heat to move out of the electronics to the heat sink. The available thermal potentials are $\Delta = T_{max} - T_{melt}$ = 353°K - 343°K = 10°K for Woods Metal and 80°K for ice, which is eight times larger.

Two further improvements to thermal protection involve changes in dewar design. The first change required increasing the thickness of the inside wall. This adds thermal mass which increases the downhole lifetime and also strenghtens the inside cyclinder. The increased strength is enough to allow the addition of an electronic fluid to displace air in the electronics compartment thus decreasing the film resistance. The second design change involves using a rigidly-mounted electrical connector on the insulating plug. The connector replaces the hole in the plug and provides further reduction

All of the above improvements have been made to passive thermal protection systems. They are limited in downhole lifetime by the heat sink volume and the quality of the heat transfer barriers provided. Further improvements in downhole residence time or increases in oprerating temperature will probably require systems to operate at steady state which implies active refrigeration downhole.

Several types of active refrigeration systems have been investigated. Each system was examined in enough detail to produce a conceptual design and a preliminary analysis that included the relevant engineering parameters. Each preliminary analysis suggested possible design improvements that were noted, but left for later evaluation. Comparison of all the preliminary results will provide several systems as condidates for further study.

Systems and methods of refrigeration investigated include the following:

(1) thermoelectric cooling
(2) vapor-compression refrigeration
(3) gas cycle refrigeration
(4) absorption refrigeration
(5) acoustic refrigeration
(6) magneto-caloric refrigeration
(7) chemical potential (fuel cells)

Based on the preliminary investigation, the feasibility of each process in comparison to the others is ranked in decreasing order as:

(1) vapor compression refrigeration
(2) acoustic refrigeration
(3) Brayton cycle refrigeration with a turbine
(4) Brayton cycle refrigeration with a throttling valve
(5) magnetocaloric refrigeration
(6) absorption refrigeration
(7) fuel cell cycle refrigeration
(8) thermoelectric refrigeration.

The vapor compression calculations using water as a refrigerant resulted in a feasible system, although unattractive, because of the high pressure ratio required in the compression step. The acoustic refrigerator is feasible and more attractive than the Brayton cycle with a turbine because of its higher thermodynamic efficiency and its simpler, less intricate mechanical design.

The Brayton cycle with a throttling valve is marginally unfeasible because the required power input is almost twice of what is available on a single conductor.

The remaining refrigeration cycles were rated in decreasing order of feasibility because of the magnitude of the unknown information or availability of a suitable refrigerant material. The magnetocaloric refrigerator requires extensive knowledge of magnetic and thermal properties as functions of temperature and applied magnetic field intensity in both the ferromagnet and the permanent magnet materials. Because of the small achievable temperature difference in any of the refrigerants, the system requires a cascaded series of magnets and implies large physical size and weight.

The absorption refrigeration cycle requires finding a binary solute-solvent mixture capable of operating in a two phase mode between the stated temperatures. If a binary system were found, extensive thermodynamic data would be required for the enthalpy of the pure vapor and the vapor-liquid mixture as a function of temperature and pressure.

The fuel cell refrigeration cycle requires determination of how each of the candidate chemical reactions can be made to occur in reverse. This would most probably require catalysts and additional chemicals which must be included in the overall heat and mass balances and also be reuseable in the proposed closed system.

The single-stage thermoelectric refrigerator is very definitely unfeasible because it cannot provide any refrigeration at the specified temperatures, and requires as a minimum sixty times more power input than is available.

SUMMARY

Research and development to thermally protect downhole instruments has yeilded several improvements in the performance of passive systems. Each change was described and the results in improvements in thermal performance were reported. An outline of work in progress on active thermal systems and the preliminary qualitative results were also given. Projections on increasing demands in the thermal performance of downhole instruments will require specially hardened electronics components or active cooling for partially hardened electronic components.

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