HIGH TEMPERATURE DOWNHOLE TOOL DEVELOPMENT

N Halladay & M Manning

CSM Associates Limited, Penryn, Cornwall, United Kingdom

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Abstract

The design of any downhole tool, whether advanced in specification or simple, is an interative process.

Some of the issues involved in producing such tools are discussed along with the status of the current technologies involved.

GENERAL TOOL DESIGN

The design of any downhole tool, whether advanced in specification or simple, is an iterative process involving the specifier of the operational criteria and the design/development engineers in a necessarily close working relationship. A fundamental requirement is for the design team to understand the operational criteria and specification along with the reasons for and the factors controlling them. The need for this is due to the complex nature of tool design. If the specification has any flexibility only the design team are in a position to exploit it. Advanced tool designs in particular may have conflicting problems which may be solved individually but collectively require performance compromise.

Within a particular instrument system there are three primary systems, namely - Thermal, electronic and mechanical.

In simple instruments these systems can often be considered independently, however, for complex, advanced specifications it is essential that the three systems are fully integrated.

A typical design history for an instrument would be as shown in Figure 1. Various activity loops can be seen where review/redesign actions occur. Not so obvious interactive action takes place during the detail design phase. Here the three primary systems are brought together. Figure 2 lists some of the parameters and components that require consideration to meet the needs of the thermal design process. Similar lists can be produced for the electronics and mechanics systems.

Consider the three systems.

THERMAL

From a thermal perspective all downhole instruments can be separated into two fundamental groups, those that require thermal protection systems and those that do not.

The need for a thermal protection system cannot be based upon downhole temperature alone. Factors such as electronic systems functions, downhole duration, serviceability and price may all influence or dominate the design concept.

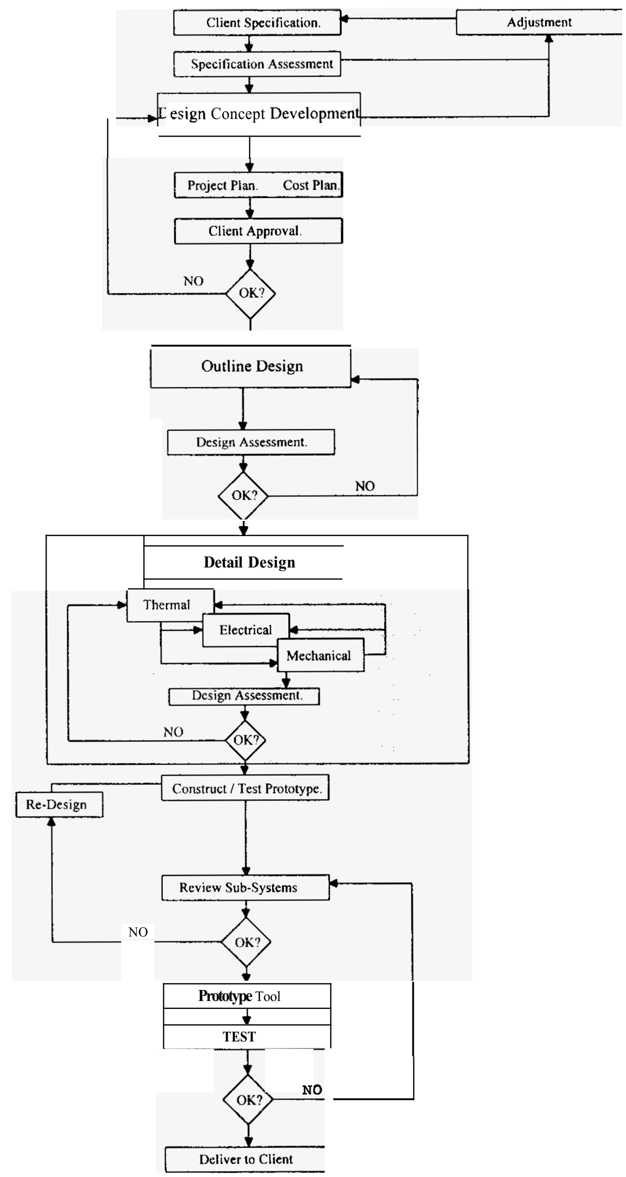

Figure 1 Instrument Design History

THERMAL

DEWAR PERFORMANCE PARAMETERS
HEAT LEAKAGE INTO SYSTEM
INTERNAL INITIAL TEMPERATURE
INTERNAL FINAL TEMPERATURE
THERMAL RISE TIME
HEAT TRANSFER RATES
HEAT SINK (STORE) SIZE - JOULES

MECHANICAL

DEWAR DIMENSIONS
MATERIAL PROPERTIES C_p, α, k, ρ
MASS OR HEAT STORES
LOCATION OF HEAT PIPES
SUPPORT STRUCTURE
VIBRATION/SHOCK LOADING
ACCESS/SERVICEABILITY
CONNECTORS
WIRE LOOM RUNS

ELECTRONICS

PCB SIZE
PCB HEADROOM
OPERATING TEMPERATURE LIMITS
HEAT OUTPUT
HOT SPOT LOCATIONS
PCB LAYOUT FOR COOLING ACCESS

C_p = Specific Heat Capacity
α = Co-efficient of thermal expansion
k = Co-efficient of thermal conductivity

Figure 2 Thermal Design Issues

No Thermal Protection

Downhole instruments may operate without thermal protection systems for several reasons, including:

Low downhole temperatures <175°C
Long downhole life >24 hours
Very simple, thermal tolerant, downhole systems cost

For temperatures below 175°C complex electronic and mechanical systems can be designed and constructed with comparative ease.

For long downhole life a thermal protection system will generally be inadequate as they are effective for limited periods of time only.

Simple systems that use few components and perhaps no "electronic" devices can be made to withstand exposure to very high temperatures but are usually very limited in accuracy.

Thermal systems can be expensive so it is possible given a suitable application to consider disposable electronics.

An example of one such instrument system is CSM Associates Ltd (CSMA) hydrophone string which uses sophisticated downhole electronic systems but is deployed at temperatures upto 175°C for continuous periods of six months and more. No practical system could offer thermal protection for such extended periods of time.

In general instruments that operate in environments of 125°C or below offer few temperature problems to the designers. Above this temperature the design of the electronics gets increasingly difficult. At temperatures above 150°C commercial and military specification electronics are essentially unproven and reliance is placed upon custom developed databases of components and systems. The latter is particularly important as many components may appear to function well at 175°C but may be unable to support system functions. CSMA has spent many years developing databases and testing components and systems at temperatures of up to 220°C for periods ranging from 1000 to 10,000 hours. These databases form the core of the high temperature system design and without which no such design work could be undertaken with any confidence.

When designing the electronic systems it is necessary to consider not just the circuit and its function but also the physical layout of components, circuit board materials and board mounting methods. Care has to be taken to ensure that components with high heat dissipation do not over-stress neighbouring components and that the heat can be moved away to avoid local overheating. Immersing the electronic components in thermally conductive liquids enables efficient heat dissipation but having to seal the electronics into 'tanks' filled with a liquid greatly reduces the serviceability of the systems. When incorporating such liquids into the design, care is needed to avoid the trapped liquid and air expanding with temperature and pressurising the components.

Thermal expansion, differential expansion and general distortion of materials must be considered to ensure the mechanical stresses do not become excessive. Mounting circuit boards on 'soft' flexible mounts having a high degree of compliance not only avoids this but also aids resistance to high vibration and its potentially damaging effect.

Thermally Protected Systems

Thermal protection systems are usually required for the following reasons:

Temperature limited components (<150°C)
Protection from thermal shock
Very high external temperatures 200-450°C

The principal component in a protection system is the heat shield or dewar into which the systems requiring protection are placed. The dewar is a vacuum flask consisting of concentric metal tubes connected together at each end and the cavity between them evacuated. The ends of the dewar are either fully open (constant bore diameter) or more typically open at one end and the other either fully closed or reduced to a small diameter bore for wiring access.

A simple protection system consists of a dewar, an end closure (plug), a heat store and the electronic system.

The dewar limits the heat leakage into the enclosed system but also contains any heat generated by that system. The heat store absorbs the heat within the dewar and controls the rate of temperature increase. The larger the heat store (mass) the slower the rate of temperature increase and hence the longer the system life (for a fixed incoming heat flux).

The above is a very simple description of the function of a dewared heat store system. In practise the heat leakage into the dewar is greater at the ends (a function of the construction) and a single heat store is not sufficient to control the internal temperature distribution. To achieve this several discrete heat stores are used and the internal mechanical structures designed to maximise their thermal hedt capacity.

Using solid heat store materials, such as copper, a controlled internal temperature gradient can be produced. Substituting eutectic materials for the heat stores enables both the specific heat capacity and the latent heat of fusion to be utilised. During the melting phase a plateau in the temperature gradient can be produced which could be essential if low temperature rated devices are included in the electronic systems. The disadvantages of eutectic materials is need to construct tanks in which the material is sealed in order to control it in the molten state.

Having achieved sufficient 'heat store' capacity, an even heat distribution is produced using highly (thermally) conductive heat pipes. These heat pipes offer thermal flux densities up to 1000 times greater than copper and can readily move heat from high to low temperature regions. By designing heat pipes into the basic internal structures and ensuring heat generating devices are suitably connected into the thermal system even heat distribution is effected.

Thermosyphons

One potentially undesirable feature of dewared systems, as a result of their ability to keep heat out by insulating the internal system, is their ability to keep heat in. Once the internal system has heated up it will remain hot, often for periods in excess of that taken to heat up.

To over come this problem a thermosyphon system has been developed which behaves as a thermal diode. The thermosyphon thermally connects the internal heat management system to the pressure housing of the instrument (outside of the dewar). The system is highly thermally conductive in one direction only and conducts heat from the inside of the dewar to the external environment when it is cooler. It will not transfer heat in the reverse direction, thereby preserving the dewars insulation integrity.

Using thermosyphons enables instrument systems to cool down at accelerated rates without the need to disassemble the dewar.

Thermo-electric Cooling

CSMA has experimented with thermo-electric cooling devices and found them to be a practical means of active cooling up to 250°C (hot side temperature).

Systems have been constructed which give a 40°C reduction in temperature from a 220°C ambient. The electrical load of the electronics system was 6 watts. This allowed continuous operation of the electronics at 180°C.

The power supplies for the cooling system were designed to work continuously at 240°C. The heat dissipation of the power supply itself means that it cannot exist within the cooled system that it supports. Therefore it was necessary to design the power supply to function continuously at the ambient temperature of the tool environment. Thermo-electric cooler power requirements are quite simple requiring only a raw unregulated DC feed. This allowed the construction of a fairly simpln unit transforming an AC feed down to 5 V DC at 10 amps. The system operated at 240°C for over 4000 hours with no serious problems. The unit was placed away from the electronic systems but in good thermal contact with the tool body and hence wellbore fluid to aid cooling.

ELECTRONICS

High Temperature Electronics Systems

It is possible to design and build electronics systems for continuous operation at 200°C. This is a system which requires no cooling and relies upon semiconductor technology to withstand the ambient temperatures within the borehole tool.

This system offers indefinite operation at high temperature with mechanical simplicity. There is no benefit in combining such a system with passive cooling as this would limit tool duration. However, the use of active cooling systems can extend the operating temperature but with increased complexity.

High temperature electronics are still very much in their infancy. The technology was advanced somewhat in the late 1970s when the US Department of Energy commissioned a number of studies into this area principally for use in the geothermal industry. The work demonstrated that certain semiconductor technologies can be made to function at temperatures up to 300°C. Most of the work addressed component performance and did not consider the cperation of systems where component specification is critical. As a result it is possible to generalise about the temperature performance of a specific technology such as Metal Oxide Semiconductors (MOS) but difficult to obtain a suitably fabricated part that has the required specification performance.

Various semiconductor manufacturers have produced high temperature (200°C) integrated circuits of varying complexity but the lack of an adequate market for the products has meant that the actual product range is very limited. High temperature electronics above 220°C is still very much in the laboratory.

Current inhouse developments include a feasibility study into the construction of a 50 watt switched power supply. This unit will operate at 200°C continuously and survive a high degree of thermal cycling.

The present upper limit of temperature for continuous operation is probably 200°C. This could be extended by the use of an active cooling system to 250°C utilising thermo-electric heat pumps. Complex mechanical designs using compressor systems may extend this beyond 250°C with disadvantages of the loss of reliability and increased size and cost.

Components

For the past 10 years, CSMA have been researching and developing electronic and allied systems that can operate reliably at 200°C. The original applications were for geothermal seismic instruments that could operate for long periods at these temperatures. A consequence of the work has been the development of a database of electronic parts that can operate at 200°C continuously.

Components that were deemed suitable for the application were tested for function and parameter variation at temperatures up to 220°C. Specifically the testing concerned itself with the selection of parts for the direct application. As such, many aspects of particular devices function were accepted as being inferior but adequate or irrelevant to the application. Life tests at 220°C were carried out in excess of 1000 hours.

Tool Management Systems

A data acquisition, control and telemetry unit has been constructed for continuous downhole operation at 180°C.

The system uses CSMA qualified standard electronic components and a limited range of high temperature parts available from specialist manufacturers.

A block diagram of the system is shown in Figure 3. It combines 6 channels of high bandwidth (4 kHz) seismic data with a tool management data acquisition and control system. Seismic data is telemetered in a frequency modulated (FM) format with a modem operating at the low end of the mulitplex sending and receiving tool management data.

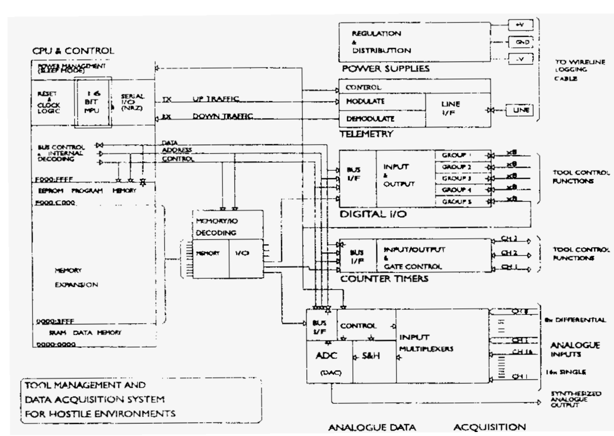

Figure 3 High Temperature (220°C) DAS, Control & Telemetry System

Tool management is seen as critical to the operation of borehole tools in high temperature environments. Typical information required of the tool operational conditions are:

1 Power supply states.

2 Internal temperatures (various).

3 Environmental temperature.

4 Circuit reference points.

Control outputs can be achieved locally under software control or from the surface,

Future Electronic Systems

Considered as a whole system the current temperature which electronics can achieve function and rehability is probably 200°C.

New processing techniques with Silicon (SOI) may increase this to 250°C. However, moves to 300°C plus will probably only be achieved by new technologies - Silicon Carbide (SIC), Diamond etc. This is a fairly distant prospect although some limited parts in SIC are available now.

Less glamorous passive components, circuit boards, connectors, wiring etc, are the support products which will need more attention in the future if any of the new technologies are to find a commercial application.

Wire Lines

Above 260°C multi conductor wirelines are essentially limited to metal sheathed, mineral insulated types. These cables are expensive and difficult to handle.

For temperatures of 400°C CSMA is developing slick line based memory systems. These will be self contained battery powered systems with a limited (typically 6 hours) downhole life, capable of recording pressure, temperature, flow-rate, fluid conductivity and possibly pH. It will also operate electromechanical systems. Pre-programmed instructions will be controlled by an on board clock system. The battery and electronics will run at internal temperatures as high as 200°C enabling the downhole life to be achieved.

MECHANICS

The high temperature, downhole environment can present severe corrosion problems to the structure of the tools.

Crevice Corrosion, Stress Corrosion Cracking (SCC), Sulphide Stress Cracking (SSC) and Galvanic Corrosion are well known phenomena to designers of downhole hardware. A great deal has been published on the subject and guidelines such as NACE-0175-94 produced for hydrocarbon applications. High nickel content alloys and various grades of titanium offer the designer useful strength properties combined with good corrosion resistance. Various surface coatings and surface treatment processes can upgrade specific material properties on a local basis. For example, the known problem of galling associated with stainless steels and titanium can be virtually eliminated by silver plating, typically on threads. However, at high temperature silver is not very corrosion resistant and can cause cracking when applied to titanium. Alternative processes such as titanium nitride (TiN) coating can overcome both problems.

CSMA is currently researching corrosion properties of materials for use in highly corrosive 400°C geothermal brines. At these temperatures very little is published on geochemical and corrosion effects upon materials. Specific research is essential.

At temperatures of 200°C the task of the mechanical engineer/designer is relatively straight forward with many excellent publications and products available to solve many problems. It is at temperatures greater than 250°C and pressures above 70 MPa (10 KPsi) that mechanical design issues become more difficult.

Considering a device which raises many of these issues: the cablehead - the link between the wireline and the downhole tool.

The basic elements of a typical cablehead are; a mechanical housing (multi-component), high pressure connector/feed through, elastomer boot, elastomer seals and rope socket/weak point assembly.

Considering these inturn:

Mechanical Housing

Part of the housing will be pressure balanced and requires a basic tensile strength commensurate with the required weak point strength and fishing neck load capability. Part of it will be subject to the full differential pressure stress. At 250°C the room temperature tensile strength of a metal will be reduced by some 20% depending upon the alloy. To avoid galling dissimilar materials can be used but galvanic corrosion effects must be considered very carefully. At elevated temperatures anticipated galvanic effects based upon the electrochemical series can be reversed with the more nobel metal corroding first.

Various coating systems can be considered, Silver and TiN are identified above. Also useful are Hard Chrome, Nickel, PTFE filled nickel composites and Plasma (metallic and ceramic) coatings. These coatings can offer improved corrosion resistance, wear resistance, electrical insulation and low friction surfaces.

High Pressure Connector/Feed-through

Several sources of high quality single and multi-conductor feed-throughs exist. In general they are limited to 250°C but capable of 140 MPa (20 KPsi) operation. Many larger diameter cableheads use several individual single conductor feed-throughs. The small diameter cableheads tend to use multi-conductor connector/feed-throughs. The multi-conductor connectors used tend to be very inferior in design and have no keying system to their mating housing or mating connector. The operator assembling the cableheads must exercise great care to ensure correct alignment of the mating connector pair (the male connector in the tool top).

Small diameter cableheads with redeveloped connector systems to eliminate the risk of poor assembly have been produced by CSMA.

Elastomer Boots

Two issues exist here, the boot design and the material. The boot is designed to seal onto the insulation of the wireline conductors and the neck of the feed-through. The seal onto the insulation is achieved by an interference fit causing the boot to be stretched, squeezing onto the insulation. A similar arrangement occurs on the feed-through, though with the addition of a raised lip (dognot) on the feed-through and matching recess in the boot. Higher temperature boot systems include a PTFE liner to aid electrical insulation. As pressure is applied the boot squeezes harder on the feed-through and insulation maintaining the seal.

This design works well in many applications until the boot material begins to degrade due to temperature, gas and chemical attack.

In severe conditions the boots will fail on one single exposure to the downhole environment. In lesser conditions boots tend to fail due to cycling associated with repeat logging runs.

CSMA has experimented with different boot materials, in general different grades of fluorocarbons, and fitting metal gas sleeves to restrict the area of the boot exposed to the well fluid and to confine any swelling.

Though this has improved the reliability, failures still occur too frequently. As a result a new cablehead concept has been developed which has the capability of removing the need for the boots altogether. At the time of writing this is being field tested.

Elastomer Seals

In the same way boot materials degrade so do the 'O' ring seals. Various materials are on the market offering performances beyond the basic fluorocarbons but with significant cost penalties. Increases in the order of 50 times are not uncommon.

The very high performance seals come in three main categories - metal, energised PTFE and perfluoroelastomers.

Metal seals offer very high temperature and pressure capabilities (+1000°C, 340 MPa) but are difficult to use reliably because of their intolerance to surface imperfections and contamination. They are generally only suitable for static applications.

Energised PTFE seals use virgin and filled grades of PTFE in a hollow, open section ring containing an energising spring (elastomeric or metallic). Suitable for static and dynamic applications these seals have for been tested by CSMA at temperatures as high as 370°C at a pressure of 117 MPa (17 KPsi). Though not as forgiving as 'O'rings they are easier to use than metal seals.

Perfluoroelastomer seals appear as conventional 'O' rings, their application and ease of use being the same as for more conventional 'O'ring materials. Various grades for perfluoroelastomers exist, some offering better chemical resistance at the expense of thermal capabilities. In general they are limited to 280°C maximum, their pressure limit being dependant upon the installation design details (140 MPa should not be a problem).

Rope Socket/Weak Point Assembly

In large diameter cableheads, the weakpoint is a separate structure to the rope socket, whereas in small cableheads the weakpoint is part of the rope socket assembly.

There are two basic types of rope socket, one traps the logging cable armour strands between a series of concentric cones which are forced together locking them in place. The other type requires the armour to pass through the centre of the assembly and then bend sharply back around the outside. Once on the outside the armour is either held in place by trapping it in a core assembly or by threaded collars.

For the small diameter cablehead both methods have disadvantages. The concentric cones have to grip all the armour strands and to achieve a weakpoint the outer armour is partially cut through producing a point of reduced but uncertain strength. The bending method allows discrete numbers of armour strands to be gripped producing a more calculated strength weakpoint but the bend can cause corroded armour to fail prematurely at greatly reduced loads.

The concentric cone assembly represents the better rope socket but a properly designed and engineered weakpoint capable of resisting bending and shock loading has had to be developed.

CONCLUSION

As can be seen from the above there are a great many issues involved in the design of downhole instruments, both simple and complex for low and high temperatures.

As the temperature requirements increase so less is known and published on materials and components and more reliance is placed on specialist research and development. Systems for use at 400°C are being developed with the inherent benefit to instruments designed for lower temperatures.