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Analysis of Thermal Behavior of Materials to be used as Insulators in Logging Tools for Oil Wells

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ABSTRACT
Measurements of thermodynamic and geophysical parameters in gradually deeper and hotter wells has driven design modification that enhance the performance in sensors and downhole electronic instruments and their associated thermal protection systems. In Mexico the oil reservoirs are located at mean depths of 6,000 m, hence the requirements for measuring these types of parameters is challenging. This paper describes preliminary work related to thermal protection systems using both three different materials and two equipments. The materials used were ceramic fiber, refractory cement and mineral wool, and the equipments were a borosilicate glass cell and a Dewar vessel. Temperature trials were conducted in the laboratory up to 250 °C. The material compositions, their thermal characteristics and the behavior during the heating tests are discussed. The obtained results are useful in the criteria formulation about the efficient use of each material for a specific objective, such as a sealing system, a protection system or an isolation system.

Introduction
The characteristics of petroleum reservoirs are an influencing factor for their exploitation. Well logs from probes lowered into boreholes have provided some of these properties, for instance porosity, temperature, pressure, among others (Hartmann and Beaumont, 1999). This recording information is useful in the reservoir characterization, since these tools are in direct contact with the reservoir formation. Pressures and temperatures in petroleum reservoir fix the endurance of sensors and electronics in these probes. Hence, these parameters are considered during the design of these tools to assure reliable logs. The gradients prevailing in the area are useful for assuming bottomhole conditions. Ordinarily (Grant et al., 1982; Craft and Hawkins, 1992) the geothermal gradient is estimated in 30 °C/Km, while the normal gradient pressure for petroleum systems varies between 0.1 and 0.16 [(Kg/cm²)/m]. In some critical cases, this pressure gradient would be estimated in 0.26 [(Kg/cm²)/m].

The oil wells depths are progressively increasing and currently, in some cases, are more than 7000 m. Therefore, assuming ordinary gradients of pressure and temperature, it would be possible to obtain conditions of high temperature and high pressure (HPHT) at these depths. Figure 1 shows a graph of the behavior of such gradients.

Since the very beginning, petroleum industry measurements, taken at bottomhole conditions, were used for the reservoir characterization, its management and the establishment of its exploitation designs. Initially mechanical sensors were used in well logs, but with the advance in technology, electronic tools were incorporated. However, high temperatures prevailing in increasingly

Figure 1. Behavior of pressure and temperature profiles in an oil well, assuming a temperature gradient of 30 °C/Km and pressure gradient of 0.10 to 0.16 [(Kg/cm²)/m].
deeper wells are an important restriction for a reliable operation of electronic sensors. Schlumberger (2008) has focused its efforts in the application of well logs to petroleum wells. Kuster Co. has developed mechanical tools for measurements of temperature and pressure in wells since 1928, initially in oil wells and since 1960 for geothermal wells (Kuster, 2011). But since 1990, Kuster Co., started to develop well logs with electronic memory available to operate at temperatures higher than 200 °C.

Schlumberger (2008) shows a classification for wells of high pressure, high temperature, whose mean values are of 205 °C and of 138 MPa (see Figure 2).

An important restriction that the wells of high pressure high temperature (HPHT) impose is the period of time that tools, materials and chemical products, must tolerate while they are immersed in this harsh environment. Hence, laboratory evaluations are focused in three main categories: a) fluids; b) mechanical accessories; and c) electronic parts. Mechanical accessories, but mainly electronic components and sensors, are highly vulnerable to high temperatures. Consequently, the trials carried out in the laboratory are directed to yield information that help to define the appropriate time duration that those materials can resist under HPHT conditions.

Concepts of Theory and Practice of Thermal Insulation

An approach to assure good operation of electronic components and sensors is to possess a thermal protection system for high temperatures. Accordingly, if there is an efficient thermal protection of the electronics, the probabilities of a good performance during operation would be higher.

One of the best thermal insulators is a vacuum; however, it is rarely used because of the difficulties to obtain and maintain full vacuum conditions in a system. The air is discarded as thermal insulator due to heat transfer by convection. Alternatively, other materials are used as thermal insulators such as fibers and porous materials, which have the capability to immobilize dry air and confine it in their internal cells.

Each material reacts in a particular manner to different heat transfers (conduction, convection and radiation). Hence the thermal transfer coefficient ordinarily is used for comparing thermal characteristics of different materials. Thermal behavior results of three different materials were obtained in laboratory. The materials used during the trials were: mineral wools, ceramic fibers and refractory cements. The thermal characterization of these materials is focused to determine the feasibility of using them as thermal protectors of the electronic components in a well logging tool.

The density of mineral wool could vary between 0.1 y 0.16 (gr/cm³), its thermal conductivity coefficient varies in the range of 0.030 and 0.041 W/(m °K) and its fusion point is over 1200 °C (Ashby, 1999). Density of ceramic fibers varies between 0.064 and 0.128 (gr/cm³), its point fusion is estimated in 1745 °C (Bunsell and Berger, 1999) and diameter of each fiber would be between 3 and 3.5 microns.

Thermal conductivity of ceramic fibers varies according to its density and average temperature. Table 1 shows thermal conductivity of a ceramic fiber at two different densities for temperatures between 200 °C and 1200 °C. The behavior of thermal conductivity of the ceramic fibers as a function of temperature is shown in Figure 3.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Thermal conductivity W/(m °K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>0.05</td>
</tr>
<tr>
<td>400</td>
<td>0.10</td>
</tr>
<tr>
<td>600</td>
<td>0.19</td>
</tr>
<tr>
<td>800</td>
<td>0.32</td>
</tr>
<tr>
<td>1000</td>
<td>0.48</td>
</tr>
<tr>
<td>1200</td>
<td>0.69</td>
</tr>
</tbody>
</table>

Figure 2. Classification, after Schlumberger, of oil wells according to their conditions of mean temperature and pressure (Taken from Oilfield Review, Winter, 2008).

Table 1. Thermal conductivity of ceramic fibers as a function of temperature, recorded for two different densities.

Figure 3. Behavior of thermal conductivity [W/(m °K)] of a ceramic fiber as a function of temperature using two different densities.
The density of refractory cement is of 3.093 (gr/cm³), its fusion point is about 2016 (°C) and, its thermal conductivity varies according temperature (Kelly, 1992). Table 2 shows the behavior of thermal conductivity of refractory cements as a function of temperature.

Table 2. Thermal conductivity of refractory cements as a function of temperature.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Thermal conductivity W/(m °K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>260</td>
<td>5.61</td>
</tr>
<tr>
<td>538</td>
<td>4.42</td>
</tr>
<tr>
<td>815</td>
<td>3.68</td>
</tr>
<tr>
<td>1093</td>
<td>3.11</td>
</tr>
<tr>
<td>1371</td>
<td>2.75</td>
</tr>
</tbody>
</table>

The graphic behavior of data of Table 2 is shown in Figure 4.

The experiments were carried out using the samples constructed from the selected materials. In this work, the results of one of the tests performed using refractory cement samples, are shown. The sample tested is cylindrical with diameter of 1.4 cm and length of 8 cm. The thermal controller was used to supply the heat. Figure 5 shows a scheme of the experimental setup.

In order to evaluate the thermal behavior of the sample, three thermal sensors were located at the inner wall of the sample. Figure 6 shows the graphs at room temperature and the behavior of temperature in the three sensors during the heating stage.

### Development of Laboratory Tests

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#### Experimental Design

In order to find materials for protecting electronic components of a well logging probe under design, several laboratory trials were carried out using refractory cement, ceramic fiber and mineral wool; additionally, two equipments, a borosilicate glass cell and a Dewar vessel were used in the tests.

The experiment was setup using temperatures about 200 °C. Due to the structure and consistency of ceramic fibers and refractory cement, samples of 2 cm diameter were constructed, and a thermal sensor was introduced in their interior for logging continuously the thermal behavior as a function of time. The mineral wool only was used as protection to borosilicate glass cell.

The experimental setup included the following materials:
- Samples test (refractory cement, ceramic fiber).
- Sensors (located inside of samples test) for continuous logging of the thermal behavior.
- System of data acquisition (communication card, personal computer)

Trials using a borosilicate glass cell and a Dewar vessel were performed in order to assess their thermal behavior. In a similar way to the samples of material, inside both equipments, thermal sensors were introduced and connected to an acquisition system for logging continuously the inner thermal behavior during heating.
Several trials were carried out using a borosilicate glass cell and a Dewar vessel, taking continuously logs of their internal thermal behavior. Figure 7 depicts a graph showing the thermal behavior of three different points where the thermal sensors were located. It can be observed that the temperature inside the borosilicate glass cell is down 50 °C compared with temperature in its external face. Besides, it is observed that the thermal behavior is the same outside of the glass cell (mineral wool) and at its inner.

Figure 8 shows a comparative graph of the thermal behavior of a borosilicate glass cell and a Dewar vessel during the thermal trials. Both containers were tested simultaneously; hence, the period of time and the temperature supplied were the same. Therefore, it can be considered a fair comparison. As can be seen in the graph of Figure 8, there is a difference in more than 150 °C in the measurements logged at the inner of both containers.

**Conclusions**

This work has given an account of a thermal protection system performance using ceramic fiber, refractory cement, mineral wool, a borosilicate glass cell and a Dewar vessel. The attained results are focused on how to improve the design of a downhole HTHP probe with temperatures requirements up to 200 °C. The following conclusions can be drawn from these results: a) samples using refractory cement, ceramic fiber and mineral wool were tested employing average temperatures of 200 °C in order to know their thermal behavior; however, these materials provided limited thermal protection. b) Two types of containers were used to evaluate their thermal behavior. The former a borosilicate glass and the latter was a Dewar vessel. Almost all materials tested showed overheating within the first two hours of testing. However, the Dewar vessel showed interesting results, depicting the best performance during long exposures to heat. Inside this container, the temperatures measured were the lowest. Nonetheless, these are preliminary results since the trials do not considered the heat that the electronics can transfer inside a Dewar vessel, suggesting that the downhole probe will require either specifically hardened electronic components or active cooling thermal protective systems. The next stage tests are focused on using a Dewar vessel and placing inside a hardened electronic component to assess their thermal behavior.

**Acknowledgements**

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**References**


