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Field Results of Thermal EOR Well Monitoring in Bahrain Field using High-Density Thermocouple Technology

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ABSTRACT

Tatweer Petroleum is producing heavy oil from the Rubble reservoir, a highly fractured carbonate with low permeability, in which much of the heavy oil in place is stored in the lime-mudstone matrix presenting significant production challenges. Steam EOR piloting efforts have led to encouraging results using a high rate/high volume CSS injection into closely spaced wells. Temperature and pressure monitoring of this process becomes critical for effective steam operations and pump control. As part of the piloting effort, Tatweer Petroleum has embarked on evaluating a range of downhole monitoring technologies, including a new high density thermocouple array sensor. This sensor combines mature type K thermocouple technology with innovative sensor packaging based on a durable polymeric insulation material capable of operating up to 300°C. This array is integrated in a compact cable design that allows for a high density of high resolution temperature measurement points to be distributed over the length of the well, or concentrated across critical zones. This paper will discuss challenges in thermal EOR being overcome by Tatweer Petroleum in producing from the Rubble heavy oil reservoir, and motivation for high temperature downhole monitoring tools with high measurement performance. An overview of the downhole monitoring evaluation program in Bahrain will be presented. A discussion on the design and reliability of the new thermocouple array technology will follow. Field results of the sensor installed in a Tatweer Petroleum CSS well will be presented along with a discussion on its expected longer term reliability. Trial data confirms successful sensor operation with high data quality in the thermal well environment, which is an important milestone in being the first installation of the technology in the Middle East.

KEY WORDS

Tatweer Petroleum, Bahrain, W. L. Gore & Associates, Petrospec Engineering Ltd., cyclic steam stimulation, CSS, EOR, high temperature reservoir monitoring, Rubble Zone, distributed temperature sensing, DTS, type K thermocouples, GORE® High Density Sensor Cables, HDSC, engineered fluoropolymer, EFP, Temp-Tube™.

INTRODUCTION

The Kingdom of Bahrain's Tatweer Petroleum has been piloting Cyclic Steam Stimulation (CSS) as an enhanced oil recovery (EOR) method to influence heavy oil recovery from the shallow Rubble Zone in the Awali Field.

The Late Cretaceous Rubble reservoir is a highly fractured carbonate with average porosity of 21% and average permeabilities between 1 and 3mD with a geometric mean of 1.1mD. The reservoir contains heavy oil with oil gravities as low as 11° API gravity, and viscosities up to 700cP. The low permeability matrix and water bearing fracture systems of the Rubble lime-mudstone play a major role in recovery efficiency (Al Balushi et al, 2016).

High temperature instrumentation for downhole temperature monitoring across multiple points in the Rubble reservoir is key to assisting Tatweer optimize EOR development in the field. The Petrospec Temp-Tube™ featuring GORE® High Density Sensor Cables, a multi-point temperature monitoring instrument packaged inside a capillary armor and installed downhole, provides Tatweer with a reliable tool for monitoring temperature profiles across horizontal CSS wells in the reservoir.

OVERVIEW OF THE RUBBLE HEAVY OIL RESERVOIR DOWNHOLE TEMPERATURE MONITORING

Edmonton, Alberta based Petrospec Engineering Ltd. has supplied Tatweer Petroleum with temperature monitoring instrumentation for the Rubble heavy oil reservoir. Both optical and electrical based systems in the form of fiber optic distributed temperature sensing (DTS) and type K thermocouples have been individually installed into discrete wells and are currently providing Tatweer with reservoir temperature data.

In thermal EOR involving steam injection there are a number of key production and reservoir parameters that temperature monitoring sensors can deliver. During field development and production, thermal operators may use multi-point temperature profiles distributed across the producing zones to assist in determining the following information:

1. Determination of optimum flow back or pump back conditions after each steam cycle.
2. Permit evaluation of steam chamber growth/distribution.
3. Help determine optimum development well spacing.
4. Observe inflow regimes.
5. Permit optimization of steam injection requirements.
6. Allow early steam injection control during communication with adjacent well bores.
7. Observation of critical horizontal well heel performance.
8. Optimize production well drawdown performance between wells during cycle operations.

Optical sensors in the form of high temperature, hydrogen-tolerant Raman type DTS fiber optic cables are utilized in the Rubble reservoir.

Raman type fiber optic DTS technology is based upon the scattering effects of high intensity light propagation in a silica core optical sensing fiber. Interactions stimulated between the silica fiber and the light are such that portions of the light energy are lost, thereby increasing the wavelength of the light. This loss is referred to as Stokes-shift. Concurrently, the transferred energy is donated to excited state atoms thereby decreasing the wavelength. This is referred to as Anti-Stokes shift. The amount of energy, and the relative intensity of backscattered Anti-Stokes light, is quantifiably related to the amount of atoms in an excited state as a function of temperature. In these systems, light pulses are launched into a sensing fiber and the return time and intensity of backscattered signals are recorded to calculate temperature typically at 1m intervals along the full length of a linear fiber optic cable to yield a fully distributed temperature sensor (Padberg et al, 2014).

Electrical temperature sensors in the form of type K thermocouples are utilized in the Rubble reservoir.

The junction of dissimilar wires can form a thermocouple. The application of heat at the junction generates a measurable electrical potential correlating directly to temperature, this principle is known as the Seebeck Effect. There are hundreds of combinations of dissimilar wires which could produce an electrical potential between them, but there are only eight combinations which are standardized internationally: Type E (chromel–constantan), type J (iron–constantan), type N (nicrosil–nisil), type T (copper–constantan) and type K (chromel–alumel) are base metal pairs, while types B, R, and S thermocouples use platinum or a platinum–rhodium pair (Liptak B, 2003). The temperature range of type K thermocouples, -200°C to 1250°C, is well suited for thermal heavy oil downhole temperature monitoring and is the most commonly used type in the industry.

Type K thermocouples have been provided to Tatweer in the following configurations:

1. Ø⅛" stainless steel sheathed, mineral insulated (MI), continuous cable having a magnesium oxide (MgO) powder packed around chromel/alumel conductors for dielectric insulation. Simplex MI cables with one type K thermocouple point were provided. MI cables are available in configurations to provide up to three type K thermocouple points along their length.
2. GORE® High Density Sensor Cables (HDSC) packaged inside Ø½" stainless steel capillary tube providing eighteen discrete type K thermocouple points. HDSC sensor cables with configurations up to 60 thermocouple points are available within Ø1/2" capillary tubing.

LIMITATIONS TO LEGACY INSTRUMENTATION

While both fiber optic DTS and MI thermocouples can provide reliable data, there are limitations present as both have inherent weaknesses in their design for use in harsh thermal well environments. Silica core hydrogen darkening and embrittlement of polyimide coatings on fiber optic cables are two issues which affect the reliability of DTS systems. MgO insulation failure and the practical limitation on the number of thermocouple points that can be packaged and distributed within a well affect MI thermocouple systems.

Hydrogen darkening in DTS systems is the distortion of the optical transmission quality of the sensing fiber caused by optical absorption resulting from the dissolution or reaction of molecular hydrogen in the silica network structure. Diffusion of hydrogen in optical fibers typically causes absorption peaks at vibrational frequencies of the hydrogen species present, some of which occur in the operating range of DTS applications, causing significant signal degradation (Bonnell, 2015).

Embrittlement corrosion of high temperature sensor fiber polyimide coatings in DTS systems is also a great concern to the reliability of the system. A temperature dependent chemical reaction between system trapped water molecules and the fiber polyimide coating can cause deterioration of the polyimide material properties (Ozari et al, 1979) leading to mechanical failure of the fiber optic cable.

The main concern of MI thermocouple performance in humid oil and gas environments relates back to the hygroscopic nature of the MgO which can cause a failure if the metal sheathing is compromised. The absorption of moisture results in a significant decrease in insulation resistance, and potentially, an electrical short or creation of a virtual junction (Barberree, 2004). The exposure to moisture is not just a problem when MgO insulated thermocouples are exposed to harsh (humid) environments, but can originate as a problem from humidity trapped during production and later exposed to high temperatures in the field. Drying processes used to mitigate moisture entering the sensor before it is sealed in a metallic tube are cumbersome and still involve risks. To compensate for these shortcomings, MgO insulated thermocouples are limited in the number of measurement points for a given cross sectional area of cable (Penny et al, 2015).

Finally, practical limitations to packaging a high number of MI thermocouple points in a downhole installation can under represent, or miss entirely, critical temperature changes along an area of keen interest or significance.

To assist in overcoming the limitations presented by legacy instrumentation the Petrospec Temp-Tube™ featuring GORE® High Density Sensor Cables presents a rugged multi-point temperature monitoring system based upon novel packaging of type K thermocouple technology using an engineered fluoropolymer insulation material. The GORE® High Density Sensor Cables (HDSC) provides improved reliability in permanently installed instrumentation systems, enabling practical and cost effective installation of a high density of accurate temperature monitoring points along the linear length of the well.

HIGH DENSITY THERMOCOUPLE ARRAY

The new high density sensor cable technology from Petrospec Engineering and W. L. Gore & Associates was first introduced and discussed in Penny, 2015: *A New Approach to Thermal Profiling in High Temperature Reservoirs Based on Advanced, Polymeric Insulated Thermocouples to Increase Measurement Point Density*.

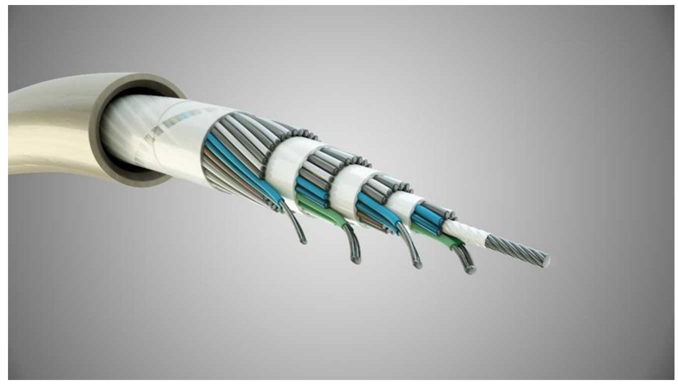

Figure A-1: GORE® High Density Sensor Cables

The construction of the HDSC sensor cable is shown in Figure A-1. The main component in this construction is Gore's engineered fluoropolymer (EFP) which acts as insulation dielectric material for the thermocouples.

The combination of a standard type K thermocouple with the unique thin EFP reveals the possibility of creating a high density sensor cable including up to 60 thermocouple points packaged in a Ø½" alloy steel capillary tube. In order to control the diameter over length and to allow for the highest density within the tubing, each individual sensor wire is composed of a thermocouple pair, its junction and a filler material. Additionally, the thin polymer sheathing and overall design of the sensor enables a faster response time relative to other, thicker, polymer insulation.

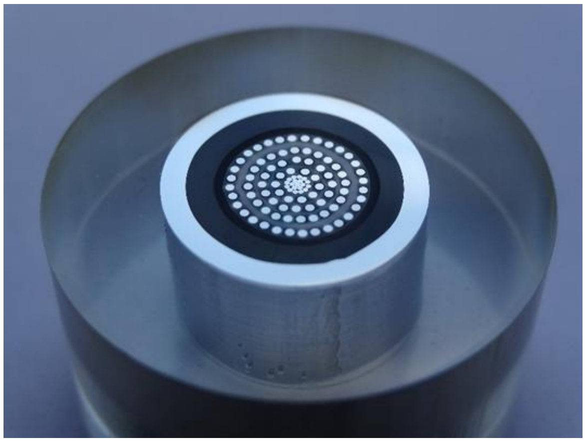

Figure A-2: Cross section of a 42pt GORE® High Density Sensor Cables in Ø½" capillary tube

The qualification of the HDSC sensor cable was based on an extensively lab testing program that subjected test cable to a range of simulated use experiments, and later qualified in a field trial (s. Figure A-3).

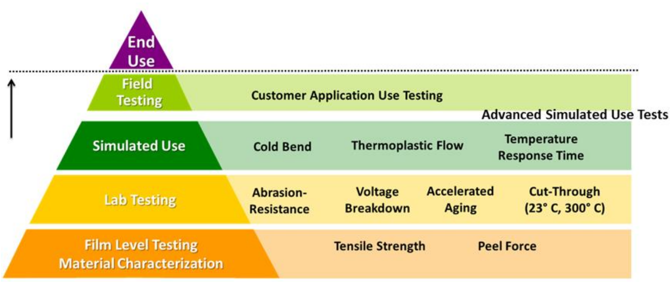

Figure A-3: Development approach/phases.

A highlight of the testing was achieving a qualified operating temperature of 300°C of the EFP insulation material tested in accordance to the ASTM D3032 standard. The procedure was as follows: An accelerated Arrhenius test was performed to estimate the expected lifetime of the insulated wire by exposing the wire to various higher-than-use temperatures in a convection oven. As described in the standard, the lowest temperature was set to 20°C above the targeted operating temperature of 300°C. Steps between each tested temperature were 10°C resulting in test temperatures of 320°C, 330°C and 340°C.

While thermocouple applications voltages occur only in the millivolt range, lifetime pass/fail criteria was conservatively defined as a 50% decrease in voltage breakdown strength of the insulation which is still 4500V breakdown voltage. In addition, each thermally aged specimen was first wrapped on a mandrel before voltage breakdown testing to simulate flexing stresses well above those expected in the application. This test procedure and pass/fail criteria was used to allow a significant safety margin in the field. The results are shown in Figure A-4. Based on the outcome of testing the cable is likely to survive more than 11 years with a continuous temperature exposure of 260°C.

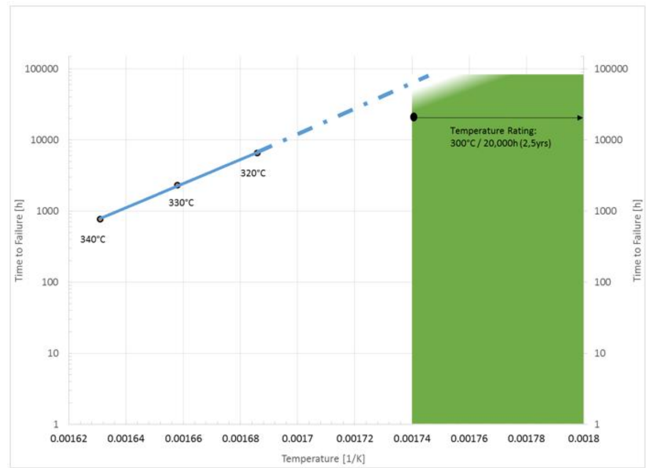

Figure A-4: Accelerated Arrhenius Testing

In addition to the Arrhenius testing the Thermoplastic Flow test was performed in accordance to the NEMA MW1000 standard. Electrical integrity, characterized by insulation resistance, is one of the main properties which prevent the thermocouple pair from failing. A prerequisite for electrical performance is the thermo-mechanical stability of the insulation material. Therefore, this test is considered to be as critical as the Arrhenius test for qualifying the material for high temperature thermocouple insulation. The load of this test was adjusted to 0.3kg to ensure an adequate response relative to alternate fluoropolymer approaches. In this series of tests the oven temperature is increased with a specified ramp rate, up to the point when the insulation wires make contact (electrical short) against each other. This temperature point is the response value.

Sample	Thermoplastic Flow Temperature
PFA (Perfluoroalkoxy)	245°C
EFP	358°C

Table A-1: Thermoplastic Flow Test Results with a load of 0.3kg

Results from the thermoplastic flow tests are shown in Table A-1 and shows that the EFP outperforms the PFA insulated wire with a temperature of more than 350°C due to its structure and morphology.

The detailed qualification plan and test results can be found in Penny, 2015. It is important to note that in both the accelerated aging and thermoplastic flow tests, which expose test articles well in excess of the anticipated sensor cable service temperature, key material insulation and mechanical properties return. Therefore the GORE® High Density Sensor Cables can be temporarily exposed to thermal events above its service rating to allow for some overhead in the event of experiencing spurious high temperature well conditions that can permanently damage the performance and reliability of other sensors.

HDSC FIELD RESULTS

For Tatweer Petroleum, an HDSC sensor cable with eighteen type K thermocouple points was packaged inside Ø½" capillary tubing, thus forming a Petrospec Temp-Tube™ featuring GORE® High Density Sensor Cables (Temp-Tube™). This Temp-Tube™ provides permanently installed multiple point temperature monitoring, along the well's horizontal section, during both steam injection and production phases of the Rubble reservoir CSS cycles.

The instrumented well is horizontal and completed with a tubing rod pump inside 2.875" production tubing. Below the pump a string of perforated 2.375" tubing tail joints runs the length of the horizontal liner to the toe. The completion allows the Temp-Tube™ to be affixed to the production and tail string exteriors via custom sized tubing clamps providing an instrumentation installation from the toe to surface.

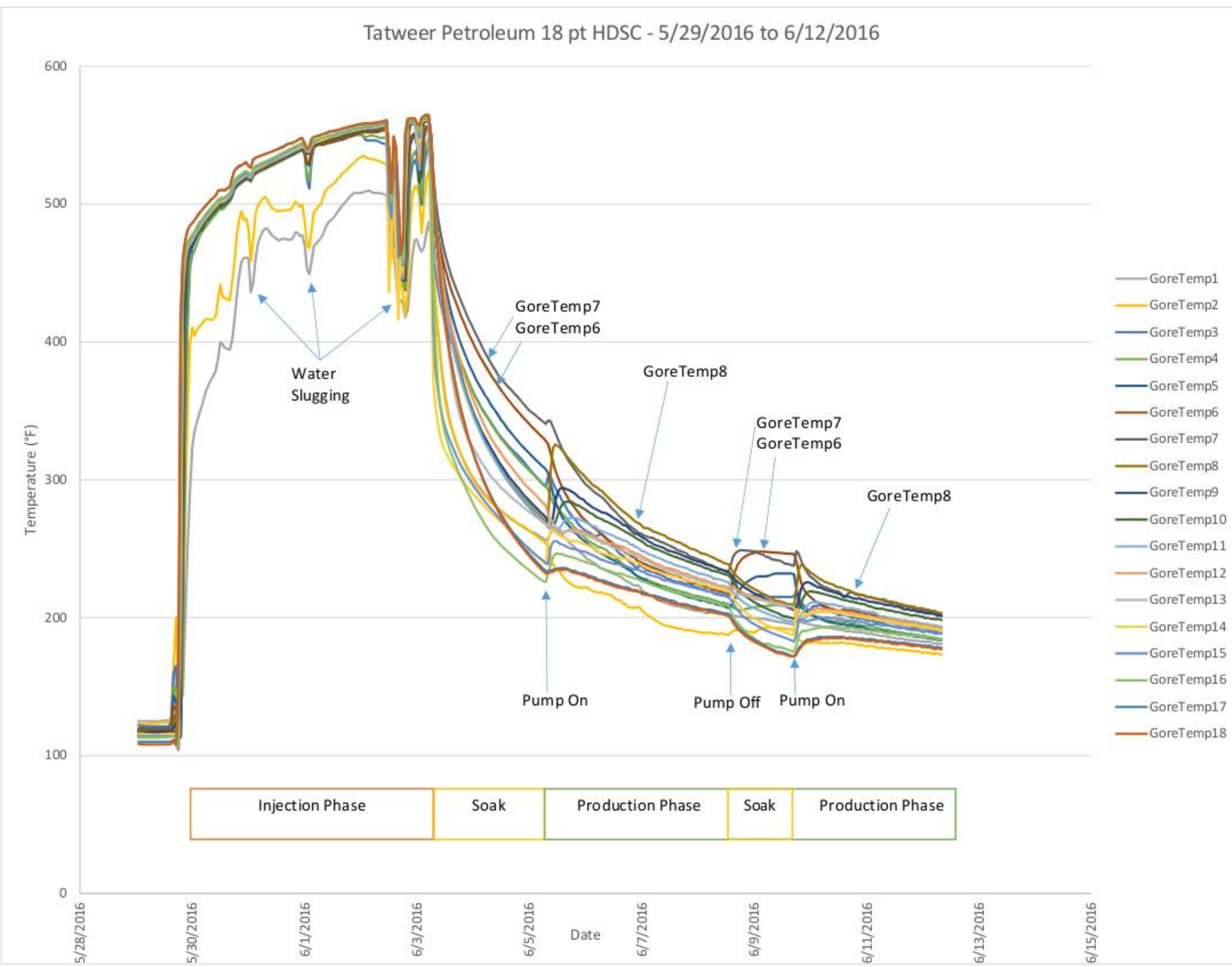

Figure A-5: Field data from 18 point Petrospec Temp-Tube™ featuring GORE® High Density Sensor Cables

The Temp-Tube™ was installed and commissioned in March 2016, and has been programmed to log hourly reservoir temperature data, from each type K thermocouple point, from date of commission to present day. Field results in Figure A-5 show the responses from the 18 point Temp-Tube™ during cold production, steam injection and production phases without incident.

As of June 12, 2016, two steam injection phases have been completed in the well. The first was a test of the surface and downhole infrastructure by injecting a small quantity of steam over a 24 hour period in early April. The successful completion of this test enabled Tatweer to bring the well online as a part of their CSS program. The second, on May 29, 2016, saw the commencement of a full steam injection cycle over a period of 133 hours (5.5 days), reaching a maximum recorded downhole temperature of 565°F (296°C), followed by a 12 hour soak period before the start of a production cycle. From Figure A-5, each of the eighteen type K thermocouple points is represented as a graphed series of temperature (°F) over time. GoreTemp1 is the label of the deepest type K thermocouple point near the toe of the well, with the linear depth of each point numerically progressing back along the horizontal leg of the well up to point GoreTemp18 – identified as the shallowest type K thermocouple point uphole of the heel.

Upon commencement of the steam injection phase, the data identifies a rapid temperature increase from an average of 112°F (44°C) to 472°F (244°C) over a span of four hours. This aggressive steam ramp-up provides a testament to the ruggedness and durability of the GORE® High Density Sensor Cables in the system.

Throughout the injection phase (May 29 to June 3), GoreTemp1 and GoreTemp2 are noted as consistently cooler than the remaining points. This can be attributed to initial wellbore fluids and water slugs from the steam injection line being bullheaded against the toe by the higher quality steam injecting behind it. At specific points during the injection cycle, slugs of water/lower quality steam are evident across all eighteen data points as sharp valleys from sudden drops and recoveries in temperature.

During the soak phase GoreTemp7 and GoreTemp6 rise identifying as the warmest sections of the wellbore over the period. As such, the near wellbore around GoreTemp7 and GoreTemp6 points as an area of high steam injectivity. To further this theory, there was a power outage during the production phase on June 9 where the pump turns off. During the outage, the well returns to soak conditions for several hours and GoreTemp7 and GoreTemp6 return as the warmest confirming where the greatest percentage of steam was injected into the reservoir.

The near wellbore around GoreTemp8 identifies as an area of highest productivity. During the production phase, GoreTemp8 rises as the warmest section indicating where the greatest contribution of heated heavy oil is entering the liner.

DISCUSSION

From a high level production engineering overview, the identification of the injectivity and inflow regimes provides Tatweer with useful tools for well completion design, control of thermal fluids, identification of the productivity and injectivity indices, and flow optimization.

As a reservoir management tool, multiple temperature monitoring points across prescribed areas of interest provides reliable surveillance data assist Tatweer Petroleum in making the best possible decisions on their wells and the Awali Field.

The long term prognosis of the Petrospec Temp-Tube™ featuring GORE® High Density Sensor Cables instrumentation system is very good. The system demonstrates ruggedness and durability during transportation, and installation, with subsequent delivery of high quality data under both demanding steam injection and production cycles. In concert with the value provided by multiple, distributed temperature monitoring points along the well's horizontal section, and the reliability and fast, high resolution measurement quality of type K thermocouple technology, the GORE® High Density Sensor Cables overcome some of the design limitations of legacy instrumentation to provide Tatweer Petroleum and other thermal operators with a new integrated high quality productivity enhancement tool.

CONCLUSION

High temperature instrumentation for downhole monitoring across multiple points in the Rubble reservoir is key to assisting Tatweer Petroleum to optimize thermal EOR development in the Bahrain field. This has spurred the company to embark on a comprehensive program to evaluate a range of downhole monitoring technologies, including the new GORE® High Density Sensor Cables. This sensor combines mature type K thermocouple technology with innovative sensor packaging based on a durable polymeric insulation material capable of reliable operation up to 300°C. This new sensor addresses some of the shortcomings of other thermal monitoring technologies, to present a viable alternative for distributed multipoint thermal monitoring with high reliability and data quality.

The installed Petrospec Temp-Tube™ featuring GORE® High Density Sensor Cables continues to provide Tatweer

Petroleum with reliable downhole temperature data to assist in thermal EOR optimization and field development. The field trial success attests to the sensor design for ruggedness and reliability through all phases of its installation and operation under the harsh well environment presented by Tatweer Petroleum's Bahrain field thermal EOR steam piloting.

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