Challenges for very deep oil and gas drilling - will there ever be a depth limit?

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ABSTRACT

The continuous and ever increasing demand for fossil fuels and in particular oil and gas has pushed drilling and exploration industry to drill in ultra deep waters (water depths more than 2000 m) with the wells drilled to depths in excess of more than 7500 m. These wells are very expensive to drill and complete with costs up to about \$100 million. Reservoir challenges are pore pressures that exceed 138 MPa beyond the limit of some current logging tools while the temperatures are not as extreme being around 125 ^{o}C. In this paper we examine the challenges placed on drilling equipment, critically review the state of the art on developing new tools and techniques to withstand these high pressures and present views about the potential depth limits for hydrocarbon drilling. In addition, techniques and innovative tools to address these challenges are presented. The abiotic theory of hydrocarbon generation from the depths of earth is also reviewed, based on prior and recent research findings, and the implications of such a theory are critically discussed. Whatever the origin of hydrocarbons, the challenges will be in the very deep boreholes and ultra deep water levels, requiring innovations and excellent teams from top notch professionals.

1. INTRODUCTION

The world is energy thirsty with an increase in demand estimated at a pace of 1.5 to 2.0% per year (Energy Information Administration, 2006) while a report to the US National Energy Council, chaired by Raymond (2007) has predicted that by 2030 the energy demand for oil and gas will increase by 50-60%. The total estimated oil in place stands today at 1,258 trillion barrels (BP, 2009), and with current oil consumption at 86 million barrels per day, the hydrocarbons in place are predicted to last for the next 42 years.

Oil production will be reaching a plateau at 100 million barrels per day which may come within 10 years, and this is of main concern for oil production companies (Rao, 2008). Rao, Senior VP for Technology in Halliburton, sees one way out of the near future crisis, the increase in the net recovery rates, which currently stands at low 30%, leaving 2/3 of the oil in place in the ground. Improving the recovery rate by 10%, the world could add a trillion barrels of oil reserves, i.e. will double its reserves.

Industry is looking also into other alternatives, to drill to ever deeper horizons and in the relatively unexplored ocean depths. Oceans cover about 70% of the earth's surface and most of the waters are at more than 2000 m deep. Hence, oil companies and the industry in general are prepared for tapping into the relatively unknown areas with potential for large discoveries. However, this presents challenges to people, technology and this is what we will be exploring in this paper.

Trying to answer the question how deep we should drill to find hydrocarbons, one should state current depth records. Finding these records for deepest wells is not an easy task as there are many records of such kind reported in various magazines of the industry; they could be deepest gas wells, deepest onshore wells, deepest drilled offshore wells, and deepest offshore producing wells. We have gathered some relevant information to give the trend as to where we stand in terms of the depth of the hydrocarbon wells and what depth limits are at stake. Deepest gas wells have been in Anadarko basin, Oklahoma, USA. There were two wells, drilled in the 1970s. Well GHK/Lone Star Bertha Rogers #1-27, for which drilling started in 1974 and stopped at 31,441 ft (9,583 m) when it struck molten sulfur. The second deepest U.S. well was the Lone Star/GHK #1-28 E.R. Baden well (total depth 30,050 feet), for which drilling started in 1970 and ended in 1972. Deepest hydrocarbon oil producing subsea well is in the Perdido field, located 200 miles south of Freeport Texas operated by Shell. The deepest producing offshore well is in the Tahiti field in the Gulf of Mexico, in a depth of more than 8138 m (26,700 ft), a record for the Gulf, according to Chevron (Moritis, 2009). Deep water and remote locations increase the time from discovery to first oil. Tahiti produces 125,000 b/d of oil and 70 MMcf/d of gas and it took 15 years "from first hunch to first oil" (Maksoud, 2009a).

2. CHALLENGES AND RISKS FOR DEEP OIL DRILLING

Challenges for ultra deep waters are plentiful, with some listed in the schematic of Figure 1. At extreme depths, very hard rock is encountered slowing down the drilling process. It has been reported that for wells deeper than 15000 ft, 50% of drilling costs are spent in the last 10% of the well because rates of penetration

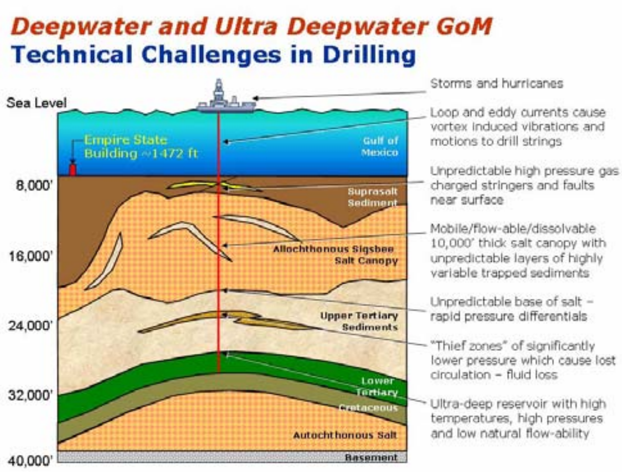

Figure 1: Gulf of Mexico ultra deepwater drilling technical challenges (from Close et al., 2008).

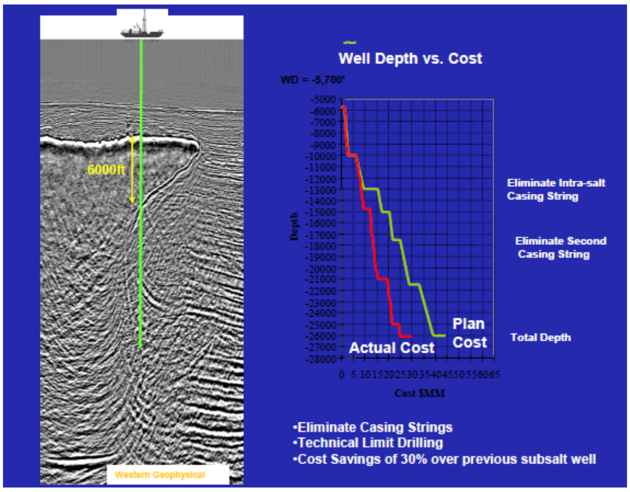

Figure 2: Sub-salt drilling challenges and achievements (from Payne, 2002).

are around 2-3 feet per hour (Schlumberger, 2004). In many of these developments, ultra low fracture gradient are encountered placing severe limitations for drilling fluids used in terms of density and circulating pressures. This has pushed industry to develop new drilling techniques grouped under the name of Managed Pressure Drilling (Oyeneyin et al., 2009).

Very deep drilling encounters salt domes which usually overlain the lower tertiary sediment, which are 30 to 60 million years old. It is very difficult to 'read' through the salt and also extremely difficult to drill through it, because it closes on the well (Fig. 2). Because of salt, the rocks underneath are not compacted, they are rubbleized, making extremely difficult to drill and hence these wells are much more costly (Rao, 2008). Huge oil and gas accumulations may lie underneath salt rock as the recent finds offshore Brazil have proved with the Tupi and Jupiter fields. The Tupi field has been estimated to deliver 8 to 10 million barrels (Abramo, 2008), it has been discovered in 2007, after drilling through 2100 m of salt, in 2100 m of water and 4900 m below seafloor, at a cost of 240 million US$. The development may require investments of up to 5 billion US$ and is expected to be in full production in 2013. First oil was pumped of Tupi field on May 1, 2009.

Ultra deep wells also encounter High Pressures and High Temperatures (HPHT wells) requiring much better, thicker and very costly metals for equipment. For e.g. the walls of Logging While Drilling (LWD) tools will be thicker leaving less room for electronics resulting in more sophisticated components, extending the current, already extreme capabilities of working in 10427 m total depth offshore well, at 138 ^oC and 2068 bar (Radzinski, 2007). The high pressure at sea bed in ultra deep waters require specially made unmanned submarines for setting up the platform, as the pressure at almost 3000 m of water can be as high as 310 bar. At these high water depths, temperatures can be as low as 40 ^oF, which may cause drilling fluids to gel, risking the creation of gas hydrates. These are the nightmare for oil well drilling and production, although some believe it could be alternative future energy source (Raymond, 2007).

Young depositional formations are encountered in deep waters which differ from shelf and onshore rocks. Adverse temperature gradient, negative from the surface to seabed and positive from seabed to bottom hole present unique modeling challenges for fluid properties and hydraulics. Drilling in very deep water where low temperatures are encountered, requires use of synthetic base fluids because of their lower tendency for low temperature gelation. However, due to small fracture gradients, severe fluid losses incur thus increasing dramatically the costs. Low temperatures alter the properties of cement, requiring new designs of cement slurry composition (Rasheed, 2002). These demand more casing strings to be placed compared to conventional drilling (Fig. 3), presenting additional challenges, like, ultra good hole cleaning for successful cement practices in narrow tolerances, and application of optimum cement placement techniques (Kelessidis et al., 1994).

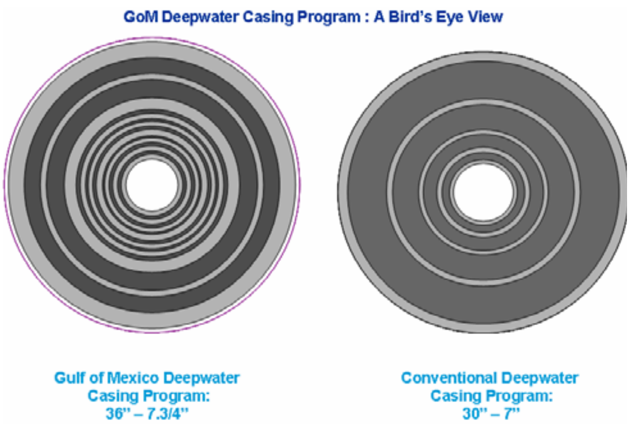

Figure 3: Casing programs - increase in strings by 4, from 5 conventional deep water and elsewhere to 9 for Deep water (from Close et al., 2008).

Figure 4: Thuderhorse platform, after hurricane Denis hit it, (Leduc, 2006).

Very deep field exploration in the seas requires super large structures which are more vulnerable to disasters. For e.g. Thunderhorse, the world's largest platform ever built, operated by BP and located in the Gulf of Mexico, with a planned oil capacity of 250,000 barrels a day, has been struck by hurricane Dennis in 2005 (Fig. 4). The field is located in a lease in the northeast region of the Gulf, about 125 miles from New Orleans. Drilling started on the first day of 1999, in the Mississippi Canyon's Block 778. On July 4 that year, the BP well reached its final depth of 29,000 feet, after having gone through 6,000 feet of water and 2,500 feet of salt. There, BP made the biggest discovery in the Gulf of Mexico. The field, holding one billion barrels of reserves, became known as Thunder Horse (Mouawad, 2006). After the disaster and with engineering at its best, the field has been put into production in less than 30 months. On December 18, 2008, it was announced that the field was put back into production flowing 200.000 barrels oil per day.

Deep waters call for immense structures to hold drilling and production platforms. Of a new revival is the spar design, a huge single cylinder with a solid ballast at the bottom to hold the structure from tilting, that extends 200 m under the water surface. Mooring lines hold the spar into place. Of the spar design is Perdido (Fig. 5), which is the deepest drilling and production facility in the world, placed in 2382 m

Figure 5: Spar of Perdido platform, getting moved to position in the Gulf of Mexico (from Canty, 2008).

of water, operated by Shell in the Gulf of Mexico. Full development plan calls for a total of 35 wells. The field, discovered in 2002, is expected to deliver first production in the beginning of 2010.

3. ULTRA DEEP HYDROCARBON DRILLING

The deepest holes ever drilled are the scientific holes (Fig. 6) which have as a primary aim to recover intact cores from the depths of the earth and measure various rock properties which could provide clues about earth's violent prehistory. Of course, the question arises, whether there was any oil or traces of oil found while drilling. Interestingly enough, there have been recent publications about analysis of hydrocarbon gases measured while drilling in scientific exhibition. Trace and more than trace amounts have been encountered in deep scientific drilling holes, like the super deep borehole in KOLA peninsula in the former Soviet Union at a depth of more than 12000 m. The KOLA borehole, drilled in 1984, reached the crystalline basement, and gases like, He. H_2, N_2, CO_2, methane and other hydrocarbons flowed (Kozlovski, 1984) at a depth of 9101 m (Erzinger et al., 2006). Hydrocarbon trace gases also flowed in the Mallik deep holes in Canada (Erzinger et al., 2006), in the Unzen scientific drilling project in Japan (Tretner et al., 2008), in the Chinese continental scientific drilling project (Luo et al., 2004) and also in the Swedish deep hole exploration program (Kenney, 1994).

A number of minor hydrocarbon shows have also been reported during scientific ocean drilling (Katz, 2003) suggesting potential hydrocarbon plays in many deepwater areas around the world. One should be aware, though, of the small amounts of gas in mud when scientific drilling. Thus, use of the equipment utilized during hydrocarbon drilling, when large gas quantities are anticipated, is not beneficial, especially when considering the fact that the systems used for monitoring gas in the mud are very inaccurate and better techniques to extract gas from the mud should be implemented (Kelessidis et al., 1989).

4. DEEP DRILLING PROSPECTS IN MEDITERRANEAN SEA

Offshore drilling in the Mediterranean sea has been in full swing in Egypt, Israel, Libya, Italy, Algeria, Morocco and Tynisia. Recent discoveries for natural gas have been reported in the Ruby field in Egypt, in 920 m of water but at relatively shallow total depths of 1957 m in gas

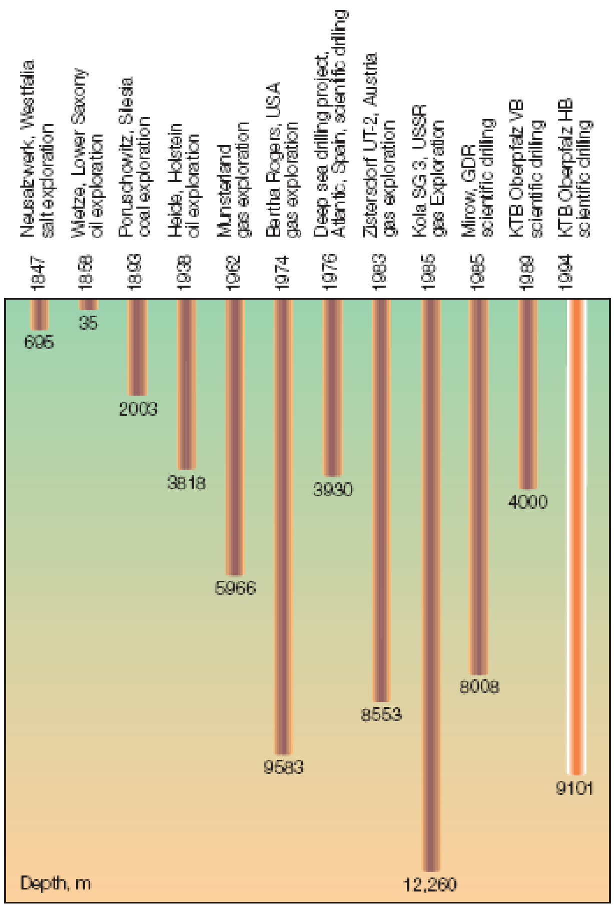

Figure 6: Depiction of deppest scinetific boreholes (from Bram et al., 1995).

bearing sandstones (Anonymous, 2009). An ultra-deepwater drilling campaign with three exploratory wells in the North East Mediterranean Deepwater Concession has been implemented in 2004. They have set new water depth records for Egypt and the Mediterranean, with drilling in over 2400 m of water. The KG45-1 well was drilled 94 miles (150 km) off Alexandria and struck undisclosed amounts of oil and gas after drilling to 10,374 ft (3,613 m). More deep Mediterranean drilling is in the works offshore Morocco after Malaysia's Petronas signed in 2004 an exploration agreement for the deepwater Rabat-Sale Haute Mer area with depths ranging between 1,000 m and 4,000 m (E&P, 2004). No success has been reported to date, but company officials stated that drilling was challenging (Reuters, 2008).

In Israel, Noble, the drilling contractor, has recently announced deep gas well prospect discoveries. It concerned the Dalit subsalt prospect, around 48 km offshore Israel, in about 1400 m of water with total depth of 3700 m and net pay of 33.5 m. Similarly they have announced good results for the Tanar subsalt prospect, in 1700 m of water, which was drilled to 4900 m total depth with 140 m of net pay in sandstones (Maksoud, 2009b). A 2007 exploration licensing round was held for offshore Cyprus, in deep waters, and a contract has been awarded to Noble, while Cyprus will pursue a second licensing round (Kambas and Kyriakidou, 2009).

5. INNOVATIONS AID DEEP DRILLING CAMPAIGNS

Oil industry has to meet the challenges mentioned above with respect to ultra deep water and very deep well drilling in the search for exploitable hydrocarbon reservoirs and is doing it by investing heavily on research and technological development. Recent additions to the arsenal of the industry include, but not limited to the following innovations.

Advanced rock mechanics models have been around for some years, however it is only recently that industry has paid more interest. Better geomechanics models will allow estimation of flow induced structures, rock failure mode and evolution of wellbore stability (Schlumberger, 2004). At the same time, monitoring of almost all downhole pertinent parameters and at high sampling rates will produce wealth of data. Thus, very efficient data management for real time processing coupled with geomechanics models will allow for safer and less expensive drilling practices in deep wells and deep waters (Saputelli et al., 2003). Newly built reservoir simulators, coupled with stress analysis can now provide solutions to problems such as casing collapse, reservoir compaction, fault activation and many others (Papanastasiou and Zervos, 2005).

Casing drilling is a drilling technique gaining in popularity to advance drilling practices. There is dual rotation system rotating independently casing and bit-down hole assembly so that when total depth is reached, the bit can be removed and leave the casing in place, thus eliminating many of the problems associated with hole stability (Schlumberger 2004; Oyeneyin et al., 2009). Drilling very deep wells and at high pressures and temperatures requires better formation and well evaluation tools, hence tool development has been suggested in the areas of elastomers, batteries, electronics and sensors (Proehl and Sabins, 2006).

Reelwell of Norway received one of the awards from Offshore Technology Conference (OTC, 2009) for the introduction of a new drilling method that challenges the limitations of conventional drilling. The method uses dual drill string to protect wellbore walls and return mud and cuttings to the surface though the inner string (Fig. 7). The method provides accurate pressure management and improved well control through closed loop fluid circulation, hence it can be implemented in all aspects of Managed Pressure Drilling (MPD). By introducing a specially constructed piston, down the hole hydraulic Weight On Bit (WOB) can also be provided for increased reach when drilling horizontal sections, thereby providing additional capabilities for Extended Reach Drilling (ERD) wells. The system has been pilot tested in April 2008 and it is in operation since then.

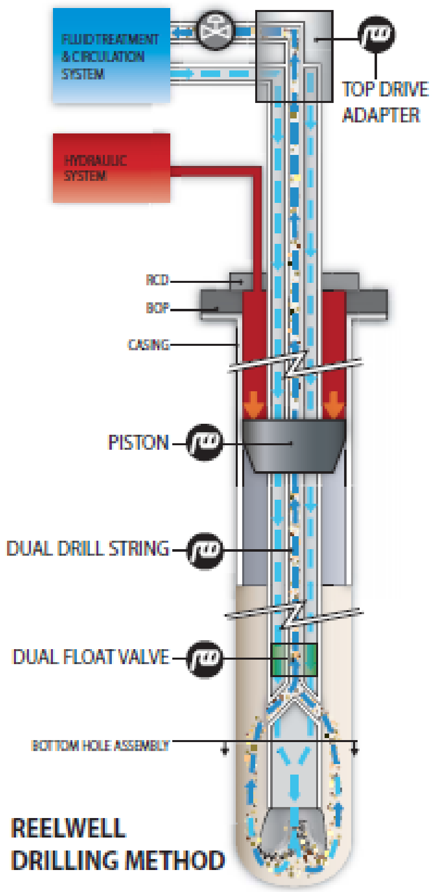

Figure 7: Dual drill string, from Reelwell.

6. THE ABIOTIC THEORY OF HYDROCARBON GENERATION

The general saying among oil well drillers is that oil is where you find it, meaning that oil has been found in traditional and non-traditional places. What of course is considered traditional is that oil is found in sedimentary rocks, very close to the surface in the beginning of the century, while nowadays it may be found at considerable depths, now reaching almost 9000 m from the surface. There are of course finds in fractured basement rocks (metamorphic or igneous rocks) from where they are produced (Sircar, 2004). Batchelor and Gutmanis (2005) have compiled an extensive list of fields producing hydrocarbons from basement rocks, although most petroleum geologists dismiss them as being of non-commercial value.

However, White Tiger, the oil field in Vietnam may prove them wrong because it is an excellent example of production from basement rock. The field currently produces 350.000 barrel oil per day, expecting to produce overall 600 million barrels (47 years of production at this pace). The granitic basement rock is highly fissured (Fig. 8) with apparent permeabilities ranging from a few mD to up to 464 mD (Chan et al., 2006). The oil that is produced, however, has been characterized of biogenic origin (Nemchenko et al., 2007) with migration from underlying sedimentary rocks.

Of course, we find oil 'where it is', where it has remained for ages, but how was it formed? Current belief is that oil is of biotic origin, through accumulation of organic matter (plankton, single cell organisms that floated on ocean surface) and sedimentation followed by burial. For large periods organic material has been under very high pressures and temperatures, in the range of 130-150 ^{o}C, in a 'cooking pot' and gradually transformed to petroleum. Because of its lower density, it has migrated upwards and some surfaced and was lost, while some has hit non-permeable layers (the seal) and accumulated in the porous sedimentary rocks creating the world's oil and gas fields.

There is, however, another school of thought, not very well known until recent years, which is gaining, though, momentum. It is the theory of abiotic (or abiogenic) origin of petroleum, that hydrocarbons have been formed in the depths of earth by reduction of CO_2 and H_2 gases in the presence of metal catalysts (Gold and Soter, 1980; Kenney, 1994; Krayushkin et al., 1994; Glasby, 2006; Wikipedia, 2009). The consequences of course of such a theory, if true, could be extraordinary, as earth's mantle becomes the inexhaustible provider of the cheapest energy source on earth, by today's standards, and shattering not only the oil-depletion myth but also pointing out to oil-rich regions in places devoid as prolific as before, because of belief of bio-

Figure 8: Natural fractures in basement rock from White Tiger field (from Chan et al., 2006).

genic origin. Alexandrovich Kudryavtsev (Kudryavtsev, 1951) was the first to start the theory of abiotic generation of hydrocarbons, in what has become the modern Russian-Ukrainian theory of abyssal, abiotic petroleum (Kropotkin, 1986; Kenney et al., 2002). However, Abbas (1996) starts the history as early as 1877 by Mendeleev and provides a good overview as well as pros and cons about the two points of view.

In principle, the abiotic theory states that under high pressures (less than 5000 bar) and high temperatures (between 500 and 1500 ^oC) methane could be formed from reduced carbon resulted from calcite. The process has been supported theoretically, via thermodynamic analysis, and experimentally (Kenney et al., 2002). Methane may also be formed from volatile rich fluids resulting from partial melting of rocks within earth's interior (National Academy Press, 2007). Thermodynamics indicate that at 1300 K, CO_2 and CO should be the predominant carbon rich gases, while at lower temperatures CH_4 should be predominant (Eugster and Skippen, 1967), with Symmonds et al., (1994) supporting the first argument by measurements.

Strong support for this hypothesis is the fact that methane and hydrocarbons are abundant in the outer solar system (Gold, 1979, 1984, 1985, 1993). There is reported evidence of abiotic formation of complex organics from methane in Saturn's satellite Titan's atmosphere (National Academy Press, 2007), although it is stated that there may be no connection to primitive earth, because at the low surface temperature of Titan (at 46 K) all water is turned into ice. Methane, ethane and acetylene have also been discovered in Comet C/1996 B2 Hyakutake (Mumma et al., 1996). The finding of very deep gas reservoirs, down to almost 10000 m, with extremely high success rates of more than 55%, has also been reported as evidence of abiotic generation of hydrocarbons (Corsi, 2005). Very recent works (Cathcart, 2007; Paropkari, 2008) have been suggesting that we should be rethinking about oil exploration strategies in view of the substantial evidence about abiotic hydrocarbon origin.

Kenney et al. (2002) analyzed theoretically, via thermodynamic computations, the possibilities for hydrocarbon generation at high pressures and temperatures and showed that it is possible. They went on and performed successful experiments, using a specially built high pressure apparatus (Nikolaev and Shalimov, 1999) at pressures of 50 kbar, temperatures to 1500 ^oC. Using only as reagents solid iron oxide and 99.9% pure marble, wet with triple distilled water, they were able to generate methane. They reported that at pressures lower than 10 kbar only methane was formed while at pressures greater than 30 kbar a multi-component hydrocarbon mixture was formed including methane, ethane, propane, n-alkanes as well as alkenes, in distributions characteristic of natural petroleum.

Scott et al. (2004) have also reported in situ observations of hydrocarbon generation via carbonate reduction at upper mantle temperatures and pressures, forming methane from FeO, $CaCO_3$-calcite and water at temperatures ranging between 500 and 1500 ^oC and pressures between 50 and 110 kbar. The authors were confident of the abiogenic theory of hydrocarbon generation thus concluding that Earth's hydrocarbon budget is much larger than it is currently thought.

Petroleum generation under hydrothermal conditions, with certain metals or alloys used as catalysts, has been amply demonstrated at lower temperatures and pressures. For e.g. Horita and Bernt (1999) used a nickel-iron alloy, similar to what could be found within earth's crust, to catalyze the slow, under other conditions, reaction of methane generation from dissolved bicarbonate, under hydrothermal conditions at 200 and 400 ^oC and 500 bar. Without the catalyst, no methane was formed, concluding that abiogenic methane may be more widespread than originally thought.

Proskurowski et al. (2008) suggested, through analysis of components in hydrothermal oceanic vents that abiotic synthesis in nature of hydrocarbon fluids may occur in the presence of ultramafic rocks (which comprise mostly Earth's mantle), water and moderate amounts of heat. On the other hand, Konn et al. (2008) analyzing data from same and other vents did not find conclusive evidence of the fact. He noted that, although amounts of hydrocarbons attributed to abiogenic origin were found, their signature has been difficult to characterize owing to the abundance of biogenic material. This is not far from the findings of Robinson (1963) who had noted at the time that the observed petroleum composition cannot really be attributed to biological origin, suggesting a primordial mixture to which bioproducts have been added. Ji et al. (2008) also presented results of generating a range of alcanes up to pentane, not only methane, from CO_2 and H_2 in hydrothermal conditions with cobalt as catalyst at 300 ^oC and pressures as low as 300 bar.

Szatmari (1989) suggested the hypothesis of petroleum formation by Fischer-Tropsch synthesis, which is distinct from the organic and the inorganic coming from degassing theory of Gold. Foustoukos and Seyfried (2004) also demonstrated the acceleration of hydrocarbon production from CO_2 and H_2 with the Fischer-Tropsch reaction, using chromium and iron bearing minerals as catalysts, at 390 ^oC and 450 bars. Recent reports (Sherwood-Lollard et al., 2002) have identified traces of abiotically derived hydrocarbons in Kidd Creek hard rock mines. In the laboratory, abiotic synthesis of more complex organic compounds has been reported in aqeous media (McCollom et al., 1999).

Glasby (2006) gives a historical overview on the origin of hydrocarbons. He dismisses both the Russian-Ukrainian theory and the theory of gas degassing by Gold, as being non thermodynamically sound. He does not discuss, however, the Fischer-Tropsch type of reactions, pointed out above. Hence, his work serves as a very good reference, but to the author's opinion, the final arguments are not as strong as they should have been. Interesting to note that he dismisses the Ukrainian theory on the basis of better evidence for the origin of higher hydrocarbons from organic matter, using better techniques, and noting that the theory is even forgotten in Ukraine, which is not true, as it has been recently demonstrated (Kutcherov, 2007; Kitchka, 2007).

7. DISCUSSION

Humanity should be looking at all energy sources to cover earth's energy budget, but we should not lose sight of the fact that hydrocarbons play the most significant role in our energy balance equation. Wells of the future will be horizontal and multilateral wells with smart well technology, meaning necessary hardware for producing when it is needed while optimizing recovery (Rao, 2008), operated by top notch, multidisciplinary people. As Robert Ryan, vice president of global exploration at Chevron recently explained, 'the world is full of resources - the question is how we can apply technology to make them energy resources" (Maksoud, 2009a). We would add that we must do this while posing no threats to the environment and maintaining sustainability.

The way forward will require "more creativity, more innovation, and more integration" as mentioned by Ryan. There was an interesting notion by Ryan, "Peak oil will be reached when we reach peak technology, and peak technology will determine when the world reaches peak energy" (Maksoud, 2009). Thus, it is through technological advancement, ingenuity and creativity and educating our people that we could extend the oil depletion window. Of course, if the abiotic theory of oil generation is true, then, the sky will be the limit and the pressure will be on finding the oil, not on finding ways to replace it.

8. CONCLUSIONS

An analysis has been presented of the current hydrocarbon exploration trends, addressing the challenges that oil-industry is facing to move into ultra deep waters and very deep boreholes. Future breakthroughs for safer drilling into very deep wells taping oil resources will be drilling to the earth model where integration of drilling, completion and seismic comes into play, with seismic interpretation while drilling guiding drillers more intelligently.

A review of the recent and prior work has also been presented of the theory of abiotic origin of hydrocarbons. Recent theoretical and experimental evidence demonstrates the possibility that hydrocarbons may have formed in the depths of the earth. If the theory is substantiated further, then oil-depletion becomes a myth and the industry must be ready to face the new challenges of drilling even deeper, to the basement rock, where huge oil fields may await to be discovered, as White Tiger in Vietnam has proved.

No matter, though, of what the origin of hydrocarbons is, the sure trend is that drilling depths will be increasing in the future and the industry should be geared up and ready for meeting the many challenges. In order to accomplish this, the industry should continue to thrive in excellence, developing innovative tools and techniques, while at the same time relying on top quality people. Upstream petroleum industry has performed wonders until today and all of this has been achieved through people and excellent team work. The extra challenges the industry will be facing make the demand even stronger for ever more coordinated and multidisciplinary work and with extra focus on innovations.

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