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Technological Developments in Utilizing Unconventional Resources of Oil and Gas

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Abstract

Unconventional resources (tight gas, shale gas and shale oil) are defined as conventional oil and gas trapped in shale, sandstones, siltstones and carbonates where the permeability of the host rocks are sub 0.1 milliDarcy (mD). Unconventional gas resources, particularly shale gas, have become an important source of resource growth in North America and select European countries. The oil and gas industry, particularly in the US and Canada, has undergone a renaissance brought on by extracting oil and gas from ultralow permeability reservoirs. These developments have been made possible through horizontal drilling, hydraulic fracturing and an evolution in completion technologies. Hydraulic fracturing in particular has been the key technique that has enabled economic production of gas and oil from shale. Recent advances in engineering designs by completion engineers are improving stimulation effectiveness and hence well production in unconventional reservoirs. Through the use of technology, American and Canadian oil and gas operators are converting previously uneconomic oil and gas resources, which accounted for a significant portion into proved reserves and production. The goal of this paper is to review and explain some of the technologies involved in shale gas and shale oil production. Future of unconventional resources in the Arab countries is demonstrated.

Unconventional reservoirs provide special challenges because they are heterogeneous reservoirs composed of highly stratified sometimes generally thin sediments. Staying within a reservoir zone during horizontal drilling is a difficult task. Consequently, the wellbore intersects variable lithology, which exhibit dissimilar petrophysical and mechanical properties. Unconventional reservoirs are also anisotropic and naturally fractured. Shale possesses layering and this layering causes rock properties, such as permeability, elastic moduli and electrical resistivity to be anisotropic. Natural fracture may cut across this layering and superimpose additional anisotropy on the shale. Both natural fractures and anisotropy complicate the propagation of hydraulic fracturing which is the main process to exploit unconventional resources.

Exploration and exploitation of unconventional resources is not an easy task particularly in the Arab countries. It is an expensive operation and requires technology in drilling, high pressure/high temperature drilling and hydraulic fracturing with advanced completion technology as well as trained manpower. Furthermore, hydraulic fracturing requires a vast amount of water which can be a challenging obstacle for a majority of the Arab countries.

Introduction

Unconventional resources are defined as conventional oil and gas resources trapped in shale, sandstones, siltstones and carbonates where the permeability of the host rocks are sub 0.1 milliDarcy (mD). Unconventional resources consist of shale gas, shale oil, tight gas, coalbed methane and gas hydrates (Figures 1 and 2). This report will concentrate on unconventional resources of shale gas and shale oil. The objectives of this presentation are to review the history and the reasons behind the shale gas/oil boom in the U.S. and to review the advances in technology in the exploitation of such resources and finally whether or not such technological advances can be implemented in Arab countries to exploit its huge unconventional resources. Economically extracting oil and gas from shale requires two important technologies: A. Horizontal drilling and B. Multi-stage hydraulic fracturing. The latter is the key technique that enabled the economic production of natural gas and/or oil from shale. This technique effectively cracks the shale along several planes in a horizontal leg and ultimately exposes the horizontal wellbore to a high surface area compared to that of a single, vertical wellbore.

Historical Background of Shale Gas in the United States

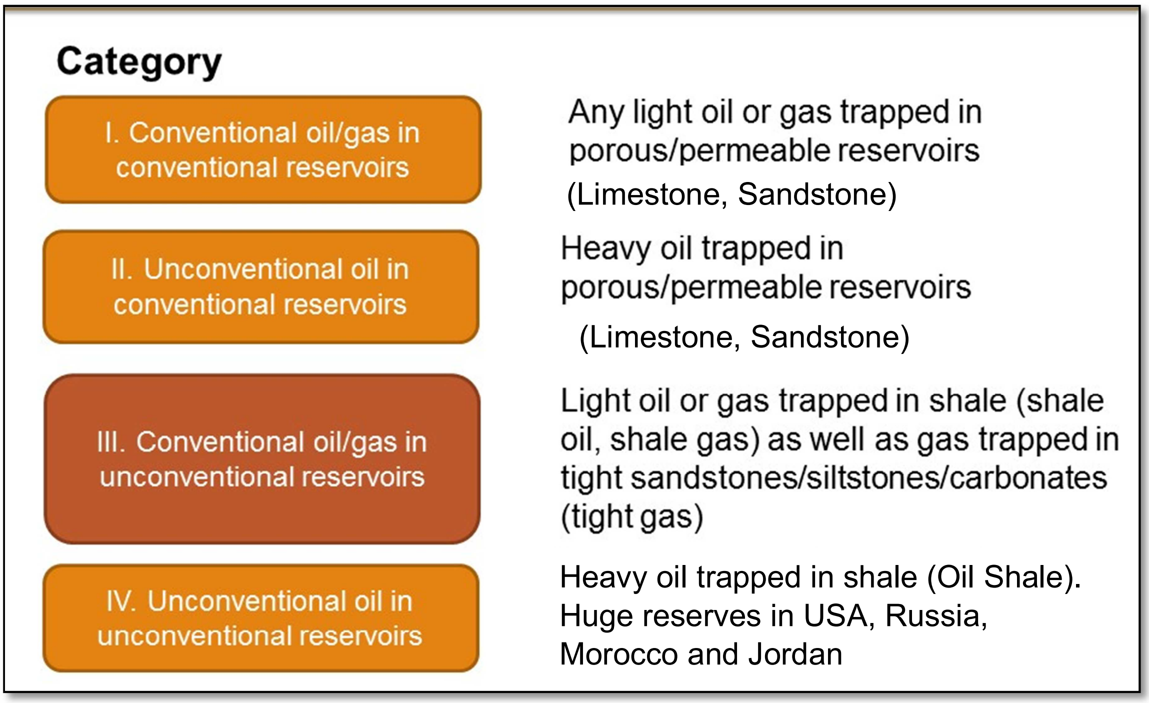

Figure 1 – Definitions of Conventional and Unconventional Resources

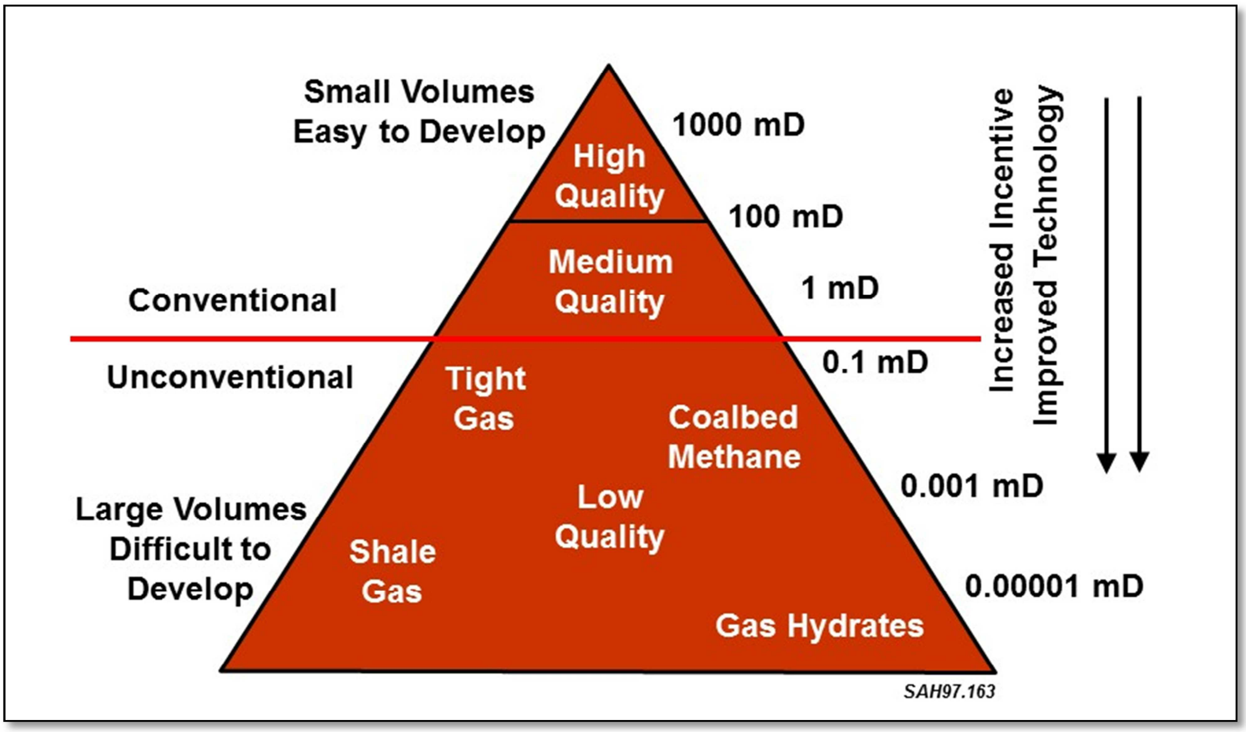

Figure 2: The Gas Resource Triangle

The global unconventional shale (oil and gas) boom is one of the biggest technology breakthroughs in decades. Starting in Texas, USA in the late 1990s, natural gas prices were climbing and geologists and engineers knew that shale contained vast volumes of natural gas (Figure 3). Due to the low permeability nature of shale, geologists were very aware that this vast amount was "residual" in shale which was not migrated to reservoirs. Independent oil companies in Texas attempted to crack open the shale (as a reservoir) through vertical wells and to release the gas by injecting sand, water, and chemical into the rock – a process known as hydraulic fracturing or "fracking". However, such process was not profitable. Then, an Independent oil man in Texas by the name of George Mitchell, while wildcatting in the Barnett shale formation began to break the code and started the innovation of drilling horizontally into the shale exposing thousands of feet of gas bearing shale rather than tens of feet of shale units. Furthermore, horizontal drilling provides more exposure to the formation than vertical well. This increase in reservoir (shale) exposure, creates a number of advantages over vertical well drilling. For example, six to eight horizontal wells drilled from only one pad can access the same reservoirs volume as sixteen vertical wells. Using multi-well pads can also significantly reduce the overall numbers of well pads, access roads, pipeline routes and production facilities required, thus minimizing impact to the public and the overall environmental footprint.

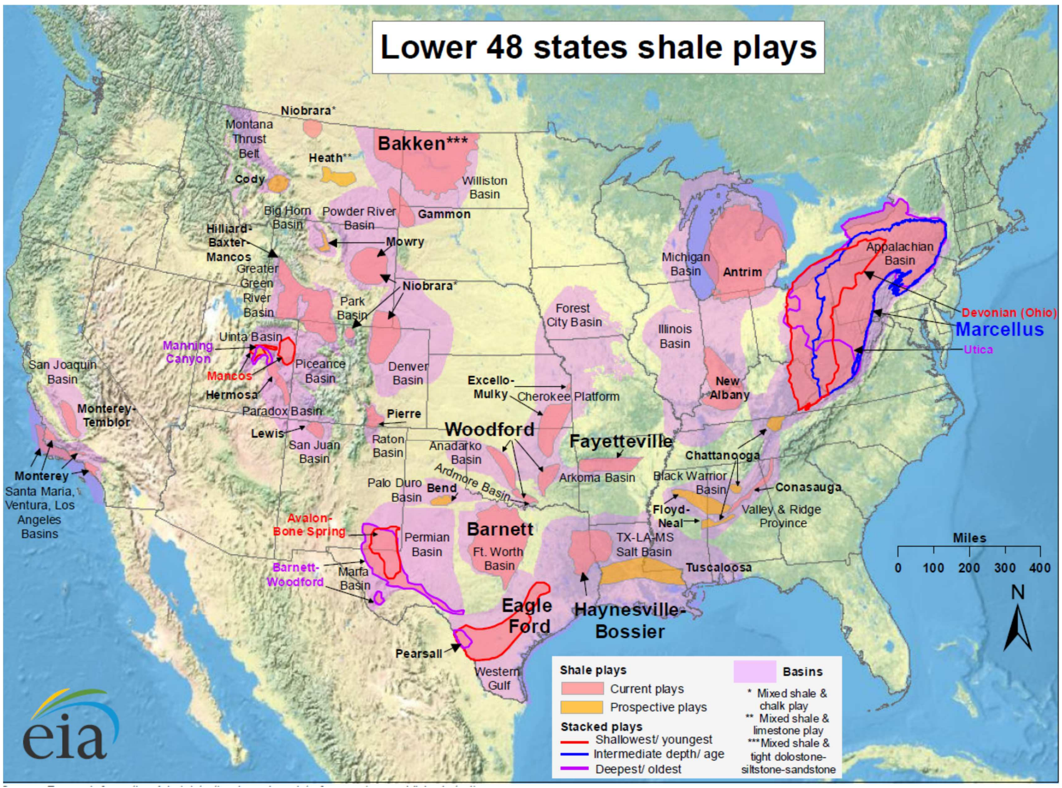

Figure 3 - Shale Oil and Gas Plays in the US

In 2002, Devon Energy, bought Mitchell's company and developed more innovation necessary to exploit the Barnett shale formation. Several other independent oil companies joined in, thus starting the U.S. shale boom. Eventually, giant multinational companies such as ExxonMobil, BP, Shell etc. participated in the boom. Today, United States has surpassed Russia as the world's largest natural gas producer. Not only did the independent companies transform the natural gas industry, but also did the same with oil. The new gas supply caused the price of U.S. natural gas to drop from a high of about $13.50 per thousand cubic feet in 2008 to around $3-4 in 2009. With the high price of oil (around $100 per barrel) and low gas price, companies started to apply the technologies they had successfully developed for gas to extract oil from shale formations with impressive results.

According to International Energy Agency, the United States will soon surpass Russia as the world's second biggest oil producer by the end of this decade and it may surpass Saudi Arabia in becoming the world's largest producer.

None of the exploitation of shale gas and shale oil could have happened without the United States' legal framework. Only in the U.S., and substantially smaller parts of Canada, do landowners have the rights not only to the surface of their property but also to everything below the surface. Accordingly, in the United States any company can strike a deal with a willing landowner to lease the rights to the oil and gas under his land and start drilling. Since the shale boom started, over a decade ago, companies have drilled about 150,000 horizontal wells in the U.S. exposing hundreds of thousands of miles of shale, while the rest of the world drilled only hundreds of horizontal wells in shale.

Furthermore, horizontal drilling provides more exposure to the huge numbers of horizontal wells with hydraulic fracturing allowing continuous experimentation of technologies and hence cost savings. In other words, an enormous numbers of wells have been refined from cost-effective horizontal drilling and hydraulic fracturing technologies. These two processes, along with the implementation of protective environmental management practices, have allowed shale gas development to move into areas that previously would have been inaccessible within the United States. Among the other countries that have huge shale gas/oil are China (double the reserves of the U.S.) and Russia. It is unlikely that other countries can catch up to the United States in shale oil/gas exploitation. Simply, drilling shale gas/oil wells require huge amount of investment and logistics (high numbers of operators and service companies to conduct drilling and sophisticated completions)

Shale Characteristics

Oil and gas is generated within shale, clay and marls, which is often referred to as source rock. Source rocks are normally high in organic materials. Through time, pressure and heat, the degraded organic matter is converted into hydrocarbons, eventually expelled into a reservoir rock. However, oil and gas still be partly trapped in shale through: 1. between the pore spaces, 2. in-fracture spacing, or 3. Adsorbed in the kerogen (organic material). The best quality shale acts as the source rock, seal and even as reservoir rock. Usually, the pore size spacing (permeability) within shale are below 0.1 milliDarcy (mD).

Kerogen Type of Shale:

Source rocks are defined by the type of kerogen or organic material they contain. Under enough pressure, heat and time, kerogen will eventually transform into oil and/or gas. The concept of which shale generates oil or gas is the function of the kerogen type in shale:

1. Type I kerogen is defined by the ratio of atomic hydrogen to carbon (H/C) being greater than 1.4. This kerogen type has a tendency to produce oil.
2. Type II kerogen is defined by the ratio of atomic hydrogen to carbon (H/C) being between 1.2-1.4. This type has a tendency to produce oil and gas. Usually, Type I and II kerogen make for good oil source rocks.
3. Type III kerogen is defined by ratio of atomic hydrogen to carbon (H/C) being less than 1.0. This type has a tendency to produce gas only. Type III kerogen make for good gas resource rocks.

Maturity of Shale:

Maturity is a reference to the amount of thermal alteration the shale rock has been subjected to. Thermal maturity is the degree of alteration of the organic material within the shale. It is a function of burial history of the shale which is determined primarily by pressure, temperature and time. Immature shale has not had sufficient thermal maturity to have generated hydrocarbons. Immature shale can be damaged by drilling fluid and are often more ductile because of the existence of particular clay type in the shale.

Shale Evaluation:

Not all shale is created equal or uniformly prospective for gas or oil. Productive capability is dependent on geochemical, petrophysical, geological, mineralogical and economic factors. The first step in evaluating a shale prospect is to drill, core, and analyze the rock samples displayed in the cuttings. With abundance of technical information on the quality of a source rock/shale, the most important factors to evaluate shale are:

1. **Total Organic Content (TOC) – wt%:** represents the total concentration of organic material in the source rock. Note

that the higher TOC the better quality of kerogen or a higher potential of generating hydrocarbon. A TOC greater than 2 is considered positive for oil or gas shale systems.

2. **Remaining Hydrocarbon Potential (S2):** is calculated through a Rock-Eval pyrolysis procedure that heats a rock sample in an inert environment while measuring the volatilization and cracking of the kerogen. A high S2 unit suggests a higher potential for hydrocarbons to be stored in the rock. S2 Plotted against TOC will provide clues into whether the shale or the source rock contains a Type I, II, or III kerogen.
3. **Tmax:** is calculated via a Rock-Eval pyrolysis analysis. Tmax is an indication of the maturation stage of the kerogen. A Tmax of 430-455 degree C suggests that the source rock likely falls in the oil or 'mature' window. At Tmax less than 430 degree C, the source rock is likely 'immature' which means it is currently composed of non-producible organic matter. At a Tmax greater than 455 degree C means 'overmature' or gas window.
4. **Vitrinite Reflection (Ro):** is equivalent to Tmax in that it also measures the thermal maturity of the source rock. Less than a 0.6% Ro suggests the source rock is immature. Between 0.6-1.0 percent Ro suggests that the kerogen is likely falls within the oil window. While a 1.0-1.4% Ro suggests a condensate-wet gas window. Finally, a Ro greater than 1.4% suggests the source rock is likely within the dry gas window.
5. **Hydrogen Index (HI):** is the ratio of hydrocarbon to organic carbon (mg hydrocarbon/g organic carbon) in the rock i.e. the ratio of S2 to TOC. If HI is between 200-375 is considered to be a Type II or III kerogen meaning the source rock is either oil and/or gas prone. If HI is greater than 375 it tends to be a Type I and II kerogen indicating an oil prone window.
6. **Mineralogy:** is a function of the original constitutes that make up the rock and the digenetic alteration of these same components. Note that more mature shale contains more non-expanding clay (illite). This combined with high silica content suggest the rock can be effectively fracture stimulated.
7. **Silica content (%):** is a parameter used to determine the brittleness of rock. The higher this value, the more brittle the rock and hence it is more amenable to multi-stage fracture stimulation. It has to be pointed out that too high silica content could potentially result in pore throats being restricted or blocked.
8. **Clay Content (%):** On the opposite end of the spectrum, shale with low silica contents will likely see correspondingly higher clay or carbonate content. Clay is more flexible and therefore more resistant to fracture propagation. Accordingly, higher clay content is not desired as a reservoir characteristic.
9. **Other Considerations:** Along with the geochemical, petrophysical, and mineralogical parameters, it is also important to consider the pressure, temperature and depth of the reservoir and how it plays into the production, drilling and completion design.

Horizontal Drilling

To extract gas from shale efficiently and economically, drilling must be horizontal to expose thousands of feet of shale units. This is done by drilling vertically downward until the drill bit reaches a distance around 900 feet from the target shale unit. At this point, a directional drill is used to create a gradual 90 degree curve, so that the wellbore becomes horizontal as it reaches optimal depth within the shale. The wellbore then follows the shale formation horizontally for 5,000 feet or more (Figure 4). Multiple horizontal wells accessing different parts of the shale formation can be drilled from single pad.

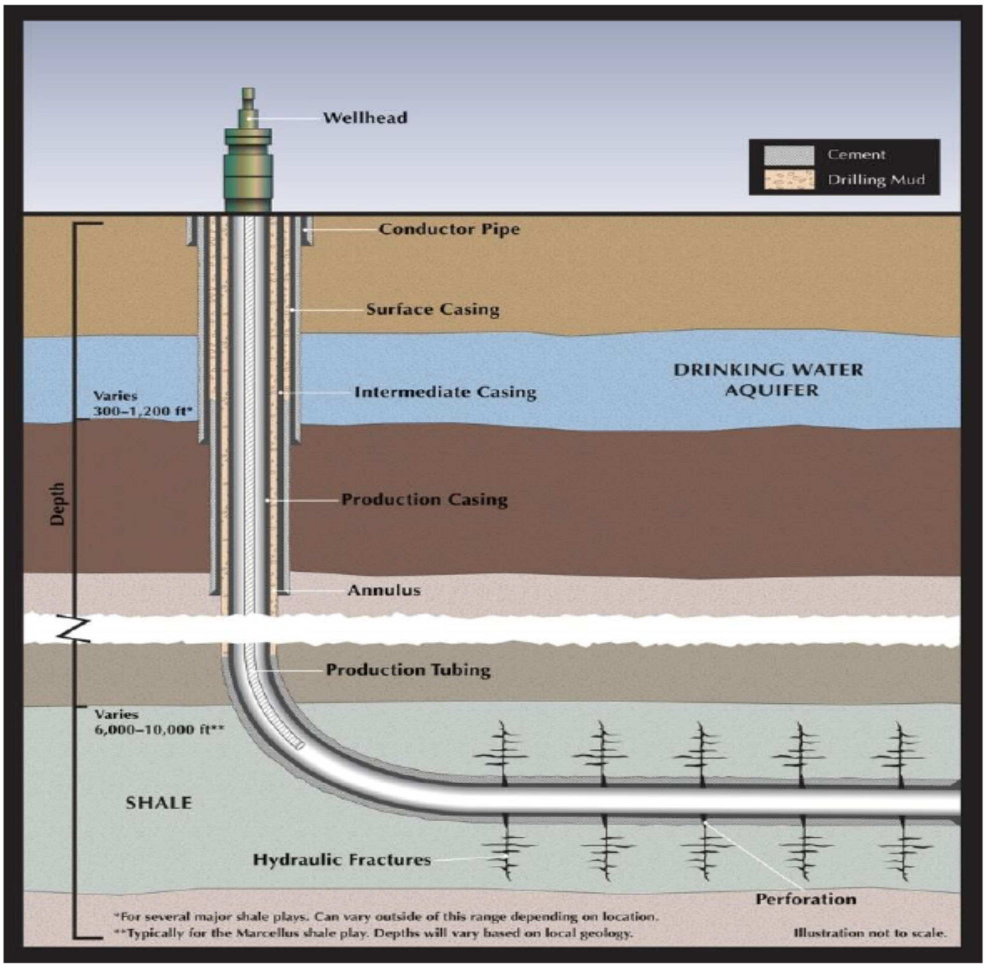

Figure 4 - Multi-Stage Hydraulic Fracturing

Hydraulic Fracturing

Besides horizontal drilling, hydraulic fracturing is the other technological key for economic recovery of shale gas/oil. Hydraulic fracturing techniques have been used to stimulate production in the oil field since 1920s in cased vertical wells. In recent years, these techniques have been developed to allow operators to apply this technology to horizontal well particularly in shale gas/oil resources. It is a formation stimulation practice used to create additional permeability in a producing formation, thus allowing gas or oil to flow more readily toward the wellbore. This process involves typically pumping several millions gallons of a fluid composed of 98-99% water and proppant (usually sand) at high and predetermined rate and pressure into the well to generate fractures or cracks in the target formation. The rest of the fracking fluid (0.5-2% by volume) is composed of a blend of chemicals, often proprietary that enhance the fluid’s properties. These chemicals typically include acids to ‘clean’ the shale to improve gas flow, biocides to prevent organisms from growing and clogging the shale fractures, corrosion and scale inhibitors to protect the integrity of well. The fluid also include gels or gums that add viscosity to the fluid and suspend the proppant and friction reducers that enhance flow and improve the ability of fluid to infiltrate and carry the proppant into small fracture in the shale. Once the fracture has initiated, additional fluids are pumped with high pressure into the wellbore to continue the development of the fracture and to carry the proppant deeper into the formation. The additional fluids are needed to maintain the downhole pressure necessary to accommodate the increasing length of opened fracture in the formation. This fluid pushes through the perforation in the well casing and forces fractures open in the shale i.e. connecting pores and existing fractures and creating a pathway for natural gas to flow back to the wellbore. The proppant lodges in the fractures and keep them open once the pressure is reduced and the fluid flows back out of the well. Approximately 1,000 feet of wellbore is hydraulically fracture at a time, so each well must be hydraulically fractured in multiple stages beginning at the furthest end of the wellbore. Cement plugs isolate each hydraulic fracture stage and must be drilled out to enable the flow of natural gas up the well after all hydraulic fracturing is complete. Once the pressure is released, fluid (called flowback water) flows back out the top of the well. The recovered fluid not only contains the proprietary blend of chemical but also contain chemicals naturally present in the reservoir, including hydrocarbons, salts, minerals, and naturally occurring radioactive materials that leach into the fluid from the shale or result from mixing of the hydraulic fracturing fluid with brine (salty water) already present in the formation. In many cases, flowback water can be reused in subsequent hydraulic fracturing operations depending on the quality of flowback water and the economics of other management alternatives. Flowback water that is not reused is managed through disposal.

Fracture Design:

The process of designing hydraulic fracture treatments involves identifying properties of the target formation including fracture pressure and desired length of fractures. The current formation stimulation practices are sophisticated and advanced engineering processes designed to emplace fracture networks in specific rock units. Every rock units require certain specific design that suits the characteristic of that particular shale unit (thickness of shale, rock properties etc.). Mechanical rock properties include: Young's modulus; Poisson's ratio; and tensile strength. Understanding the in-situ reservoir conditions and their dynamics is critical to successful stimulations. Fracture designs are continually refined to optimize fracture network and maximize gas production. Fracture designs can incorporate many sophisticated and state-of-the art techniques to accomplish effective and highly successful fracture stimulation. Some of these include modeling, microseismic fracture monitoring and tilt-meter analysis.

Recently, Schlumberger engineers analyzed production logs from more than 100 horizontal shale gas well is six U.S. shale basins to identify factors that influence the effectiveness of hydraulic fracture completions. Their analysis showed that increasing the number of fracture stages and decreasing the distance between the stages and between perforation clusters correlated with a rise in production rate from well. Stimulation design is a compromise between the extremes of a single customized fracture stage and of multiple stages to cover a wide variety of rocks. The study showed that increasing the number of perforation clusters and stages is not guarantee for success. The important point is that the fracture stages should target rocks with similar petophysical and rock properties.

Currently, there are a number of commercially available software on reservoir stimulation design. They are for engineering modelling and designing hydraulic stimulation. This software facilitates a systematic strategy for designing multistage stimulation centered on single well to improve production.

Why Shale Gas/Oil Boom in the U.S. and not in the Rest of the World

There are a number of factors that come together in recent years that made shale gas/oil and tight gas production in the U.S. economically viable. Some of these factors are:

1. The legal system framework that allow landowners to have the rights not only to the surface of their property but also to everything below the surface.
2. Advances in horizontal drilling efficiency and hence decreasing in the cost.
3. Advances in hydraulic fracturing and completion technology.
4. A large existing amount of well control from historical production. There are 4 million drilled wells in the U.S. compared to 1.5 million drilled wells in the rest of the world.
5. Tax and royalty incentives from the government (federal and state) to the operators.
6. Existing a significant number of services companies.
7. Existence of huge number of infrastructure (roads, pipelines, oil and gas facilities etc.).
8. High associated condensate production within the shale paired with robust condensate pricing i.e. Marcellus, Eagle Ford etc. that can make shale gas reservoirs very economic, despite lower prices relative to the mid-2000s.

Environmental Risks with Unconventional Shale Production

The shale gas/oil boom brings changes to the environmental and socio-economic landscapes, particularly in those areas where shale gas development is new activity. There are a number of environmental concerns, a few of them serious, associated with shale gas production. Some of these concerns have held back exploration and development in certain US jurisdictions and other countries. For example, France has banned hydraulic fracturing entirely. Germany has put a de-facto moratorium in place. The main concerns are:

1. Large-scale use of water in hydraulic fracturing inhibits domestic availability and aquatic habituates. The amount of water needed to drill and fracture one horizontal shale gas well ranges from 3-4 million gallons (70,000 to 95,000 barrels) depending on the basin and formation characteristics. Water supply is a major concern of policymakers within the U.S. particularly given heightened competition

between competing industries and shrinking supplies.
2. Hydraulic fluids that contain hazardous chemicals can be released by leaks, faulty well construction. The Environmental Protection Agency of the U.S. has issued various reports linking contamination of residential water sources to nearby hydraulic fracturing. Although some of these studies have been deemed unreliable.
3. After drilling and fracturing of the well is completed, water is produced along with natural gas. Some of this water is returned fracture fluid and some are natural formation water (flowback water). The wastewater contains dissolved chemicals and other contaminants that need treatments before disposal or re-use. Despite the widespread use of fracking in the oil and gas industry in the U.S., many municipal treatment plants are not designed to remove all water constituents associated with shale gas/oil extraction. Disposal of wastewater is typically done using deep injection wells, onsite recycling or re-use or it is sent to a facility equipped to process the contaminated water.
4. United States Geological Survey (USGS) has confirmed that hydraulic fracturing can cause small earthquakes and seismic activity (called induced seismicity). Hydraulic fracturing caused small earthquakes, but they are almost always too small to be a safety concern. In addition, fracking fluids and formation waters are returned to the surface. This waste water is frequently disposed of by injection into deep wells. This injection into the subsurface can cause earthquakes that are large enough to be felt and may cause damage.
5. Drilling horizontal wells for shale gas has not introduced any new environmental concerns. On the contrary, the reduced number of horizontal wells needed coupled with the ability to drill multiple wells from a single pad has significantly reduced surface disturbances and associated impact to wildlife, noise and traffic.

Future of Unconventional Resources in Arab Countries

Except Qatar and perhaps Algeria, Arab countries have relatively low proven reserves of conventional natural gas. In particular, Bahrain and Oman have an immediate need for gas for industrial and power use. There are more than 7,000 TCF of unconventional resources (tight gas, shale gas/oil) within Arab countries. Almost all the Arab countries have high demand for natural gas due for similar reasons to Bahrain and Oman - growth in population, industrial, power and petrochemical use. However, development of unconventional resources is an expensive operation and requires technology in drilling and well completion as well as trained man power. As it was demonstrated in the text, hydraulic fracturing requires a vast amount of water which is not easily available in the majority of Arab countries.

Oman, KSA and may be Algeria will be the first countries to exploit unconventional shale gas and tight gas. At present, only Oman has been significantly involved in tight gas production, where BP has already started commercialization of tight gas resources at Kazzan-Makarem gas fields.

The writer does not see in the next five years any commercialization of shale gas in the Arab countries as the case in the North America except in Oman.

In order to start and expedite the development of unconventional resources in potentially higher gas-consuming Arab countries, independent oil companies with extensive practical experience in exploitation of shale gas/oil and tight gas need to be invited to participate in the development. Fiscal terms of contracts need to be improved. Given the cost of the utilized sophisticated techniques, a price of over $4 per thousand cubic feet of gas has to be considered to lure the experienced independent companies.

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