A Vision for Future Upstream Technologies

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Abstract

This paper presents the author's vision of the most influential technologies for the next 2 decades. Unabated global demand for energy will translate into growing demand for traditional hydrocarbon resources. This growing demand represents a significant challenge to which the industry must respond. Several companies have announced ambitious expansion plans for the next several years. However, demand growth is expected to be a long-term phenomenon, for which new technologies must be developed to increase the effectiveness by which hydrocarbon resources are found, developed, and produced.

The paper briefly reviews technologies that the author considers most influential in the past decades, namely 3D-seismic data, horizontal drilling, and geosteering. Each of these technologies has had a profound effect on the industry, emerging from humble beginnings to mainstream applications. Next, the author discusses his vision of the potentially most influential future technologies. These technologies include extreme-reservoir-contact wells, smart inflow-control devices, autonomous fields, passive-seismic monitoring, gigacell simulation, smart fluids, bionic wells, and nanorobots. Though most of these are just dreams, significant strides that have been made to achieve them are highlighted.

Challenges of the Future

The oil industry, especially the upstream sector, has received much attention lately. Some attention has been positive, and some not so positive. This attention stems from many factors, including the rising global demand for energy in general (oil in particular). The world currently has a high demand for energy (Energy Information Administration, 2005), and the demand is anticipated to increase over the next few decades by 2–3% annually (Energy Information Administration, 2006). As **Fig. 1** shows, the world's energy usage is expected to increase by approximately 50% in the next 20 years.

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Although the supply from alternative sources of energy (e.g., nuclear and renewable energy) is increasing, the increase is expected to be small. Though estimates of future growth vary, the consensus is that the main role of these alternative energy sources, at least for the next 2 decades, will be to complement and supplement—rather than replace—the use of hydrocarbons. Therefore, most of the increase in the world's energy demand will have to be met with traditional hydrocarbon sources such as oil and gas, which will continue to dominate the energy market. Meeting this demand will be a challenge.

However, the rising global demand for oil is not the only challenge ahead of us. This rise in demand is coupled with decreasing supplies from some areas of the world, including the North Sea. Additional challenges include increasing geopolitical tension in several places around the world that are critical to the supply of oil; public misconceptions about the future of oil, fueled by misleading reports that tend to mix science with fiction; general confusion about alternative sources of energy and their role and timing in key sectors such as transportation; and unprecedented levels of public concern about the environment and climate change.

Meeting the Challenges

Oil companies must intensify efforts to meet the global demand. Huge capital investments are being made throughout the oil industry. For example, Saudi Aramco has committed to increasing its sustained production capacity by 20%, reaching 12 million B/D by year-end 2009; ExxonMobil quoted spending USD 82 billion during the past 5 years, and a larger capital program is planned for the next few years (Tillerson 2007); and Petrobras quoted a current business plan of USD 87 billion (Formigli 2007). Other companies have mentioned similarly large numbers. Therefore, significant added capacity is expected during the next few years.

However, these expansion programs address only the medium-term increase in demand, whereas the growth in demand is expected to be a long-term phenomenon (Fig. 1). Hence, the world is going to need more than just incremental expansion in supply; it is going to need a significant increase

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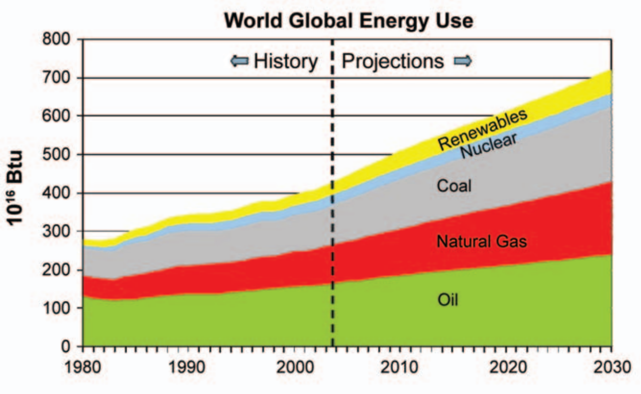

Fig. 1—History and projections for global energy use [Energy Information Administration (2006)].

in the effectiveness by which new oil resources are found and by which these resources are developed. I cite, by way of an example, Saudi Aramco, which has announced ambitious long-term targets to cope with the rise in demand.

Resources of Saudi Aramco were 722 billion bbl of discovered oil at year-end 2006 [in this paper, the term resources will refer to the oil initially in place (OIIP)]. Not all of these resources are recoverable with current technology, and some have already been produced. Some 109 billion bbl (15% OIIP) has been produced during the company's 75-year history. The 260 billion bbl of currently recoverable reserves represent approximately one-fourth of the total conventional reserves worldwide.

The goal of discovery (exploration) is to increase the discovered resources. Saudi Aramco has set a target of increasing its discovered oil resources by 25% over the next 20 years. The goal of recovery is not to increase the total size of the resources, but to get the most out of them—in other words, to convert more of the resources into reserves. The company has set a goal of increasing recovery by an incremental 20% in its major producing fields in the next 20 years by use of both improved conventional recovery and enhanced oil recovery, thus improving the recovery in many fields to as high as 70%. Meeting this goal translates to approximately 80 billion bbl of additional proven oil reserves, given today's resources, or roughly 25 years at current production levels. Achieving these targets will be facilitated by development and application of new technologies, which is the subject of this paper.

Most-Influential Technologies of the Past

It is the author's view that three technologies played a substantial role in the discovery and development of conventional resources during the past few decades. These technologies are 3D-seismic data, horizontal drilling, and geosteering. Others have their own preference regarding the most-influential technologies, influenced to some extent by the challenges they face. The technologies cited here are those especially applicable to conventional resources of the Middle East, rather than unconventional resources, or production environments common elsewhere (i.e., deep sea, Arctic, and others). With an expanded scope, one could add other influential technologies as well, such as deepwater drilling and heavy-oil production.

3D-Seismic Data. The use of seismic data began in the 1920s with refraction surveys. Reflection surveys became more popular in subsequent decades, culminating with the advent of 3D-seismic acquisition in the 1970s, facilitated by advances in computer technologies (Bednar 2006). The use of 3D-seismic data revolutionized the way resources are found and developed. These data facilitated many new play concepts and propelled the use of seismic interpretation from structural investigations to full stratigraphic interpretation that transcends the limited structural analysis into characterizing the quality of the reservoir. Today, 3D-seismic acquisition, by various methods, forms the backbone of reservoir characterization and field development around the world.

Horizontal Drilling. The roots of horizontal drilling go back to 1891, when John Smalley Campbell was granted a patent for the use of flexible shafts to rotate drilling bits. The US Department of Energy credits the first "true horizontal well" to a well drilled in Texon, Texas, in 1929 (Energy Information Administration 1993). During the 1950s, the Soviet Union drilled 43 horizontal wells but concluded they were uneconomical despite being feasible to drill. In the mid-1960s, the Chinese drilled two horizontal wells but likewise concluded that they were not economical.

In the 1980s, with the advent of improved downhole drilling motors and other supporting equipment, horizontal drilling became an economic reality, with pilot projects by Elf Aquitaine at Italy's Rospo Mare Field in 1982; BP and Arco at Prudhoe Bay in 1984; and Oryx, Mobil, Amoco, and Union Pacific in the Texas Austin chalk trend (Shelkholeslami et al. 1991). This use increased by more than 1,000% over the next decade, to the point that some companies now require management's prior approval to drill vertical wells. In Saudi Aramco, the giant Shaybah field was held in inventory for nearly 30 years, until its development in the 1990s became attractive (relative to other field-development opportunities) with the advent of horizontal drilling. It was the first field that the company developed exclusively by use of horizontal wells.

Geosteering. Since the 1980s, it has been possible to navigate (geosteer) the drill bit by use of two-way communication (through the mud system in most cases) to place the bit at the desired location within a geological zone. The drilling assembly is packed with sensors and electronics to measure the petrophysical properties of the rocks, in addition to the orientation and location of the bit. Geosteering has facilitated placing horizontal wells very accurately in very thin beds (e.g., keeping the well within a 10-ft interval for several thousand feet at a depth of more than 15,000 ft is now routine). The use of geosteering has made horizontal drilling much more effective. In many companies, every horizontal section of every well is geosteered, often from a central geosteering hub.

Most-Influential Technologies of the Future

The following eight technologies show promise as most influential over the next 2 decades. For the most part, these

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Fig. 2—MRC wells will give way to extreme-reservoir-contact wells. Right: Wireless telemetry will allow an unlimited number of smart laterals and an unlimited number of valves per lateral.

technologies represent dreams at the moment, at least partly. However, it is only through dreams that the goals of the future can be achieved.

The author believes it is a principal role of oil companies to create the dreams—a vision for the future—and then to collaborate with research centers, service companies, academia, other oil companies, and others to achieve these dreams. However, it is not enough just to have dreams. Two points are emphasized: Dreams must be well defined, otherwise they do not form a solid basis for meaningful collaboration for achievement; and we must start pursuing these dreams, because having dreams without pursuing them is fruitless. Therefore, in describing these technologies, the status of their pursuit is included, frequently citing examples from Saudi Aramco by way of illustration.

Extreme-Reservoir-Contact Wells. Maximum-reservoir-contact (MRC) describes smart multilateral wells that encounter more than 3 miles of the reservoir through branches (laterals) from the main wellbore. Such wells became very popular and very effective in draining the reservoir, especially because the increase in the number of laterals leads to a significant increase in productivity, assuming the laterals are properly designed to optimize drainage. This increase is particularly important for tighter, more-heterogeneous reservoirs. The recent Haradh III field of Saudi Aramco, for example, relied exclusively on such wells to produce 300,000 B/D from 32 smart MRC wells.

However, the difficulty with these wells is that there is a limit of only a few smart laterals per well because mechanical control lines to the wellhead are required for each lateral. In the future, smart wells will have a large number of laterals to optimize drainage and access difficult isolated stringers. Replacing hydraulic lines with wireless telemetry to control downhole valves, a goal currently pursued, will eliminate the need for mechanical control lines in these wells. A downhole control module sends wireless commands to every control valve, which would eliminate mechanical lines and would, therefore, facilitate a theoretically unlimited number of smart laterals as well as an unlimited number of valves within each lateral **(Fig. 2).** Power will be provided to these valves from a rechargeable battery that can be trickle-charged from the energy provided from the flow of the fluids.

Wireless telemetry will enhance many applications, including permanent downhole monitoring, because downhole "wiring" is becoming increasingly more difficult with the addition of downhole devices. Alternatively, electrically wired control valves can be used. This approach would not require wireless telemetry, but would still need to send power and signals across short distances at the connection between the main bore and each smart lateral (such that all the laterals are powered from the wellhead). This method can be achieved with inductive-coupling technology.

Smart Inflow-Control Devices. Inflow-control devices allow even distribution of flow throughout the horizontal section of a well by introducing additional drawdown in more-prolific sections of the well (achieved by moving the fluid through helical flow paths within the devices). This balanced production profile impedes gas cusping from the gas cap or water coning from the aquifer, thus increasing economic recovery.

However, existing conventional inflow-control devices have no means of adjusting their configuration once deployed in the well and cannot, therefore, respond to changing well conditions. Smart inflow-control devices will add either autonomous adjusting of flow in the device segments according to the gas or water content in the crude, or electric or wireless control of downhole valves attached to each device segment. These solutions are being pursued, and all would allow the inflow-control devices to respond effectively to changing well conditions with time and to errors in estimating the well-productivity profile before deploying the device.

Intelligent Autonomous Fields. Traditionally, the term intelligent field refers to integrating all relevant field information—including reservoir pressure and temperature, wellhead fluid composition, pipeline flow, and plant information—such that the field is managed in real time through live data feeds. Various forms of this concept are in use through subsurface instrumentation linked to central processing. For example, in the Haradh III field, each well is equipped with a permanent downhole-monitoring system that conveys real-time reservoir data to the surface, where these data are integrated to provide real-time monitoring of the field **(Fig. 3).**

However, future intelligent fields will be much more sophisticated, moving beyond self-monitoring to become fully self-run (i.e., eventually completely autonomous). The field will gather downhole reservoir data, integrate it with

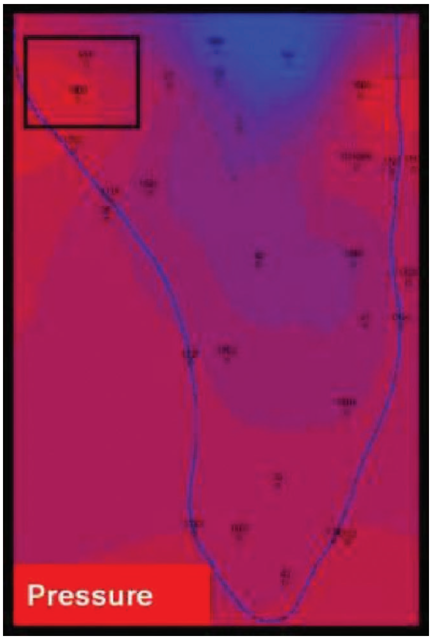

Fig. 3—Real-time reservoir-pressure monitoring in Haradh III identifies anomalies quickly (box).

wellhead information and management, run a simulation of the reservoir in real time, derive the optimal production and injection allocations, and send commands to downhole control valves in every well to implement this self-generated production strategy. The field also will analyze the data constantly in real time for effective data mining and control; for example, it can identify wells with water breakthrough by comparing the downhole and surface pressure and temperature measurements to detect trend anomalies to identify the onset of the flood front. The role of the reservoir engineer in these autonomous fields will be monitoring and oversight rather than intervention and control.

Passive-Seismic Monitoring. Thousands of earthquakes occur frequently that have very faint magnitudes of –1, –2, and lower and have no tangible effect. Their signal can hardly be recorded by normal means. Passive-seismic monitoring involves recording of this faint natural seismicity (sometimes called microseismicity) at the reservoir level to infer the distribution of faults and fractures around the wellbore and thereby map the flow conduits away from the well locations. This monitoring is accomplished without active seismic sources such as vibrators or dynamite **(Fig. 4).**

This approach enables monitoring the reservoir in real time rather than as time-lapsed (as with 4D seismic), and it has the potential of introducing a new method of analyzing and monitoring fluid migration through the reservoir (Dasgupta 2005), pushing the effectiveness of reservoir management to a new plateau. A recent passive-monitoring symposium was oversubscribed, and received attendees from more than 50 countries with applications ranging from fault characterization, to monitoring stimulation jobs, to deducing the effect of production and injection. This technology is in its infancy but is growing at an explosive rate, and it holds promise to revolutionize how seismic data are gathered and exploited.

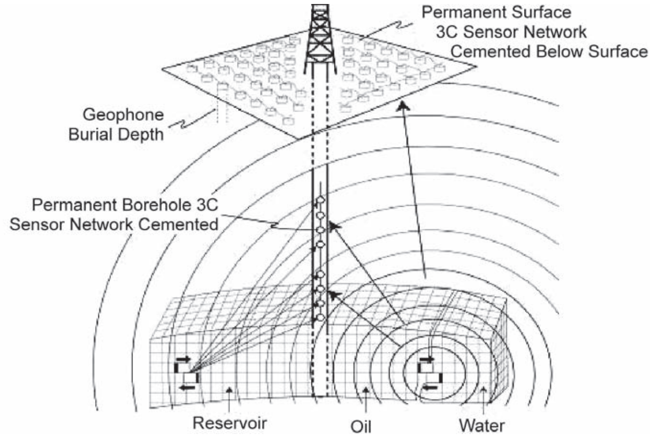

Fig. 4—Saudi Aramco's combined downhole and surface recording of microseismic events in Ghawar.

Gigacell Simulation. The widespread use of 3D-seismic data and sophisticated modeling algorithms has resulted in detailed geologic models that describe reservoir properties in high resolution. However, most of that detail is lost when these models are used for flow simulation because current simulators are incapable of handling a large number of cells. These high-resolution models are first "scaled up" before simulation, in effect severely reducing the resolution by smearing and averaging data in the effort to reduce the number of cells. Future reservoir simulators will be able to simulate giant fields [even the mammoth Ghawar field, which extends more than 280×26 km **(Fig. 5)**] in high resolution by use of the geologic models directly without scaling up. To achieve this goal, reservoir simulators must be capable of handling many more cells than is possible currently, and they need to move from the megacell models (tens to hundreds of millions of cells) to gigacell models (billions of cells).

Several efforts in pursuit of this dream are under way. For example, Saudi Aramco routinely runs simulation models having 30 to 40 million cells through its in-house-developed simulator (Dogru et al. 2002). However, the next generations of simulators will handle much larger models. Prototype runs in Saudi Aramco recently achieved successful testing of its algorithms on a 258-million-cell full-field Ghawar model. That model simulated 60 years of history and required approximately 1 day to run on a cluster of commonly available PCs. Initial results indicate that the more-refined 258-million-cell model shows water-cut behavior more in line with the physics and the field data, compared with the results with the old 10-million-cell model. The benefit of simulating the reservoir in higher resolution is tangible. With the hundred-million-cell record established, the billion-cell record will be reached soon.

The increased capacity of these simulators must come from both algorithm novelty and improved hardware. The latter alone is by far insufficient. As shown in **Fig. 6,** an almost-linear

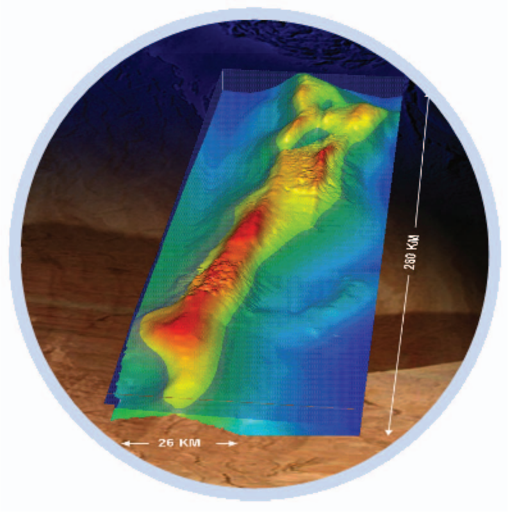

Fig. 5—Ghawar field will require future flow simulators to have models in excess of 1 billion cells to model without scaleup.

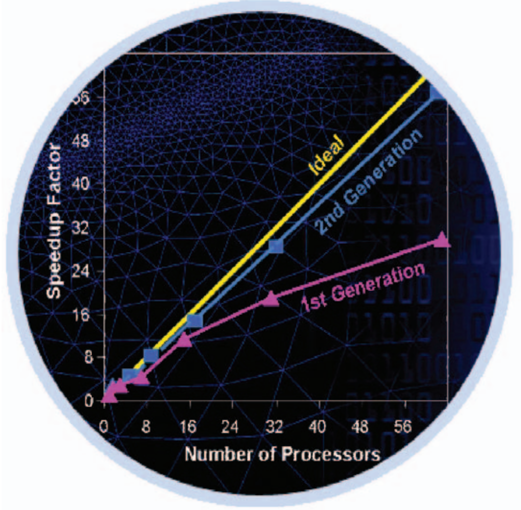

Fig. 6—Algorithm novelty will be required to handle large numbers of cells. Note improvement in scalability between two generations of simulators (nearly linear scalability in the second generation).

scalability would be required to capitalize on the new computer clusters. Innovative visualization techniques also would be required because the volume of data is such that it cannot be visualized effectively with conventional methods. Methods are being tested that allow users not only to see but also to feel the data (by navigating the reservoir through 3D haptic control devices with force-feedback) and hear the data (through smart voice alerts tied to specific events reached by the simulator).

Smart Fluids. Smart fluids are those placed in the reservoir to impart a specific desired behavior (for example, to completely plug watered-out zones while allowing the oil to flow in other zones). At first, they will be used to change the near-wellbore regions, but eventually they will be deployed deeper into the reservoir to change its properties on a much larger scale. These fluids will be custom-fit and will impart the desired behavior in the reservoir automatically. In other words, they could be bullheaded into the reservoir and left to their own means to work automatically, without requiring any sophisticated deployment techniques such as zonal isolation and coiled tubing. This technology is progressing, through relative permeability modifiers and smart emulsified gels, although it currently is available only for limited reservoir conditions and with mixed success. As an example, such fluids can hydrate and expand in the presence of water, plugging the pores and preventing water movement, while shedding the water and dehydrating and contracting in the presence of oil, thus allowing the oil to move **(Fig. 7).** Therefore, these fluids can achieve rigless water shutoff just by use of chemicals that reduce the relative permeability of water, blocking its flow in watered-out zones while preserving the oil flow.

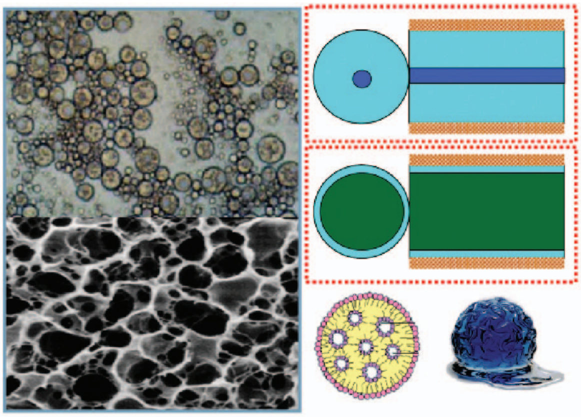

Fig. 7—Smart fluids automatically modify the behavior of the reservoir. Such fluids can hydrate in the presence of water (top left) and dehydrate with oil (lower left).

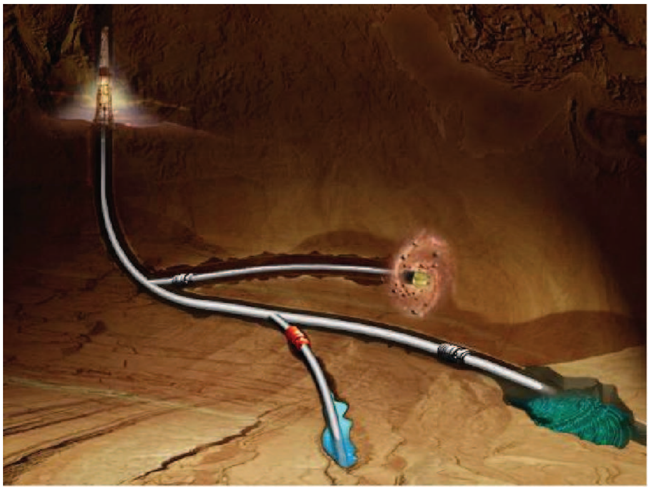

Fig. 8—Bionic wells will act like tree roots, automatically growing and pruning their laterals.

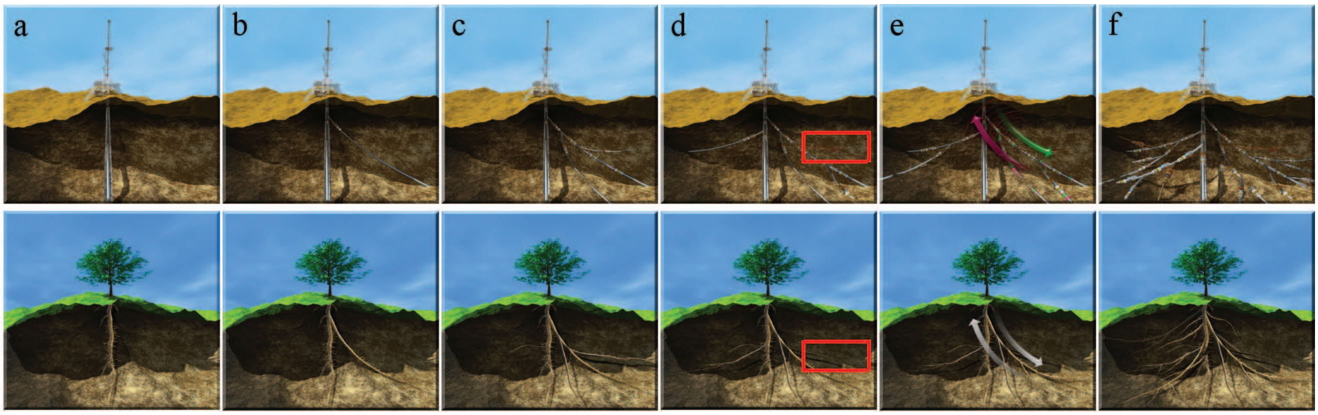

Fig. 9—A bionic well (top) acts like a root of a tree (bottom) and evolves from a simple vertical well (a) to a horizontal well (b) to a multilateral (c) adding the ability to cut off certain branches (d) and the ability to analyze and communicate flow and fluid information to the surface (e) and, ultimately, having many smart branches like a real root of a tree (f).

Bionic Wells. Wells of the future could be like plants. These wells would not be drilled; they would be planted. A tree root seeks a wet area in the soil, extending a branch of the root to that zone, then cuts off that branch once that area dries up, growing another branch to a different area, and so forth. Bionic wells would act similarly (but would follow the oil rather than the water). Once the vertical segment of the well was drilled (planting the well), the well would be "left to its own means." A smart lateral would extend to an undrained oil-bearing zone, "cut off" that lateral once the zone waters out, and "extend" another lateral to a different zone, and so on **(Fig. 8).**

Though this concept may seem too futuristic, the industry has achieved much of that dream **(Fig. 9).** Starting with vertical wells (like the root of a simple tree), horizontal wells were drilled (a more sophisticated root), and then multilaterals were drilled (similar to tree roots with several branches). Thereafter, smart downhole-control valves were added that can choke specific laterals and effectively cut off those branches (like a root cuts off one of its branches), then downhole monitoring and surface controls were added that enable analyzing the reservoir-fluid properties and predicting the onset of water (similar to the root deciding when a zone has dried up). All that is reality now. And very complicated (certainly root-like) wells are being pursued, such as the extreme-reservoir-contact well described earlier.

The remaining technology is advancement in drilling that would allow the well to "drill for itself." Admittedly, this goal is not easy, but techniques such as coiled-tubing drilling and drilling by fluid jetting exist, while others such as laser drilling are in research. These wells could have openhole completions, with downhole valves that are viscoelastic rather than mechanical, such that they change their rheology to open or close once they react with a dispatched chemical that is specially coded for the composition of that particular valve.

Reservoir Nanorobots. These robots are 1/100th the diameter of human hair and would be deployed in large numbers with the injected fluids into the reservoir. During their journey, they would analyze reservoir pressure, temperature, and fluid type and store that information in on-board memory. They then would be picked up (at least a small portion of them) from produced fluids to download that information to provide critical data about the reservoir encountered during their journey, thus effectively mapping the reservoir (depending on the size of the field, this journey can take several months). Eventually, real-time communication (perhaps over short hops to downhole telemetry stations) and mobility (powered by charging from the friction with the fluids or from downhole charge stations) also could be added **(Fig. 10).**

Imagine sending these robots ahead of the drilling bit instead of geosteering, or sending them from a discovery well to find the edges of the reservoir and the water contact, eliminating the delineation program. The possibilities are endless. Farfetched perhaps? Not at all. Advances in nanosensor miniaturization are occurring rapidly. Nanotechnology has made significant strides in material and medical applications, but not so in the oil industry. However, efforts are underway to bring these advances into our industry. For example, an SPE Advanced Technology Workshop, "Nanotechnology in Upstream E&P: Nano-Scale Revolutions to Mega-Scale Challenges," was held 3–6 February 2008 for that purpose.

The long journey to achieving functioning nanorobots starts with answering a very simple question: What is the largest-size robot that can go through the reservoir without getting caught in the pore throats? After all, there is no sense in wasting time and money on nanorobots if microrobots can do the job (microrobots can be manufactured now). However, there also is no use in deploying these robots only to then be caught in the pore throats around the wellbore, abruptly halting their journey and possibly damaging the reservoir.

To that end, Saudi Aramco has analyzed 850 core plugs from the Arab-D reservoir in Ghawar and mapped the distribution of the pore-throat sizes. The distribution is bimodal, but the important observation is that most of the pore throats are larger than approximately 500 nm. This,

Fig. 10—Artist's rendition of nanorobots. Future nanorobots may not have this appearance, but will be a reality. The size of a nanorobot (mere speckle) compared to a strand of human hair is shown to the right.

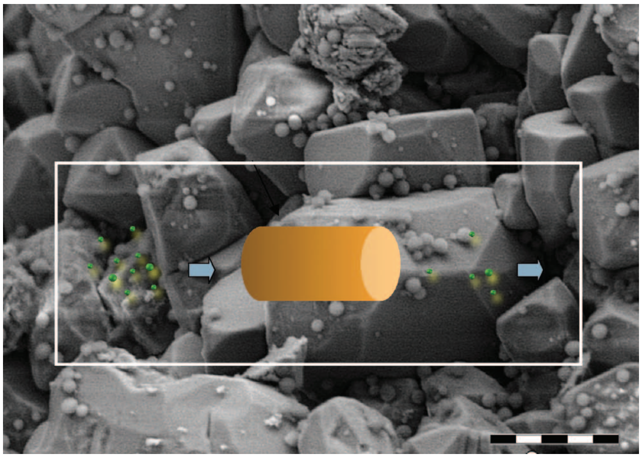

Fig. 11—Experiment attempts to validate empirically the answer to the nanorobot-size question by injecting nanoparticles in core plugs of various pore-throat sizes and comparing in the injected size with the effluent. Background shows actual picture of these nanoparticles between the grains in the experiment.

then, establishes an initial target on which our miniaturization efforts should focus (actually, to avoid bridging, the size of the robots must be approximately one-fourth of this pore-throat size). The next step is to conduct a physical experiment in which nanoparticles (dumb nanorobots) of specific size (using different sizes from this distribution) and at prescribed concentrations are injected into representative Ghawar core plugs. The number of these particles that manage to go through the plug end-to-end and emerge from the other side is counted—such that the size question can be answered empirically. This experiment is being conducted **(Fig. 11).** Likewise, the journey of the nanorobot through the pore structure is being simulated and modeled in software. In other words, the first milestone in the pursuit of the nanorobot dream would be answering the size question in three ways: by observing the pore-throat-size distribution, conducting an empirical experiment of nanoparticle injection, and by software simulation.

Looking Into the Future

The future is laden with challenges. However, it also is evident that the future is full of opportunities. Influential technologies such as 3D seismic and horizontal drilling have shaped the way that oil and gas resources are found and produced. Likewise, new innovative technologies—whether gigacell simulation, bionic wells, nanorobots, or others—will shape the way these resources will be found and produced in the future. In this paper, several dreams are described. However, the journey for each has begun, with fruitful results on the horizon. As stated earlier, it is not enough to dream; one must pursue these dreams.

Of course, it is quite likely that the most influential technologies of tomorrow will be something not yet thought of, and which this paper completely missed. This possibility is an even more exciting prospect.

Acknowledgment

This paper covers several current research topics and endeavors within Saudi Aramco's EXPEC Advanced Research Center, and draws heavily on the collective expertise of researchers in that center, whose contribution is duly acknowledged. The author would also like to thank Saudi Aramco for its permission to publish this paper and the reviewers for their critical input, which enhanced the overall quality of the paper.

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