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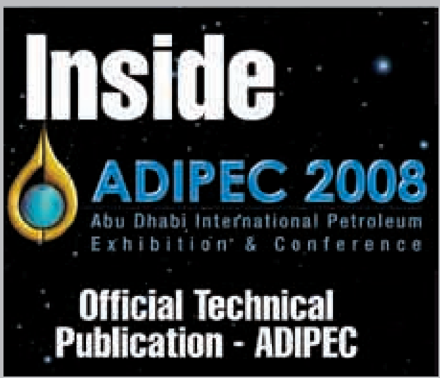

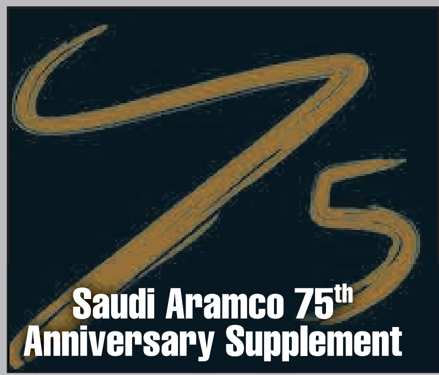

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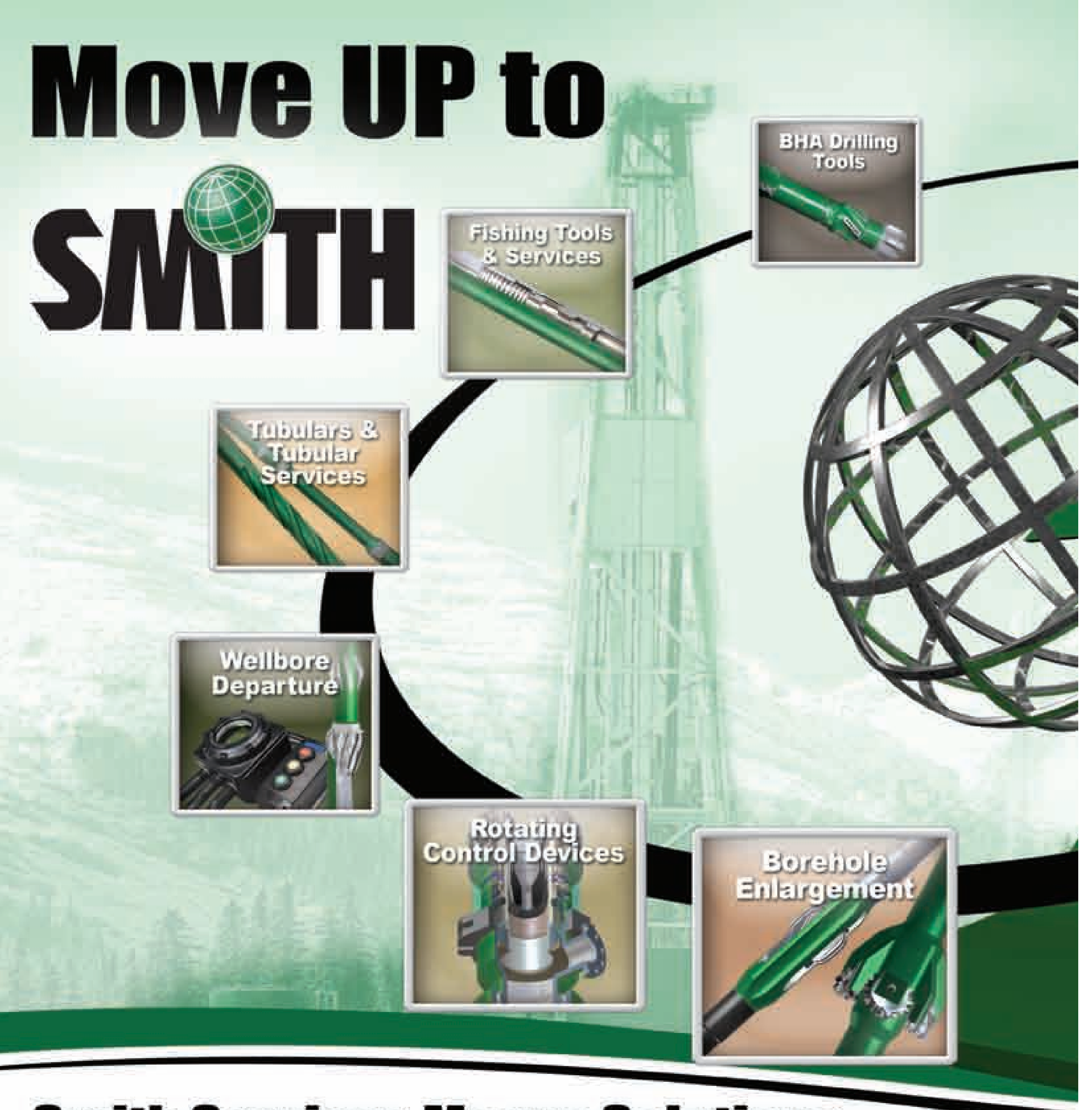
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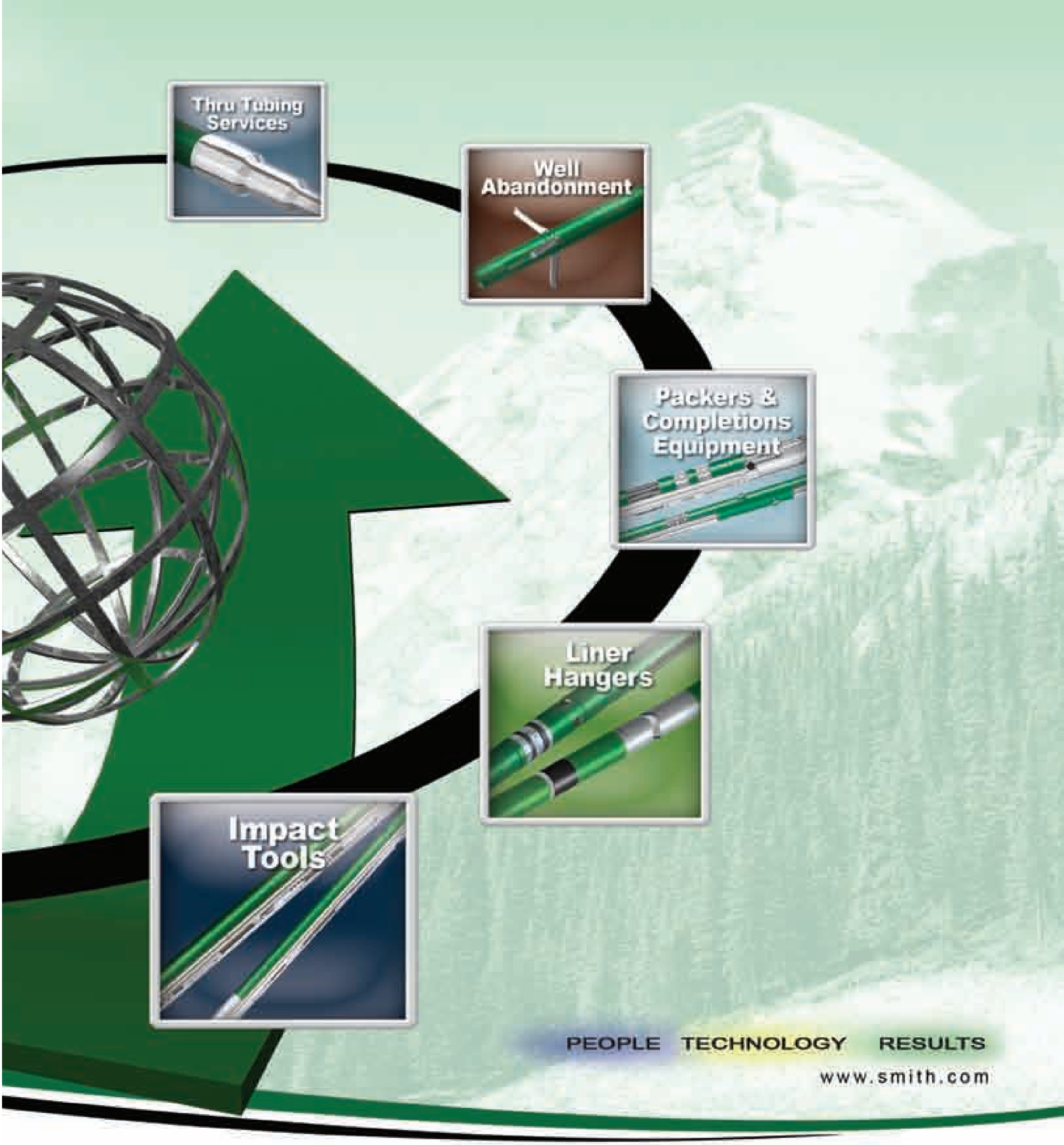

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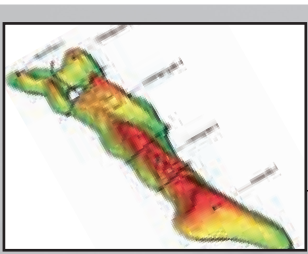

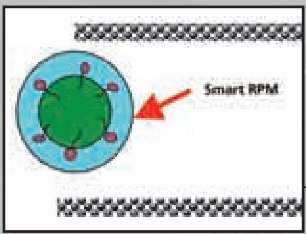

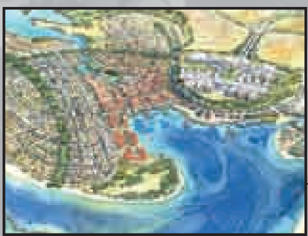

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NOTE FROM THE CEO

Welcome to Issue 8 of Saudi Arabia Oil and Gas and our special Saudi Aramco 75th Anniversary Supplement.

We are privileged and honored to have worked with Saudi Aramco to produce this special supplement focusing on Saudi Aramco's 75th Anniversary.

Thanks to all those folks involved. You know who you are!

Simply entitled '75', the supplement traces the past, present and future of Saudi Aramco and the Kingdom of Saudi Arabia's Oil Industry. Several articles from the supplement are reprinted in this issue. These are 'Pioneer Profiles' – the visionary people that helped build Saudi Arabia's oil industry. A feature on Saudi crude oil and natural gas stemming from Saudi Aramco President and CEO Abdallah S. Jum'ah challenge to the wider oil industry: find enough new resources to add 1 trillion barrels to world reserves over the next 25 years. That challenge began at home and Saudi Aramco is leading the strategic development charge to help ensure reliable energy supplies far into the future. The last article is on the building of KAUST, a $10 billion, worldclass research university that is the brainchild of King Abdullah. The new university, to be located in Thuwal, Saudi Arabia, on the western Red Sea will usher in a new era of scientific discovery benefitting the Kingdom and the entire world.

But back to the present - Issue 8 and our cover story - the Event Solution. This article describes Saudi Aramco's approach to handling uncertainty and risk which lies between the conventional deterministic method where the team agrees on one realization and the probabilistic method where a whole family of realizations is covered.

Catch up with the latest in the respective sections of Saudi Aramco's Newsroom as well as the newly elected DGS executive committee as President Ralph Bridle takes over the reins from Past President Ahmed Otaibi.

Drillers have plenty to read about in the Drilling Optimization section that has a submission from Saudi Aramco on the role of Smart Fluids. Smart fluids are not just any liquid, but fluids whose properties such as viscosity or surface tension can be stimulated to change as and when required. Interesting stuff. There is also an article on Casing and Liner Drilling applications to reduce losses and ease down troublesome casing.

The Formation Evaluation section kicks off with an excellent Saudi Aramco article on the Nuclear Parameters of Arab-D Carbonates for Enhanced Formation Evaluation. In this comprehensive study, 99 Arab-D carbonate samples from different wells in a large Saudi Arabian oil field were used as input. Complementing this is an insightful article on advances in LWD magnetic resonance which shows how logging differentiates between restricted and productive fluids in complex lithologies and increases recovery. Finally, a submission on micro-resistivity logging shows the use, value and importance of borehole images across geological, petrophysical, and geomechanical disciplines.

Reservoir Characterization has a thought provoking article from Saudi Aramco on the subject of Nanotechnology. The article asks - is it feasible to develop intelligent nanorobots – 1/100th the size of human hair that can be deployed into the subsurface reservoirs, via injected wells, as "reservoir prospectors"? Read it and see.

Lastly, 'the Oil Curtain' is an excerpt from my book Hydrocarbon Highway which will be published in March 2009. The Oil Curtain neatly symbolizes resource sovereignty and separates the Hydrocarbon 'haves' from the 'have-nots'. It has led to the major part of proved global oil reserves being booked by National or State Oil Companies. The article asks: what caused such a dramatic reversal in IOC fortune?

We look forward to your editorial contributions – whether conceptual or proven and across EP disciplines. Ultimately, this is what Saudi Arabia Oil & Gas reader's value.

So hit your keyboard and email: wajid.rasheed@eprasheed.com

Enjoy the magazine.

"EPRasheed's aim is to consider global EP Markets in a strategic manner and foster balanced coverage and commentary on the International Oilfield and key EP technologies. Saudi Arabia Oil & Gas intends to help bring together local Saudi experts and international people to remove barriers and promote interaction."

Wajid Rasheed

Founder EPRasheed and Saudi Arabia Oil & Gas

Ghawar's Magnificent 5

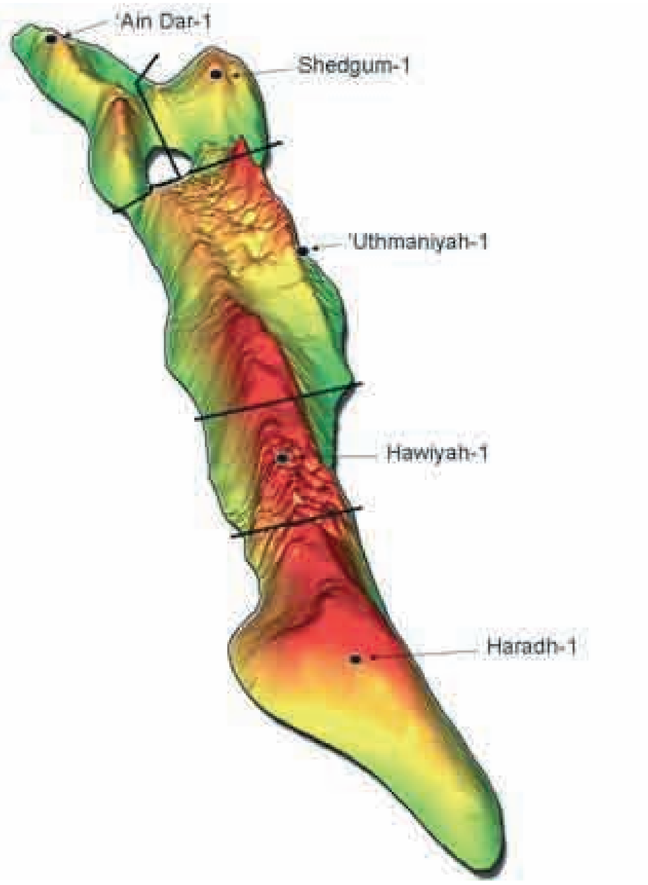
By Darryl B. Fischbuch and Adeyinka X. Soremi

Ghawar remains the world's largest oil field 70 years after its discovery. Its size and continuity were not initially apparent, but a series of early exploration wells, now called the Magnificent Five, put the pieces of the puzzle together.

Amid the important commercial oil discoveries of Dammam (1938), Abu Hadriyah (1940) and Abqaiq (1940), geologists were exploring surface features to get a better picture of the potential of the Eastern Province.

While mapping the surface outcrops, geologists Ernie Berg and Max Steineke excitedly identified a broad, low-relief dome (called an anticline). Subsequent exploration established that this En Nala anticline at Haradh continued northward all the way to Ain Dar and Shedgum and was filled with oil.

Ghawar helped catapult Saudi Arabia into its role as the world's leading oil producer. The super-giant field is 280 kilometers in length and consists of five contiguous oil fields from north to south: Ain Dar, Shedgum, 'Uthmaniyah, Hawiyah and Haradh.



A 3D rendering of the Ghawar reservoir shows the Magnificent 5 discovery wells.

Ain Dar No. 1

After World War II and with the resumption of drilling, the most obvious location to resume wildcat drilling was the Ain Dar structure because of its proximity to producing facilities at Abqaiq. Ain Dar No. 1 was drilled in 1948 and flowed oil to the surface during testing. It was put on production in early 1951 and is still producing today with the original well casings.

This well has been producing for more than 58 years with the aid of best-in-class reservoir management practices. It has produced 152 million barrels of oil and is still producing 2,100 barrels per day (bpd).

Haradh No. 1

In 1949, Aramco engineers initially wanted to drill a step-out well, Ain Dar No. 2, about 12 km to the south of Ain Dar 1. Instead, a second wildcat was drilled 185 km to the south at Haradh. At that time, no one openly suggested that the En Nala anticline would prove to be one continuous field 280 km long and up to 30 km wide. That possibility became very real when the Haradh No. 1 wildcat struck oil in 1949.

The Haradh well was nearly 200 km south of Ain Dar production facilities and, therefore, was not brought onstream until 15 years later. Haradh No. 1 was put in production in 1964 but shut down during the mid-1980s because of low demand. In 1990, after acid stimulation, it resumed production.

Today, 44 years after its first production, Haradh No.1 has produced more than 24 million barrels of oil and continues to produce at a rate of 2,300 bpd.

'Uthmaniyah No. 1

'Uthmaniyah No.1 was important in establishing that the En Nala anticline was oil-filled between Ain Dar and Haradh. This wildcat well was successfully drilled and tested in 1951. As with the other Ghawar wells, oil gravity was in the range of 33 degrees API (Arabian Light Crude).

'Uthmaniyah No. 1 was brought onstream in 1956 and has since produced more than 20 million barrels of oil.

King Saud ibn Abdulaziz inaugurates the gas injection facilities at Ain Dar in 1958.

Located on the eastern flank of ‘Uthmaniyah, close to the water, this well was the first of the discovery wells to employ water shutoff techniques to limit water production.

Shedgum No. 1

The Shedgum No. 1 discovery well was drilled in 1952 to delineate the En Nala anticline to the east of Ain Dar. The well struck oil in the Arab-D carbonate and was later brought onstream in 1954.

In 1968, the wellbore rock matrix was acidized to improve the flow of oil from the carbonate formation. In 1989, liners were run across the open hole to address future water encroachment.

Recently, the oil production rate was enhanced greatly for Shedgum No. 1 by recompleting the well with a horizontal sidetrack complemented with inflow control device (ICD) technology. Not only was the oil rate increased to more than 3,700 bpd, but the water cut has also been lowered significantly.

Shedgum No. 1 has produced more than 98 million barrels of oil over the past 55 years, and the application of new technologies will keep it producing for many years to come.

Hawiyah No. 1

The final discovery well of the magnificent five was Hawiyah No.1, which confirmed that Ghawar held oil between ‘Uthmaniyah and Haradh. Drilling was completed in 1953, and the well was put onstream in 1966, when the Hawiyah Field was developed.

The well received an acid stimulation treatment in 1977. With Saudi Aramco’s superior reservoir management practices, Hawiyah No. 1 has produced 51 million barrels of oil, and continues to produce today at 4,600 bpd.

Reservoir management

Since the discovery of the Ghawar field in 1948, Saudi Aramco has implemented best-in-class reservoir management practices and leading technologies that have evolved over the years. As a result, the Magnificent Five have demonstrated extraordinary performance with extended lifecycles and outstanding oil recovery.

One of the first reservoir management initiatives was gas reinjection in Ain Dar. In 1958, King Saud ibn Abdulaziz inaugurated the gas injection facilities in Ain Dar. The primary purpose of the program was to reinject produced gas to sustain reservoir pressure. Gas injection began in 1959 and continued for 20 years.

Water injection began in Ghawar in 1964 to provide additional pressure support — to maintain reservoir capacity to push oil to the surface. That technology, known as secondary recovery, provided a stepwise improvement in pressure support and began the displacement of oil from the outer edges of the Ghawar field toward the central regions to sustain oil production, as demonstrated by the phenomenal performance of the discovery wells.

In 1995, a comprehensive 3-D seismic campaign was conducted across the Ghawar field. The seismic profiles provided vital information on reservoir structure and distribution of fractures, guiding development and recompletions across Ghawar. That information, for example, was used to guide the placement of the horizontal well trajectory for Shedgum No. 1.

The Ghawar discovery wells, Ain Dar No. 1, Shedgum No. 1, Haradh No. 1 and Hawiyah No. 1 are still producing today with the original well casings. That speaks to the quality of workmanship and materials that went into the original wells.

Altogether, the Magnificent Five have produced nearly 350 million barrels of oil. There’s no telling how much more they will produce — as the end of their story is not yet in sight.

In 1995, a comprehensive 3D seismic campaign was conducted across the Ghawar field. The equipment used is a stark contrast to the early exploration team shown in the left photo.

Saudi Aramco and Total Refinery

The Board of Directors of Saudi Aramco Total Refining and Petrochemical Company approved the appointment of Salim Hamdan Shahin to the position of president and CEO of the company at its first meeting held on September 21 2008 in Manama, Bahrain.

The meeting was presided over by the chairman of the Board of Directors, Dr. Samir A. Al-Tubayyeb, and attended by company directors.

The company also previously announced that it is planning to offer Saudi nationals 25 percent of the company shares in an Inititial Public Offer (IPO), on the premise that the two founding partners will each retain 37.5 percent of the equity.

Saudi Aramco and Total Company of France inked the partnership agreement necessary for the establishment of their joint venture on June 22 2008, in the presence of HE Ali Al-Naimi, Minister of Petroleum and Mineral Resources during the Jiddah Energy Meeting.

These agreements were regarded as a significant step for initiating the construction works of a world class refinery, based in Madinat al-Jubail al-Sina'iyah (Jubail Industrial City) in the Eastern Province of Saudi Arabia, with a refining capacity of 400,000 bpd.

The refinery, scheduled to go on stream by the end of 2012, will process heavy crude oil and convert it into high quality refined products that meet the highest international specifications. Products will include diesel fuel, aircraft fuel, gasoline as well as petrochemical products such as paraxylene, aromatic gasoline and propylene. Saudi Aramco and Total will share the marketing of the refinery products.

The Board of Directors poses for a group photo: Chairman Samir A. Al-Tubayyeb is seated in the center, and president & CEO Salim Shahin is seated on the right.

This important project will allow further expansion and diversification of Saudi Arabia's refining and petrochemical industry infrastructure and creation of more employment opportunities within the Kingdom.

Jubail Industrial City was selected as the site of the refinery due to its proximity to the heavy crude oil supply system and other vital facilities such as King Fahd Industrial Port, the desalination and power plants and the residential area.

75th Anniversary celebrated in Maidenhead, UK

About 100 former Saudi Aramco employees from the United Kingdom congregated Aug. 21-24 to celebrate the company's 75th anniversary. Old friends and acquaintances from Dhahran, Abqaiq, Ras Tanura and 'Udhailiyah greeted each other with open arms, eager to reminisce about their Saudi Aramco experiences.

By Juvie de Koning

Thomas Henderson organized the first British Aramcons Reunion last year in Nottingham, where he announced this year's reunion as a commemoration of Saudi Aramco's 75th anniversary. Since then, Henderson, with his wife, Eileen, and a couple of friends, have worked continuously to make the reunion a success.

Like last year, Aramco Overseas Co. (AOC) sponsored the event and provided on-site support through its public relations team. Martin Wingrove, AOC Oil Spill Response coordinator, represented AOC on behalf of managing director Ahmed M. Alzayyat.

As a former Saudi Aramcon himself, Wingrove addressed the audience on a personal note: "I am here not only as a representative of AOC, but also as a genuine, bona fide, U.K. Aramcon. Someone who, like all of you here, spent many years living and working in Saudi Aramco during what many of us regard fondly as the best years of our lives."

Heads nodded, laughter broke out and comments from the audience came freely as Wingrove recalled their past. He talked about the challenging times as well as the fun times, how they adapted to life in Saudi Arabia and how they adopted some of its ways into their lives.

"We all became Aramcons at different times, in different ways and for different reasons," he said, "but my closing thought is this: Although we have now left and come home, we became members of the U.K. Aramco family in our pasts and none of us will be the same again in our futures."

Organizers meet annuitants at the door as they gather for a reunion and 75th anniversary celebration.

Friends greeted one another and reminisced about old times.

AOC Industrial Relations administrator Salah Al-Masoud, who represented AOC last year, sent his message through Wingrove. Al-Masoud thanked the Hendersons for their "tireless efforts in organizing the U.K. Aramcons reunions and Web site," and referred to these occasions as "events that represent an invaluable opportunity to get together with people who are our friends and remain an important part of our lives."

The next U.K. Aramcon reunion will be in 2010 in Edinburgh.

EXPEC ARC Advisory Meeting

The campus of Texas A&M University set the stage for the EXPEC Advanced Research Center (ARC) to present recent achievements to its International Advisory Council (IAC) and receive feedback and guidance from these academicians and petroleum industry leaders.

"We all had most beneficial discussions and hope to develop our collaboration even further."

Stephen Holditch

Nafi Toksoz

By Heather F. Bence

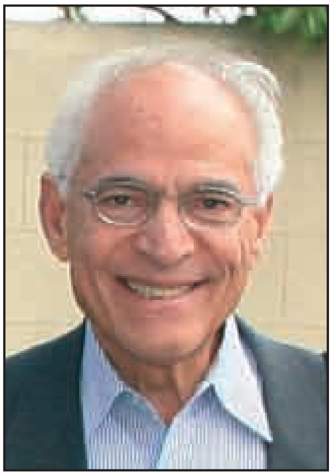
During its fourth biannual IAC meeting, held July 28, a five-member team of EXPEC ARC managers and technologists gathered to present strategic, organizational and research initiatives to the council. The advisers endorsed EXPEC ARC efforts on several fronts, including technology programs, a safety campaign, academic partnerships and human resources development.

Dr. Stephen Holditch, advisory council member and head of the Petroleum Engineering Department at Texas A&M, hosted the meeting and created the opportunity for the EXPEC ARC team to meet with faculty members.

"It was an excellent occasion to have the research center team and advisory council at College Station to discuss the remarkable initiatives and progress achieved by EXPEC ARC," Holditch said.

Advisory council members also include Nafi Toksoz, professor of geophysics and founder of the Earth Resources Laboratory at Massachusetts Institute of Technology; Farouk El-Baz, director of the Center for Remote Sensing at Boston University; Luciano Maiani, president of the Consiglio Nazionale delle Ricerche, Rome, and former president and director general of the European Organization for Nuclear Research (CERN); and Sidqi Abu-Khamsin, chairman of the Petroleum Engineering Department at King Fahd University of Petroleum and Minerals (KFUPM).

> "It was an excellent occasion to have the research center team and advisory council at College Station to discuss the remarkable initiatives and progress achieved by EXPEC ARC."


Farouk El-Baz


Luciano Maiani


Sidqi Abu-Khamsin

Upon receiving technology updates from the presenters, the council members commended EXPEC ARC for its progress in cutting-edge research and development. The council also expressed satisfaction in the growth of collaborative partnerships, including the academic components of both KFUPM and King Abdullah University of Science and Technology (KAUST), noting the potential to grow into strategic alliances.

A unique feature of this meeting was that the advisers made presentations on research topics and technology developments they deem valuable for EXPEC ARC to consider.

Other topics of discussion covered upstream issues such as passive seismic monitoring, near surface research, exploration, unconventional resources, tight gas development, and external collaborative initiatives aimed at continuing the trend in developing new technologies and advancing technical expertise.

"We all had most beneficial discussions and hope to develop our collaboration even further," said Nabeel Al-Afaleg, acting manager of EXPEC ARC.

"Many key topics were addressed and potential opportunities are now under consideration. We highly value the relationship with our IAC members and benefit greatly from such external perspective and partnership."

DGS Executive Committee

A new Executive Committee for the Dhahran Geoscience Society (DGS) took office in June of this year, and will serve the Society until the end of May, 2009. Photographs and brief biographies of the new members of the DGS Executive Committee are included below.

PRESIDENT: Ralph M. Bridle

Ralph Bridle graduated from Camborne School of Mines with a Bachelor of Science Degree (Honors) in 1979, and first worked at Shamva Gold Mine in what was Rhodesia. He left mining and turned to seismic, first with SSL and then GSI (SA) before joining Saudi Aramco. His continuous worldwide experience includes Pakistan, Bangladesh, Indonesia, Libya, Australia, Tunisia, Oman, Somalia, and Nigeria. Since 1991 Ralph has been working in Saudi Aramco's Near-Surface Modeling Team. His particular interest is in near-surface velocity layer modeling and integration of uphole and seismic shot records for model building, with the integration of other geophysical techniques.

Ralph is an active member of SEG, EAGE, and AAPG. Within the SEG Ralph is member of the Global Affairs Committee, Distinguished Lecturer Committee, and the Near-Surface Group (NSG). Other involvement in the SEG includes Chairman of the Membership Committee, and DGS representative on the SEG Council. Other non-work interests include railway preservation and photography of historic places and landscapes. He is a very bad linguist, and admits that he is still learning English.

Since 2000, Ralph has been a member of the DGS Executive Committee, having held the posts of Secretary and Publications Chairman for three years each, Vice-President, and President-Elect. His view on the future of the DGS is to encourage students, and to have frequent field trips and educational dinner meetings. He has a vision of the DGS being the leading geoscience society in the Gulf region, and this encourages more active participation of the AAPG, EAGE, and SEG in the region.

PRESIDENT-ELECT: Khalid O. Rufaii

Khalid received a Bachelor of Science Degree in Geophysics in 1989 from the King Fahd University of Petroleum and Minerals, Dhahran, a Masters of Science Degree in Geophysics in 1995 from the Colorado School of Mines, and a Ph.D. in Geophysics in 2002 from the University of Houston. He has been a member of the exploration organization of Saudi Aramco since 1989, and is currently in charge of the Technology Transfer Group that identifies, evaluates, and implements proven new state-of-the-art technology for oil and gas exploration and development.

Khalid's particular interests are in seismic data processing, especially in areas associated with complex near-surface structures that require careful noise suppression and accurate seismic imaging. He is also interested in the implementation of certain seismic attributes as tools for generating and developing new leads and prospects in non-conventional plays.

Khalid enjoys reading, surfing the internet, and talking to old friends. He is looking forward for the day that the DGS becomes a regional as well as an international authority amongst geoscience societies.

VICE-PRESIDENT: Robert E. Ley

Robert has a Bachelor of Science Degree in Geology from the University of Kentucky. He is the team leader of the Near-Surface Modeling Team, working as a geophysicist but trained as a geologist. Therefore he considers that there must be a healthy mix of geophysical and geological content in DGS activities.

Robert likes to be in nature, camp, and hike, and is currently the scoutmaster for the Boy Scout troop in Dhahran.

Robert feels he can bring a lot to the Society, having being a past president of the DGS and having helped organize meetings and courses with the major professional societies. He is also a member of the SEG and EAGE. He has always been a big supporter of the DGS for what it stands for and does as a professional society. As Vice-President he supports the values that made the DGS what it is today. This includes supporting student and DGS members in their efforts to gain more knowledge about geosciences through courses, workshops, and technical presentations. Also he feels that, as the DGS is one of the largest geoscience societies in the Middle East, it should be at the forefront of bringing in distinguished lecturers from the AAPG, SEG, and EAGE. He believes the monthly meetings should be technical but also show areas of the Kingdom and the world that would be interesting to the members of the DGS.

> "Sarah hopes to help the DGS continue to provide excellent meetings and field trips for its members."

SECRETARY: Sarah Gilliland

Sarah joined Saudi Aramco as a secretary in 2002, and joined Petroleum Engineering and Development as a Staff Analyst at the end of 2007. She has a Bachelor of Arts Degree in Hotel and Catering Management from the University of Strathclyde, and she attained a Post-Graduate Diploma in Administration and Law from the University of Ulster in 2000.

Sarah has always had an interest in nature and the environment. Since 1991 she has volunteered on, and led, working holidays with the British Trust of Conservation Volunteers, on habitat management and biodiversity projects - from tree planting and dry-stone walling in Northern Ireland, to chalk grassland management in France, and a mangrove study with turtle monitoring in Thailand. Her other interests include cooking, travel, camping, and hiking. She is currently studying for a Bachelor of Science Degree in Geography and Environment with the University of London.

Sarah hopes to help the DGS continue to provide excellent meetings and field trips for its members. She is particularly interested in encouraging local field trips, as she feels that there are many interesting geological and geomorphologic features in Saudi Arabia which we are privileged to be in a unique position to explore. She would also like to see more talks from our local geoscience experts, for example on sedimentology, pedology, hydrology, palynology, and cartography. She believes these trips and talks would be of interest to practicing geoscientists and amateur geoscientists alike.

TREASURER: Jamaan S. Yami

Jamaan joined Saudi Aramco in 1989 through the College Preparatory Program (CPP). In 1994 he earned his Bachelor of Science Degree in Cartography from Salem State College, and he received his Masters of Science Degree in Geoscience Information Systems in 2001 from Ohio State University.

From December 1996 to February 2007, Jamaan held various supervisory positions in Saudi Aramco's cartography division. He was also on a rotational development program within the exploration organization from April 2002 to March 2003. In February 2005, he was selected to be on the committee for organizing the 16th E&P Management Forum hosted by the exploration organization for the first time. In March 2007, he joined Saudi Aramco's Regional Mapping and Special Studies Division, Area Exploration Department, as Knowledge Management Coordinator.

Jamaan enjoys reading, traveling, exercising, and enhancing his computer skills in programming and building new websites.

Although he has been a member of the DGS since joining Saudi Aramco, he has not have the chance to serve in the Society. Jamaan's long-term goal is to polish the image of the DGS even more and make it rise as one of the best geoscience societies around the world.

> "Garth wants the society's newsletter, "The Oil Drop", to inform members about society news, provide geoscience-related education and even a little entertainment."

PUBLICATIONS CHAIRPERSON: Garth E. Jahraus

Garth Jahraus graduated from the University of Alberta in 1973 with a Bachelor of Science Degree with Specialization in Geophysics. After graduation, he was hired by Mobil Oil in Calgary, Alberta, where he worked until being transferred to Mobil's offices in Dallas, Texas in 1976. In 1979, Garth was seconded by Mobil to Aramco in Dhahran for two years. He and his wife, Denise, were the first married couple to live in Dhahran Hills. After leaving Mobil in 1981, Garth worked for Mitchell Energy in The Woodlands (Texas), Enserch in Abu Dhabi and Dallas, Veba Oil Operations in Tripoli, Libya, and Western Atlas/Baker Hughes in Houston. Work assignments with these companies included prospect generation, near-surface statics modeling, and reviews and recommendations of numerous farmout offers from all over the world. Garth has been with Saudi Aramco since December 2000, in the company's Area Exploration Department. He is currently Delineation Coordinator for the department. His duties also include reviewing and editing well proposals and post-drilling analyses.

Garth's interests include hiking in the mountains, travel, golf, music, and reading.

Garth was elected Publications Chairperson by the Dhahran Geoscience Society's Executive Committee in November, 2007, and he continues in the same position for the 2008-2009 term. He wants the society's newsletter, "The Oil Drop", not only to continue to inform members about society news, but also to provide some geoscience-related education and even a little entertainment. As chairman of a DGS ad hoc committee on bylaws and procedures, Garth is currently helping to work on necessary updates to these important society documents.

MONTHLY MEETINGS CHAIRPERSON: Saeed H. Ghamdi

Saeed Ghamdi joined Saudi Aramco in 1979, and worked as an electrician in the Mechanical Services Department until 1988. During that time, Saeed completed all Aramco school requirements. He then went to King Abdulaziz University, where he received his diploma in geophysics. Saeed then returned to Saudi Aramco, in the company's Geophysical Data Processing Division. In 1991, he went to Salem State College to get his Bachelor of Science Degree in geological science. After graduation, he joined Saudi Aramco's Near-Surface Modeling Team, where he stayed until 2002. Then he joined the 2D/3D seismic processing team, where is currently working.

PROFESSIONAL DEVELOPMENT CHAIRPERSON: Mahmoud E. Hedefa

Currently Mahmoud works with a special project team in Saudi Aramco's Geophysical Data Processing Division. He joined Saudi Aramco in 2001 after working for Petroleum Geo-Services (PGS) for a period of thirteen years. He occupied many positions within PGS, from Onboard Senior Geophysicist in the U.S.A. to Processing Supervisor in Abu Dhabi. He established the processing center for Petroleum Geo-Services in 1999.

Mahmoud is interested in social relationships, and soccer and table tennis are his main sports interests.

Mahmoud has supported the DGS and its members from his past involvement on the Executive Committee as DGS Public Relations Chairperson, where he managed and organized workshops and courses. He did considerable work in improving the new DGS website. In his current capacity with responsibility for Professional Development, his main objective is to bring distinguished speakers/lecturers from the AAPG, SEG, and EAGE.

Mahmoud says that the DGS is a very active and very reputable society of which he is very proud to be a member.

MEMBERSHIP CHAIRPERSON: Abdulla M. Al-Ghazi

Abdulla joined Saudi Aramco in 1995, working with the Eastern Area Exploration and Well Site Geology divisions. He currently is a palynologist in Saudi Aramco's Geological Technical Services Division, where his activities, since 2000, have focused mainly on Paleozoic palynology. He joined the Specialist Development Program and achieved his Professional degree, an 'Mphil' in palynology, in 2005 from the University of Sheffield, U.K.

Abdulla gained two years of experience in administrating an international students' society in the U.K., and was DGS Membership Chairperson in 2007-2008. During this time he proposed and wrote the bylaws of the DGS Student Chapter and proposed free membership for students (which was effective as of August 2007). A committee and subcommittee were chosen in every local university. He organized the Dammam Dome field trip and is keen to see more in-house field trips. Abdulla is interested in increasing the number of DGS active members, especially non-geoscientists, and has assisted in publicity for the DGS in initiating and organizing an educational day at Prince Mohammed University, Dammam, where there was a significant turnout of non-geoscience students and staff who joined the Society. He also promoted the DGS to SAMSO and designed a DGS leaflet.

Abdulla is keen to see DGS participation in local and international oil and gas exhibitions and conferences, to carry on being a proactive member of the DGS Executive Committee, and to see the Society continue to shine.

ACADEMIC DEVELOPMENT CHAIRPERSON: Gerald J. Kuecher

Gerald J. Kuecher is presently employed as a sedimentologist and Geological Specialist with Saudi Aramco. Prior to this he served six and a half years as geoscience project manager at Knowledge Reservoir in Houston, six and a half years at Baker Atlas as sedimentologist and image log analyst, and seven years at Marathon and three years at Amoco in the role of international petroleum geologist. He also served four years as a university educator at Northwestern and Northeastern Illinois universities in Chicago. He has extensive knowledge of rifts and rift sediments, with experience in the Gulf of Suez in Egypt, the South China Sea of Indonesia, and the Gulf Coast of the U.S.A.

Dr. Kuecher graduated from LSU under the guidance of Drs. Harry Roberts, Jim Coleman, and Arnold Bouma. His Ph.D. dissertation focused on the subsidence properties of recently deposited deltaic sediments, while his Masters thesis focused on the forcing functions responsible for the deposition of ancient tidal rhythmites.

Dr. Kuecher has written numerous articles on such diverse topics as deep-water sediments, deltaic sediments, tidal sediments, modern sediments, ancient sediments, subsidence, faulting, fluid flow, and diagenesis to the application of electromagnetics, high resolution seismic, and ground-penetrating radar in sedimentology. Gerald is a well-rounded scientist who has the abilities to integrate knowledge from various sources to answer fundamental problems in sedimentology. Dr. Kuecher has participated in the AAPG Visiting Geologist Program since 1998.

Gerry's personal interests include writing, and he just finished a book entitled "Fruitcake Hill". He plans to commence another project soon, probably a sedimentology textbook. Gerry loves photography and has a website (www.geraldkuecher.com).

Since Gerry has only been in Saudi Arabia for a little over a year, he feels he cannot address what needs to be improved. Time working with DGS will allow him to address this issue. But he can say he has a heart for college students and will do his part to arrange speakers at KFUPM, and ask students to speak here as well.

PUBLIC RELATIONS CHAIRPERSON: Ali A. Al-Salem

Ali A. Al-Salem is an exploration systems analyst working with the Exploration Applications Services Department of Saudi Aramco (Dhahran). He leads a geological and geophysical application development team that provides the exploration organization with the required computer applications and support for various geological and geophysical applications. He has completed a special assignment with the Gas Fields Characterization Division, where he was involved in building geologic models via integrated reservoir modeling projects for the Khuff and Unayzah gas reservoirs.

Ali received his Bachelor of Science Degree in Computing and Information Sciences/Mathematics from Oklahoma State University in 1988, and earned a Masters of Science Degree in Geology from King Fahd University of Petroleum and Minerals in 1996.

Ali is very active in various company volunteer activities. He was Chairman of the Saudi Arabia Section of the Society of Petroleum Engineers (SPE) in 2005, Vice-Chairman of the technical program in 2004, and Membership Vice-Chairman for two years (2002-2003). He was Membership Chairman of the DGS for two consecutive years (1999-2000). During his term with the SPE Saudi Section, Ali gained recognition and won the President Award for Section Excellence. He has received several awards from both SPE International and the local section.

Ali is a member of the Society of Petroleum Engineers (SPE).

MEMBER-AT-LARGE: Mustafa A. Shuala

Mustafa A. Shuala has been working in Saudi Aramco as an exploration systems analyst since 2001. He joined the company as a CPP student in 1996. In 2001, he got his Bachelor of Science Degree in Information and Computer Science from KFUPM. After graduation, he joined ECC/Exploration Applications Service Department. From that time, he has been supporting and developing many geophysical applications. He is now continuing his Masters Degree in Geophysics at KFUPM.

Mustafa has been an active member in the Society of Petroleum Engineering (Saudi Arabia chapter) for four years, developing and mastering the SPE website. He received many awards for his contributions.

Mustafa joined and contributed to other national societies such as the Saudi Youth Hostel Association and the Qatif Astronomy Association.

Mustafa is interested in cultural exchange, national and international environmental issues, and improving kids' and youth educational processes. He established a small educational center in his town, the goal of which is to provide innovative education with fun for kids and youth.

Mustafa has a wide range of hobbies and capabilities, such as swimming, soccer, table tennis, travel, acting and making films, speech, art, music, photography, and graphics.

> Shiv is currently the project leader for Saudi Aramco's passive seismic project and for the technology test site project.

MEMBER-AT-LARGE: Shivaji N. Dasgupta

Mr. Shivaji N. Dasgupta is currently the project leader for the passive-seismic project and also for Saudi Aramco's Technology Test Site project. Shiv is a Senior Geophysical Consultant in the EXPEC Advanced Research Center (ARC) and has been with the company for over 25 years. Before joining Aramco, he held various technical positions in the U.S.A., with Amoco Production (now BP), Mitchell Energy, and Conoco.

Shiv has published and presented over seventy papers. He has recently been granted a U.S. patent and also has three U.S. patents pending. He is the 2007-08 SEG Distinguished Regional Lecturer for the Middle East/Africa region.

He received his Bachelor of Science Degree in Engineering Geophysics from Indian School of Mines, and his Masters of Science Degree from St. Louis University and Washington University. Shiv also has a Masters of Business Degree from Southern Illinois University.

He is an active member of SEG, EAGE, AAPG, and SPE.

Smart Fluids - Their Role in Exploration and Production (E&P)

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Increasing recovery from existing reservoirs and from new sources requires technological advancements along several fronts like improved drilling, completion and well stimulation and intervention. These advancements are being made possible due to recent developments in nanotechnology, biochemistry, materials science, etc. One active area is the development of smart fluids, which are emerging as potential solutions for well remediation for improving recovery and enhancing productivity.

By Dr. Abdullah M. Al-Dhafeeri, Jin J. Xiao and Nabeel S. Al-Habib

What Are Smart Fluids?

Smart fluids[1] are not your average liquid, but fluids whose properties (e.g., viscosity, surface tension, etc.) can be changed instantly and reversibly due to some stimuli. The external stimuli can be an electrical field, magnetic field, light, pH, temperature, etc. Based on the stimuli the smart fluids can be classified in several categories. For example, Magnetorheological (MR) fluids have the unique ability to transform from liquid to solid and from solid to liquid quicker than you can blink an eye. While scientists have just recently discovered many new applications for MR fluid, it has actually been around for more than 50 years. Applications for this technology include Nautilus exercise equipment, washing machines, clothes dryers, shock absorbers for cars and advanced leg prosthetics.

Electrorheological (ER) fluids are most commonly colloidal suspensions, and their stiffening under an electric field is reversible[2]. Under the electric field, ER fluids form fibrous structures which are parallel to the applied field and can increase in viscosity. These materials are finding potential applications in clutches, brakes, shock absorbers and bullet proof vests, etc. Lithium polymethacrylate is an example of an ER fluid.

Shape memory alloys (SMA) and polymers are Thermo-responsive materials where deformation can be induced and recovered through temperature changes. When an SMA is below its transformation temperature, it has very low yield strength and can be deformed easily into any new shape[3, 4].

Piezoelectric materials are materials that produce a voltage when stress is applied. Since this effect also applies in the reverse manner, a voltage across the sample will produce stress within the sample. A common material used is piezo-ceramic (PZT)[5, 6]. PZT patches/paints[7, 8] are often used as both sensors and actuators for vibration control. Polyvinylidene fluoride (PVF) is a well-known piezoelectric polymer that can be easily handled and has a good strain to voltage conversion efficiency, but requires high voltages to function as an actuator.

pH sensitive polymers are materials which swell/collapse when the pH of the surrounding media changes. A polymer network of chitosan and polyacrylamide (PAAm) has been studied in detail[9]. The applications of these fluids shall be discussed in details later in this article. Figure 1 shows the swelling of gel with pH.

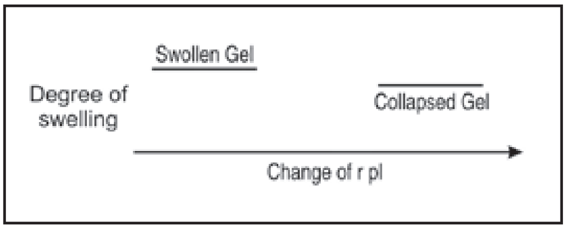

Figure 1 - PH sensitive polymers.

Recently the University of Maryland developed new photorheological (PR) fluids - that can be made simply and inexpensively. The fluids consist of the cationic surfactant, cetyl trimethylammonium bromide (CTAB), and the photo - responsive organic derivative, trans-ortho-methoxy cinnamic acid (OMCA). Aqueous mixtures of CTAB and OMCA in basic solution self-assemble into long, wormlike micelles. These PR fluids can enable microelectromechanical systems (MEMS). Those much discussed devices would integrate mechanical elements, sensors, actuators and electronics on chips that could revolutionize many different products[10].

Role of Smart Fluids in Exploration and Production

The smart fluids are being developed to achieve some specific function such as drug delivery with time and at specific points of application, etc. Most of these are being developed for low temperature applications. How these can be customized and applied in the oil fields where the reservoir conditions are very hostile like high temperature, high saline environment, and high H_2S and CO_2, etc.? What objectives can be realized using these smart fluids? Let us discuss the whole E&P cycle and conceptualize different applications of smart fluids.

Drilling

Mud systems are used to:

• Provide hydraulic power to the drill bit to cut the rock.

• Transport rock cuttings to the surface.

• Transfer heat generated during drilling.

• Stabilize the drilled hole.

There are several advanced types of mud being developed to keep pace with the development of drilling technology for horizontal and multilateral wells. When we are drilling the hole, especially in a reservoir section where the mud invades the reservoir rock, the particulates remain outside the rock as mud cake and the liquid portion of mud (mud filtrate) penetrates the reservoir rock. The penetrated mud filtrate damages the deliverability of the well by creating water blocks or changing wettability in the near-wellbore region. The result is that the productivity of the wells is sub-optimal, leading to the requirement of additional wells to meet production targets.

Can we use smart fluids to provide solutions to solve this problem so that we can have better deliverability from the well? The answer lies in developing nano-sized particles containing the remediation fluids which should remain suspended in the mud/drill in fluids. Once drilling is over and the well is completed, the

> The limitation of the VES system is that it is costly and also cannot effectively divert acid from high perms as it develops viscosity lower than that required for diversion from very high permeability streaks.

nano-particle should release the remediation fluid and break/dissolve all the mud components to clear the wellbore on flow back. The desired nano-particles have been developed which are stable up to 70 °C. Efforts are being made to achieve stability at a higher temperature.

Production

Before we start producing from the field, we sometimes get a well where the wellbore is already damaged due to mud invasion. This requires well intervention to restore the productivity of the well, or sometimes we can enhance the productivity by fracturing the formation in or near the wellbore region. During production we may face some problems leading to a decline in the production of hydrocarbons, like development of skin in the wellbore due to fine migrations, scaling, etc. This requires well stimulation to solve these problems. In addition, unwanted water that is produced from a productive zone due to reservoir heterogeneities can lead to a decline in oil production and sub-optimal recovery. This requires conformance control of a reservoir section with proper gel/ploymer fluids so that uniform drainage of the reservoir can take place. Let's see how smart fluids can play a vital role in achieving the same.

Diversion of Stimulation Fluid for Better Zonal Coverage

In the heterogeneous reservoirs, when we place stimulation fluid, it goes in the sections with high permeability leaving the low permeability sections un-stimulated. We need technologies to place the stimulation fluid all along the zone so that the whole reservoir section is stimulated equally.

Self-diverting acid (SDA) was the first smart fluid introduced in stimulation whereby the acid contained a polymer with cross linker[11]. The cross linker was selected in such a way that at a low pH the viscosity of SDA remains low, but when its pH rises during spending of acid, the viscosity increases many fold leading to a diversion of acid to low permeability sections of the reservoir.The drawback of SDA was the polymer itself which remained in the pores of the reservoir leading to sub-optimal performance in some cases.

The next smart fluid introduced to the industry was a diversion system based on viscoelastic surfactants (VES). Viscoelastic surfactants are very small molecules consisting of a hydrophilic head group and a long hydrophobic tail. In the presence of brine, they form elongated micellar aggregates. When the surfactant concentration in the VES fluid is above a certain critical concentration, the micellar structures entangle and form a mesh like structure leading to increased viscosity. Upon contact with oil or gas or dilution by formation water, the VES fluid reduces viscosity by breaking down the wormlike micelles to much smaller spherical micelles. The spherical micelles cannot entangle with each other and therefore, the resulting fluid has water-like viscosity, allowing the easier flow back. Also VES is finding wide applications in a polymer free fracturing fluid. The limitation of the VES system is that it is costly and also cannot effectively divert acid from high perms as it develops viscosity lower than that required for diversion from very high permeability streaks.

Another smart fluid which is being developed for diversion from high perms is pH sensitive polymers which change the viscosity with pH, Fig. 1. Such materials swell or collapse depending on the pH of their environment. This behavior is exhibited due to the presence of certain functional groups in the polymer chain.

There are two kinds of pH sensitive materials: an acidic group, - COOH, SO_3H (e.g., polyacrylic acid) that swells in the basic pH and others that have basic groups, NH_2 (e.g., Chitosan) and swell in acidic pH. The response is triggered due to the presence of ionizable functional groups (-COOH and -NH_2) which get ionized and acquire (+/-) charge in a certain pH range. The polymer

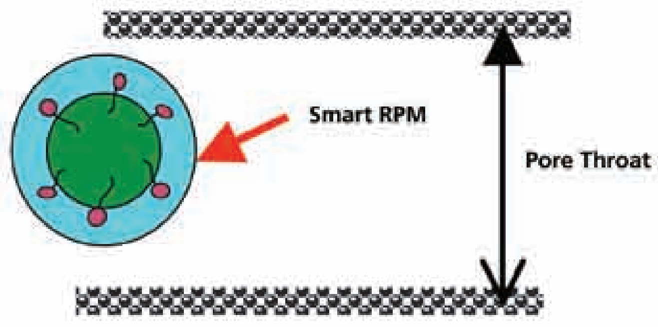

Figure 2 - Concept of smart RPM.

chains now have many similarly charged groups which cause repulsion and therefore the material expands in dimensions. The opposite happens when pH changes and the functional group loses their charge, therefore the repulsion is gone and the material collapses back. The viscosity developed due to this phenomenon is so high that it can easily divert acid from a very high permeability section to low permeability sections to ensure the proper zonal coverage.

Stimulation and Fracturing in Tight Reservoirs

In tight reservoirs we need technologies to place the remediation fluids deep inside the wellbore in order to achieve optimal productivity. Nano-particles can encapsulate the remediation fluids, and after a specified time they can break down to release the fluids once they are placed deep inside the reservoir. When it is required to fracture the reservoir near the wellbore to further increase productivity, frac fluids based on VES, are emerging as smart polymer free fluids which are easier to flow back also.

Water Shutoff With Relative Permeability Modifier (Rpm)

It is well-known that treatment of porous rocks with polymer gel systems can cause more reduction in the permeability of water than in the permeability of oil. The polymers are called relative permeability modifier (RPM) polymers, and the occurrence of this phenomenon is essential for polymer gel treatments in production wells to reduce water production. The RPM behavior of a fluid is critical to the success of water shutoff treatments in oil wells if the productive zones cannot be isolated during polymer treatments. Smart Relative Permeability Modifier (SRPM) treatments in an oil zone reservoir may have the greatest potential when oil residual resistance values are 1, Figs. 2 and 3. In other words, we hope that the effectiveness of a SRPM treatment in the production well increases with increased values of the water residual resistance factor and without affecting hydrocarbon zones (low values of oil residual resistance).

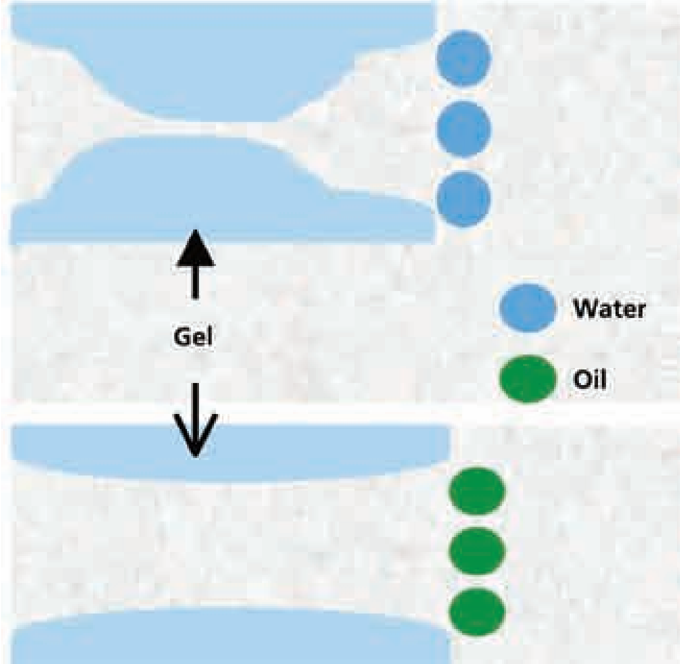

Figure 3 - Concept of smart RPM.

Extensive investigations provide possible explanations for RPM, including gravity effects, lubrication effects, gel shrinking and swelling, gel constricting water pathways, wall effects, wettability alteration, rock permeability, pore blockage by gel droplets, segregation of oil and water pathways, leaching of polymer from the gel during brine injection, gel dehydration during oil injection and capillary force and gel elasticity. In addition, gels can exhibit relative permeability modifier behavior in fracture[12, 13].

Gravity Effect

Liang et al.14, performed several core experiments using glyoxal/carboxylate acrylamide (CPAM) gels with 0.3% CPAM and 0.114% glyoxal with three different combinations of core orientation and flow direction. Their results indicated that Frro (oil residual resistance factor) and Frrw (water residual resistance factor) are insensitive to flow direction or core orientation. In addition to this finding, they also indicated that these two values did not vary with oil density. Therefore, they suggest that RPM was not caused by a gravity effect.

Gel Shrinking and Swelling Effect

It was reported[15] that water-based gel systems swell in water and shrink in oil. This behavior results in constricted pathways for water movement and more open pathways for oil movement into porous rock. Liang et al.[14], also investigated the validity of the shrinking/swelling argument in practice, as to whether changes in gel volume can be observed when a gel is in contact with water or oil. In fact, based on their experimental

The researchers interpreted a mechanism of RPM from observing that an aqueous gelant will follow the waterpreferred pathways and block these more than the oil channels. In other words, the gelant preferentially flows in the pores that are best for water and therefore reduces the permeability for water more than for oil.

work, they observed no volume changes with alternating exposure of the gels to either water or oil at atmospheric pressure. Figure 3 describes the phenomena.

Lubrication Effect

Zaitoun and Kohler[16, 17] suggested that the presence of the hydrocarbon/adsorbed-polymer interface induces lubrication to the flow of oil (nonwetting phase) through porous media. They concluded that for a given level of adsorption, the permeability reduction to water is noticeably increased by the presence of residual oil.

Segregation of Oil and Water Pathways

Another possibility proposed[18] suggests that RPM can be explained by water and oil following segregated pathways. This theory was derived at the microscopic level. A waterbased gelant will follow primarily the pathways that are available to water, whereas remaining oil pathways could be connected, and gel free after treatment. Therefore, the capacity to reduce water permeability is much more than that to reduce oil permeability. Following the same logic, an oilbased gelant will primarily follow the pathways that are available to oil, whereas remaining water pathways could be connected and gel free after treatment.

Pore Blockage by Gel Droplets

Nilsson et al.[19], performed corefloods on acid-cleaned quartz sand, Teflon powder and a mixture of quartz and Teflon. Hydrolyzed Polyacrylamide (HPAM)-based polymer with an added cross linker and a biopolymer were used as gel systems. The researchers interpreted a mechanism of RPM from observing that an aqueous gelant will follow the waterpreferred pathways and block these more than the oil channels. In other words, the gelant preferentially flows in the pores that are best for water and therefore reduces the permeability for water more than for oil.

Leaching of Polymer from The Gel

Liang et al.[20], and Seright[21-24] agreed that many gel experiments exhibit a shear-thinning behavior during brine flooding. They indicated that increasing fluid velocity causes a decrease in the residual resistance factors for water. In contrast, the residual resistance factors to oil were insensitive to flow rate. Their results from previous studies also showed that the non-Newtonian Frrw values were not attributed to gel break down. The polymer concentrations in the brine effluent were too low to be responsible for RPM.

Gel Dehydration During Oil Injection

Another explanation for mechanisms causing RPM was made by Willhite et al.[25]. They performed a series of experiments designed to determine if the phenomena of gel dehydration was observed in both unconsolidated sand packs and in Berea sandstone cores with or without residual oil saturation after injecting a chromium acetate/Alcoflood 935 gelant. They believed that oil penetrated the porous media that was occupied by gel, causing dehydration to the gel by displacing brine from the gel structure. Thus, new channels were created within the gel. This behavior caused a reduction in oil permeability from its original value. Subsequent to brine injection, trapped oils were formed in the new pores as residual saturation within the gel media. The researchers claimed that RPM occurred because of the trapping of residual oil in the new pores.

Capillary Force and Gel Elasticity

Seright[26] investigated whether capillary forces and gel elasticity may be a possible factor in RPM. This idea was suggested by the results from the micro-model experiments[27]. Liang and Seright assumed that the balance between capillary forces and gel elasticity could be a possible contributor for the RPM. Presumably, a capillary force performs to maintain a

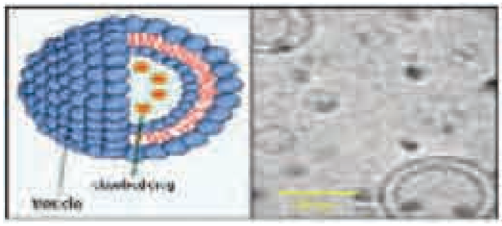

Figure 4 - Conceptual drawing of a vesicle containing a dissolved drug.

minimum droplet radius. On the other hand, the gel applies an elastic confining force to close the channel. Based on a series of core flooding experiments using gelled foam to validate this theory, they hoped that as a corollary of increasing the gel elasticity, the RPM would be more pronounced. Unfortunately, the experimental results did not support this theory. Therefore, a mechanism of balance between capillary forces and gel elasticity is not the primary mechanism responsible for RPM in porous rock.

Presently, the Exploration and Petroleum Engineering Center - Advanced Research Center (EXPEC ARC) at Saudi Aramco is working to develop a RPM polymer that exhibits a better performance, an improvement that we hope to achieve by reducing water production permeability without effecting oil productive zones. Smart Relative Permeability Modifier polymers are potentially an attempt to further improve the water-shutoff technology for application in oil wells as compared to the more conventional RPM polymer formulations.

There are other smart fluids which can significantly improve productivity and recovery of hydrocarbons.

Smart Foam for Conformance in Water Injection

The addition of surfactant in brine during water alternating with CO_2 injection or co-injection with CO_2 has proven to produce foam that reduces CO_2 mobility. Laboratory experiments have shown that some surfactants generate “smart” foam that selectively reduces the mobility of CO_2. The smart foam is useful in correcting nonuniform frontal displacement due to the heterogeneity of a reservoir formation. Smart foam is also very effective in displacing the oil - a benefit frequently overlooked by researchers testing mobility control aspects of the foam.

Tiny Containers Make and Pack Themselves

Srini Raghavan of the University of Maryland has been working with lipid molecules, which look something like a head with two tails. The lipids’ “heads” are attracted to water, while their “tails” are adverse to it. When put into water, the heads naturally cluster as they seek water, while the tails cluster to avoid it. The heads form two walls, with all of the tails between them, protected from the water. This bi-layer material naturally forms into a sphere with a hollow center, called a vesicle, Fig. 4.

As a vesicle forms, water is captured in its hollow center, turning it into a tiny container. Light and temperature can then be used to reconfigure the vesicle, which causes it to break apart and release the water trapped inside. These tiny containers can be customized for carrying stimulation fluids inside the reservoir for deeper placement.

Self-Assembled Nanostructures

Mixtures of the cationic surfactant, CTAB and the organic compound, 5-methyl salicylic acid (5 mS) spontaneously selfassemble into unilamellar vesicles at room temperature. Upon heating, these vesicles undergo a thermo reversible transition to wormlike micelles. This phase transition results in a 1,000 fold increase in the solution viscosity with increasing temperature. Small-angle neutron scattering (SANS) measurements show that the phase transition from vesicles to micelles is a continuous one, with the vesicles and micelles coexisting over a range of temperatures. These nanostructures can be a smart method of selective water control in oil wells, as these surfactants do not block the features producing oil.

Wettability Alteration Agents

The lotus effect is the observed self-cleaning property found with the lotus plant. Although lotuses prefer to grow in muddy water, the leaves and flowers remain clean of mud, Fig. 5. Their microscopic structure and surface chemistry show that the leaves never get wet. Microscopic observations of natural water-repellent systems like a lotus leaf reveal that the surface is made of micron sized bumps. This particular structure traps air under any rain droplets that fall on the leaf, creating a naturally super-hydrophobic surface.

Figure 5 - Lotus effect, i.e., water drop on leaf.

Nanotechnologists are developing methods to make paints and other surfaces that can remain dry and clean themselves in the same way as the lotus leaf. It has been observed that this can usually be achieved in the following ways:

• Treatment of surfaces with fluorochemicals or silicone.
• Treatment by using a combination of polyethylene glycol with glucose and sucrose.
• Treating with perfluorononane to a thickness of 2 nm leading to increase of the contact angle from 67° to 168°.

The lotus effect can be harnessed to change the wettability. Smart polymers are being developed which on application can change the rock contact angle and enhancing well productivity.

Nano-Emulsions

Nano-emulsions are emulsions where the droplet size of the internal phase is 500 nm or less. The emergence of nanoemulsions has led to an awkward situation regarding nomenclature: the size distribution of droplets in nanoemulsions is in many cases larger than those of microemulsions.

The systems are rather distinguished by their thermodynamics, not by the size of drops. Because of the small drop size, they are not subject to gravity-driven separation owing to the density differences of the two phases. Nano-emulsions constitute a rapidly expanding field of study, with perceived or consolidated applications to drug delivery, cosmetics, food products, etc.

Nano-emulsions generated conventionally with high agitation energy are not stable for a longtime[28]. Recently developed technology for the nano-emulsion generation of tiny droplets (30 nm - 80 nm), is based on the transitional phase inversion method. These emulsions should prove useful for the delivery of oil field chemicals in a variety of applications such as well treatments (scale inhibition, acidizing, etc.), flow assurance (multiple additive packages) and deposit removal/clean up. Because of their long-term stability and ease of preparation from a concentrated precursor, nano-emulsions are compatible with oil field logistics requirements, Fig. 6.

Conclusion

These are some of the fluids which have been termed "smart" in a sense as they do not behave as the conventional fluids, but "smartly" on the application of some external stimuli. In the E&P industry, these fluids can make well treatment solutions smarter and deliver the objective of enhancing well productivity and increasing recovery from the fields.

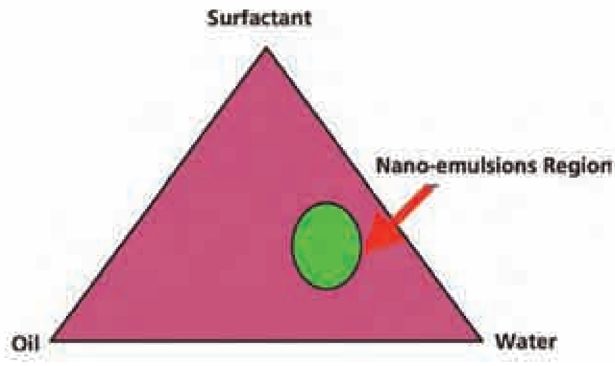

Figure 6 - Region of nano-emulsions.

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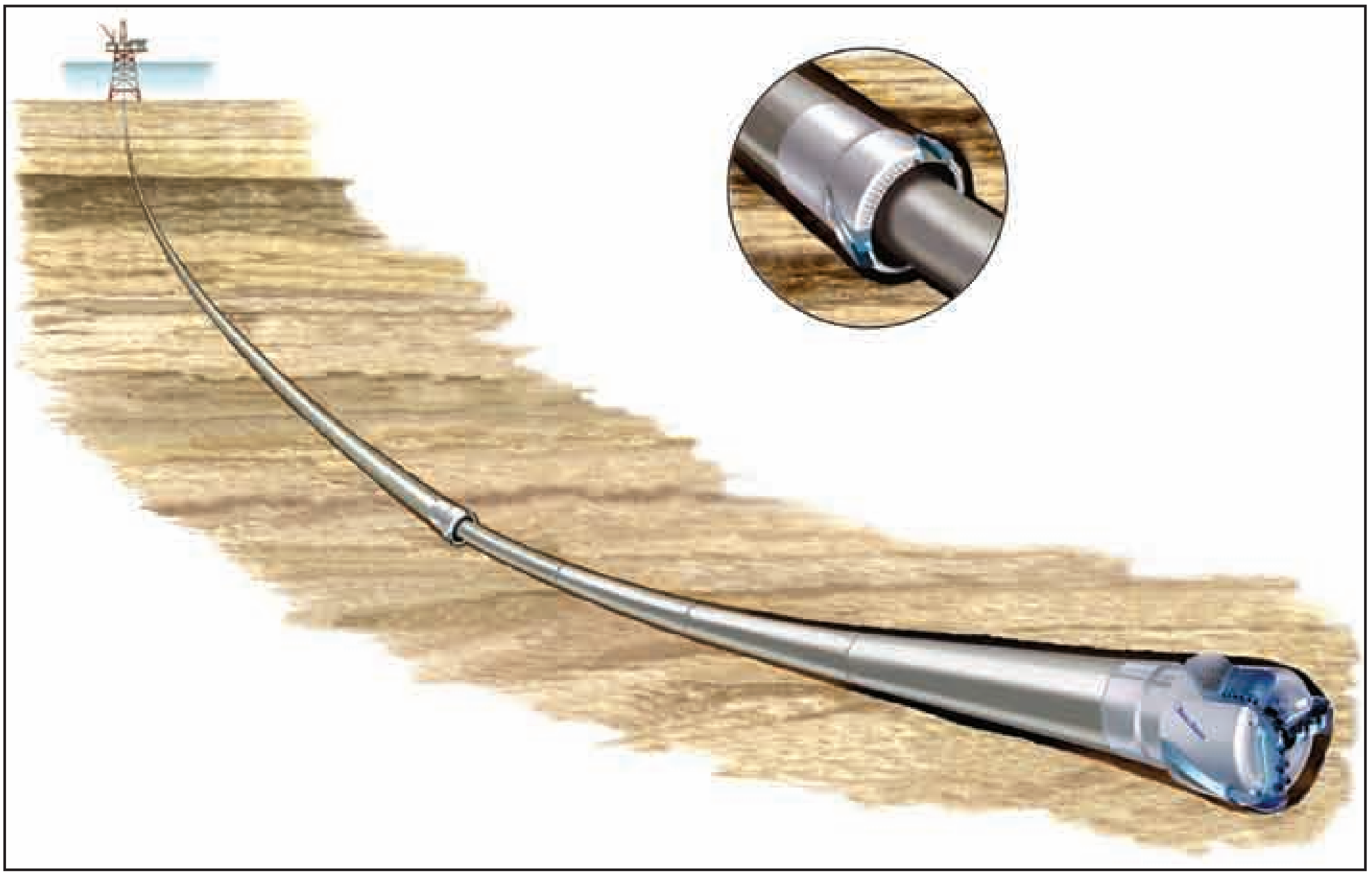
Drilling-with-casing and drilling-with-liner capabilities solve well construction problems

An operator in shallow water offshore Texas, USA faced a sizeable obstacle accessing the reservoir: a catastrophic loss zone just below 4,000 feet (1,219 meters). In earlier attempts to drill two wells through this zone, drilling was characterized by total losses, which subsequently led to stuck-pipe, twist-off and the forced abandonment of both wells. Because conventional lost circulation material was completely ineffective, the operator sought new solutions.

Weatherford's approach combined two of the company's relatively new technologies—Managed pressure drilling (MPD) and drilling-with-liner (DwL℠) techniques. In the MPD part of the solution, an 8.8 ppg drilling fluid was pumped down the annulus of the hole, where it enabled the annulus to stay full, providing the required wellbore stability to complete the operation. Meanwhile, sacrificial seawater was pumped down the drillpipe. The seawater provided the means to cool the bit while transporting cuttings up the annulus, into the loss zone.

The second key to success, however, lay in the use of liner drilling technology. Rather than using conventional drillpipe to power through the loss zone, where the large annulus between the 5-inch drillpipe and the 8 1/2-inch hole practically invited the formation to cave in, Weatherford drilled with a 7-inch liner fitted with a DrillShoe™ III assembly. The drillshoe is not only a PDC bit capable of cutting through extremely hard rock (confined compressive strength up to 18,000 pounds per square inch); it is also designed to be drilled through using conventional drill-bits when the time comes to cement the liner in place. A special bit or mill run is not required for drill-out. The liner running tool used was the company's new 7-inch best-line torque tool, which differs from a conventional liner running system in that it takes both a mechanical event (a dropped ball) and a pressure event to release the liner from the drillstring that runs it into the hole.

"These were severe running conditions," says Steve Rosenberg, Weatherford's U.S Region Product Line Manager for drilling-with-casing, "and we wanted to be sure that a pressure spike wouldn't release the liner before we were ready. "Drilling with liner creates a 'smear effect', which mitigates fluid loss problem. As the rotating casing rubs against the formation, it plasticizes the cuttings and creates an artificial filter cake that eliminates or minimizes fluid loss to the formation, helping to stabilize it. Also, these holes are less tortuous than conventionally drilled holes because the liner is stiffer than drillpipe. This produces a better-quality cement job and a better cement bond", said Rosenburg.



As a result of this double-barreled approach, the operator successfully drilled the 500-foot (152-meter) problem zone and reached the reservoir. This job represented the first commercial use—and success—of 7-inch liner with the company 's technology.

Drilling with Value

"Drilling with casing or liner is based on a fairly simple premise, but it can add so much value to other drilling technologies," says Scott Beattie, Global Product Line Manager for Weatherford's drilling-with-casing capability. "And while the technology was originally co-developed with Unocal to drill through super-soft formations offshore Thailand, the subsequent development of the drillshoe make our techniques applicable to almost any formation type. If we cannot drill the formation and the client has hole stability problems, we can adopt a reaming-with-casing or reaming-with-liner approach. By evaluating the client's offset well data, we make informed and intuitive recommendations to save the client time and money."

Simultaneous casing and drilling technology is widely used in Asia. In other areas of the world, the technique has been used to drill through problem sections with a number of advantages.

For example, they are effective in conventional drilling as well as Controlled Pressure Drilling® (CPD®) scenarios, for any section from 6 to 26 inches and any hole angle. In addition, use of Weatherford's drilling with casing eliminates the expense of sacrificial liners for running in hazard zones and eliminates the loss of hole size—an important consideration in reaching total depth. Such techniques do not incur the surge and swab forces that can lead to ballooning, breathing, nonproductive time (NPT) and/or formation damage during conventional tripping; they eliminate extra wiper trips before cementation and increase hole stability through the smear effect. And because they minimize the time between drilling and casing off the wellbore, the techniques reduce formation exposure and help prevent cave-ins, swelling and other potentially catastrophic situations.

Solving Problems in a Colorado Gas Field

The gas fields of the western Piceance basin in northwestern Colorado include dipping formation beds that lead to crooked-hole drilling and fractured shale formations that cause lost circulation and can make it impossible to return cement to surface during primary cement jobs. Sometimes casing cannot be run to total drilled depth. One Piceance basin operator decided to approach the problems associated with its wells by combining DwC techniques with stage cementing.

To date, seven wells have been successfully drilled by this operator, using the technology. In all of these wells, it was possible to keep the annulus nearly full during drilling, which minimized problems with sloughing shales. The rigid bottomhole assembly, coupled with low weight on bit, successfully mitigated the crooked-hole problems that had plagued previous drilling. Finally, the use of a multiple-stage cementing tool enabled the operator to circulate cement to surface—the key requirement for satisfying Bureau of Land Management regulations.

The system represented the first use of combined DwC techniques and multistage cementing. According to Weatherford, this combination reduced average NPT for the seven wells by 47 percent, substantially reduced fluid losses as well as reducing hole deviation by an average of 44 percent, and all wells reached or exceeded their depth goals.

Saving $4.5 Million in the Carpa Field

Production in the Carpa field offshore Veracruz, Mexico, comes from a naturally fractured limestone, prone to lost circulation, underneath a zone of unstable shale. Both zones are hard formations that lead to stuck pipe, poor cement jobs and high remediation costs. A typical well would require not only 9 5/8-inch casing but also sacrificial 7-inch liner through the producing horizon.

The company recommended a test of drilling with liner technology in one of the operator's development wells to reduce open-hole exposure time, eliminate surge and swab forces on the shale, minimize lost circulation and increase hole stability. Because the well would be nearly horizontal (75 degrees), directional control would be an issue.

In 45 hours the operation drilled 266 feet (81 meters) of 12 1/4-inch hole in a hard-rock drilling environment while maintaining 75-degree inclination and azimuth. No fluid losses or hole stability problems occurred, validating the beneficial smear effect. The single pressure event required for converting the drillshoe for drill-out and setting the liner saved valuable rig time and simplified operations.

According to the company this system saved the operator a total of 39.5 days, compared to previous conventional operations. This saving and the cost of the sacrificial liner were worth a total of about $4.5 million.

Simplifying Future Wells

"If you look at DwC technology as a whole," says Beattie, "it has so many benefits on its own—and it works so well with other Weatherford offerings. The simplicity of the way we drill with casing just lends itself to adding value across the board—with CPD services, liner systems, tubular running services, cementation and well construction."

Nuclear Parameters of Arab-D Formation Evaluation

When determining reservoir lithology and porosity using density-neutron cross-plot charts, it is required to know the end points of reservoir rock (sandstone, limestone, and dolostone) sigma, matrix density, and neutron response. If this information is not available, it is a common practice to assume that the reservoir rocks are pure minerals, thus the default values of quartz, calcite, and dolomite are used in log interpretations. Obviously such assumed reservoir parameters are less accurate since reservoir rocks are rarely pure minerals. This is especially important for giant reservoirs since a small error in porosity can be equivalent to a large quantity of hydrocarbon. This study is aimed to reduce this systematic error in reservoir porosity and lithology determination by performing nuclear parameter modeling using laboratory data of reservoir cores.

By Shouxiang Mark Ma, Abdalrasool A. Al-Hajari, Michael Herron and Steve Crary

In this study, 99 Arab-D carbonate samples from different wells in a large Saudi Arabia oil field were selected. After completion of conventional core analysis in the laboratory, the samples were crushed into powders for mineralogy and elemental chemistry analyses. Subsample sets of calcite, dolomite, and anhydrite were obtained based on X-ray diffraction (XRD) and Fourier transform infrared (FTIR) mineralogy measurements. All the core and powder data were used for nuclear parameter modeling to obtain parameters of sigma, matrix density, photo-electron factor (Pef), and thermal neutron porosity. Instead of using the default end-points values of pure minerals, the field specific nuclear parameters should be used in routine field log processing. This study demonstrated the importance of field specific core-log calibration for enhanced formation evaluation.

Introduction

Reservoir characterization is typically done using rock properties derived from well logs, after calibrating with core. In core-log calibration, core analysis data is often considered as the "ground truth" even though the quality of core data depends on many factors such as test conditions and procedures[1]. Calibrating logs to inaccurate/nonrepresentative core data is obviously not desirable. Therefore, quality control of core analysis to ensure its accuracy and representativity is essential in successful core-log calibration for satisfactory

Carbonates for Enhanced

> In mature fields where many producers and injectors have been drilled, well logs are the most important data in reservoir description and characterization due to their abundance (high data coverage of the field since almost all wells drilled are logged), and the relatively low data uncertainty, when comparing with data from core, well test, and seismic.

reservoir description. In addition, reservoir rocks are heterogeneous in terms of pore structure (which affects fluid flow and distribution directly) and mineralogy. Accurate characterization of rock mineralogy/lithology (such as sandstone, limestone and dolostone) is important for geological modeling and reservoir simulation studies.

Intuitively, reservoir rock lithology is often assumed to be pure minerals. For example, limestone is assumed to be equivalent to calcite ($CaCO_3$) and dolostone to be equivalent to dolomite ($CaCO_3MgCO_3$). Sedimentary rocks, like chemically precipitated limestones, may be essentially pure minerals. For others, such as clastic sandstones and secondary dolostones, mineralogical composition can be extremely variable and often associated with impurities due to deposition and digenesis. Because of the existence of rock impurities, a chemical formula for Arab-D dolostone has been proposed as: $CaCO_3Ca_{0.16}Mg_{0.84}CO_3$[2].

Consequently, to improve the accuracy of formation evaluation, reservoir specific matrix end points (MEP) are required for core-log calibration and log processing. That was the focus of an earlier study dealing with rock properties derived from laboratory measurements[3]. The objectives of this study are to determine nuclear parameters of rock matrix including thermal neutron capture crosssection (Σ), (Pef), apparent thermal neutron porosity (ATNP), and apparent epithermal neutron porosity (AENP) through nuclear parameter modeling.

Techniques	Scale of Investigation	Data Coverage	Data Uncertainty
Core	Inches	Low	Low
Log	Inches to Feet	High	Low
Well Test	Feet to Km	Low	Low
Seismic	Km	High	High

Table 1 - Techniques used for Reservoir Description.

Reservoir Petrophysical Description

In mature fields where many producers and injectors have been drilled, well logs are the most important data in reservoir description and characterization due to their abundance (high data coverage of the field since almost all wells drilled are logged), and the relatively low data uncertainty, when comparing with data from core, well test, and seismic, Table 1. In spite of its small scale of investigation (a few inches), core data is still the only data that can be measured directly, thus has been considered as hard data for log calibration, provided that the laboratory core analysis program is designed to be fit-for-purpose[1].

In terms of the scale of investigation, the large scale kilometers, (km) seismic survey also has higher data coverage of the field, but the uncertainties of seismic interpretation are much higher than the smaller scale (from a few inches to several feet) log interpretations because the measurements are far away from the reservoir. This long distance between the measurement sensors and the measuring object limits the measurement

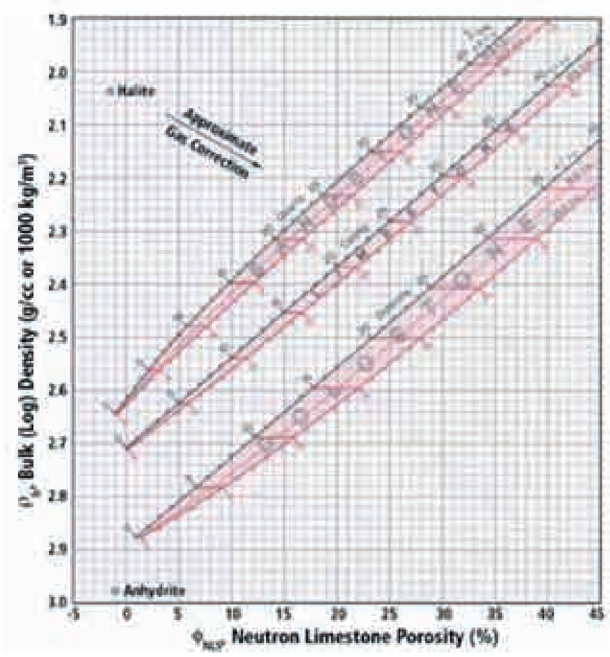


Figure 1 - An example of DNCP chart for determination of reservoir lithology and porosity (DSN-II neutron tool with fluid density of 1.00 g/cc, Halliburton, 1995).

physics to be acoustic only and interpretations are often calibrated with well logs and tests. Consequently, applications of seismic are limited to identifying reservoir structures such as large fractures/faults. Time lapse 4D seismic for reservoir fluid characterization has, so far, limited success.

Petrophysical Properties from Logs

Three fundamental petrophysical properties routinely derived from logs are lithology, porosity, and saturation. The most commonly used and straight-forward method for determining reservoir lithology and porosity is the densityneutron cross-plot (DNCP) charts, as exampled in Fig. 1. Each service provider, wireline or logging while drilling (LWD), has generated DNCP charts for their densityneutron tools.

When using a DNCP chart to determine reservoir lithology, rock MEP densities are required. For example, with known densities of limestone (ρlog,lim) and dolostone (ρlog,dol) of a dolomitic limestone reservoir (ρlog,ma), the reservoir lithology can be interpolated linearly.

$$V_{lim} = \frac{\rho_{log,dol} - \rho_{log,ma}}{\rho_{log,dol} - \rho_{log,lim}}$$

Even though Eq. 1 indicates that reservoir lithology characterization is directly related to the values of the MEP densities, a brief literature survey revealed that rock matrix densities quoted by reference books may not always be consistent, as summarized in Table 2.

	BA Charts	HAL Charts	SLB Charts	Arab-D Studies
ρ_{lim}	2.71	2.71	2.71	2.710*
ρ_{dol}	2.87	2.87	2.85	2.846*
ρ_{anh}	2.96	2.96	2.96	2.967*
ρ_{gps}	2.31	2.32	2.32	NA
Pef_{lim}	5.08	5.08	5.1	5.10#
Pef_{dol}	3.14	3.14	3.1	3.25#
Pef_{anh}	5.06	5.06	5.1	4.80#1
Pef_{gps}	3.99	3.99	4.0	NA
Σ_{lim}	5.08	5.08	5.1	5.10#
Σ_{dol}	3.14	3.14	3.1	3.25#
Σ_{anh}	5.06	5.06	5.1	4.80#1
Σ_{gps}	3.99	3.99	4.0	NA
$\phi_{TN,lim}$	0	0	0	0.40#
$\phi_{TN,dol}$	0.5	0.5	1	1.25#
$\phi_{TN,anh}$	-0.7	-0.7	-2	-0.10#
$\phi_{TN,gps}$	57.6	53	60+	NA
$\phi_{EN,lim}$	0	-0.2	0	0.00#
$\phi_{EN,dol}$	1.5	1.3	2	1.40#
$\phi_{EN,anh}$	-1.2	-0.4	-1	-0.90#
$\phi_{EN,gps}$	58.5	48.4	50+	NA

*: *Data from Table 3 of Ma, et al. (2002).*
#: *Data from this study.*
#1: *Data from this study with potential mineral transformation during laboratory tests.*

Table 2. Summary of carbonate rock properties.

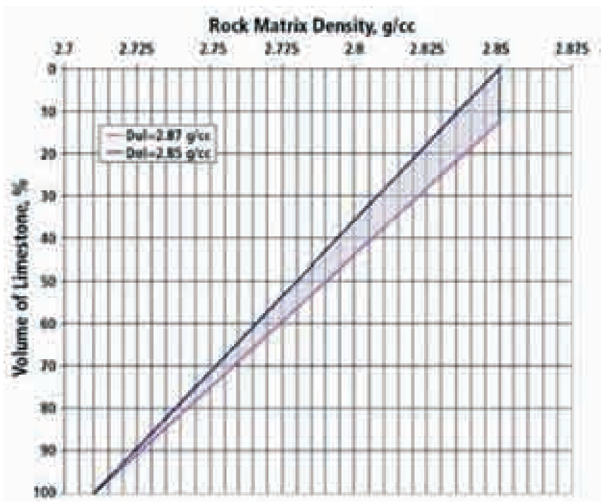


Figure 2 - Varying dolostone matrix density from 2.85 g/cc to 2.87 g/cc can result in more than 10% of calculated lithology errors for dolomitic rocks.

Depth 20.00	Sample ID
?define rock1 = 2.719 (H2O) 0.700E-02	matrix density, structural water content
?define rock2 = (SiO2) 0.740E-02	concentration of SiO2
?define rock3 = (Al2O3) 0.700E-03	concentration of Al2O3
?define rock4 = (CaO) 0.545E+00	concentration of CaO
?define rock5 = (MgO) 0.130E-01	concentration of MgO
?define rock6 = (Na2O) 0.300E-03	concentration of Na2O
?define rock7 = (K2O) 0.200E-03	concentration of K2O
?define rock8 = (Fe2O3) 0.210E-02	concentration of Fe2O3
?define rock9 = (TiO2) 0.200E-03	concentration of TiO2
?define rock10 = (P2O5) 0.000E+00	concentration of P2O5
?define rock11 = (B) 0.000E+00	concentration of B
?define rock12 = (SO3) 0.250E-02	concentration of SO3
?define rock13 = (F) 0.144E-02	concentration of F
?define rock14 = (Rb) 0.000E+00	concentration of Rb
?define rock15 = (Sr) 0.225E-03	concentration of Sr
?define rock16 = (Y) 0.000E+00	concentration of Y
?define rock17 = (Zr) 0.190E-04	concentration of Zr
?define rock18 = (Nb) 0.000E+00	concentration of Nb
?define rock19 = (Ba) 0.000E+00	concentration of Ba
?define rock20 = (Th) 0.100E-06	concentration of Th
?define rock21 = (U) 0.180E-05	concentration of U
?define rock22 = (La) 0.111E-05	concentration of La
?define rock23 = (Ce) 0.238E-05	concentration of Ce
?define rock24 = (Sm) 0.200E-06	concentration of Sm
?define rock25 = (Eu) 0.421E-07	concentration of Eu
?define rock26 = (Gd) 0.200E-06	concentration of Gd
?define rock27 = (CO2) 0.411E+00	concentration of CO2
?define rock28 = (Cl) 0.700E-03	concentration of Cl
?define rocka="rock1" "rock2" "rock3" "rock4" "rock5" ?define rockb="rock6" "rock7" "rock8" "rock9" "rock10" ?define rockc="rock11" "rock12" "rock13" "rock14" "rock15" ?define rockd="rock16" "rock17" "rock18" "rock19" "rock20" ?define rocke="rock21" "rock22" "rock23" "rock24" "rock25" ?define rockf="rock26" "rock27" "rock28" ?define rock="rocka" "rockb" "rockc" "rockd" "rocke" "rockf"	combination of rock matrix elements
?define water = 1 H2O	pore fluid, fresh water
help option sigma on help option pe on	modeling option
0.804 "rock" 0.196 SALT(0.0 a)	volume of matrix porosity, salinity
AmBe	nuclear source

Table 3 - An example of SNUPAR inputs.

It should be noted that there is a slight difference between ρma determined in the laboratory (mass density) and ρlog,ma derived from DNCP chart (electron density) as given in Eq. 2.

$$\rho_{log,ma} = 1,0704\, \rho_{ma} \frac{2Z}{A} - 0,1883 \quad (2)$$

The differences in listed matrix densities can lead to large uncertainties in computed lithology. For dolostone, 2Z/A = 0.99791, then if ρdol = 2.85 g/cc, this is equivalent to ρlog,dol = 2.856 g/cc while if ρdol = 2.87 g/cc, this is equal to ρlog,dol = 2.877 g/cc. This difference in dolostone densities of 2.85 g/cc and 2.87 g/cc can result in more than 10% lithology calculation errors in dolomitic rocks, as demonstrated in Fig. 2.

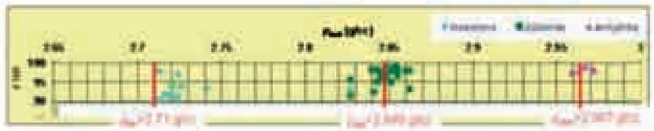


Figure 3 - Modeled matrix density vs. FTIR mineralogy.

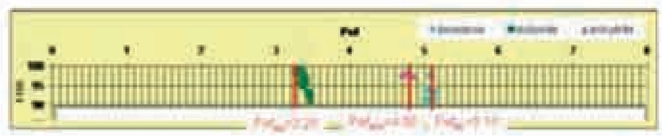


Figure 4 - Modeled matrix Pef vs. FTIR mineralogy.

Nuclear Parameter Modeling for Reservoir Petrophysical Properties

Many rock petrophysical properties can be routinely measured in the laboratory[3]. Others, such as Pef and Σ, are more difficult to obtain[4] even though they are used routinely in formation evaluation. A Schlumberger NUclear PARameter modeling software (SNUPAR) was developed for determining those difficult-to-obtain rock properties[5] and has been successfully used in developing the first lithology logging tool; the ECS (Elemental Capture Spectroscopy)[6].

In SNUPAR, there is a large database of cross sections of elements and/or isotopes commonly found in rock materials and nuclear tools that have large thermal neutron absorption cross sections; important for neutron transport modeling. The main outputs of SNUPAR are:

1. Electron density ρe and density of the material ρma.
2. Photoelectric factor Pef.
3. Volumetric photoelectric absorption coefficient U.
4. Thermal neutron capture cross section Σ.
5. Hydrogen index (HI).
6. Apparent thermal neutron porosity (ATNP).
7. Apparent epithermal neutron porosity (AENP).

Depth (Sample ID)=20

Z	Element	Atomic Weight A	Mass Fraction	Atom Fraction	Partial Density (g/cc) ρ	Number Density (atoms/b-cm)	Microscopic σ (barns)	Macroscopic Σ (c.u.) = N*σ*ρ/A	Contribution to Σ	Pef	Contribution to Pef
1	H	1.000	0.009917	0.164146	0.023620	1.41109E-02	3.3198E-01	4.685	40.843%	0.000	0.000%
6	C	12.011	0.103803	0.144192	0.247230	1.23956E-02	3.5300E-03	0.044	0.381%	0.016	0.350%
8	O	16.000	0.510035	0.531852	1.214762	4.57209E-02	1.9000E-04	0.009	0.076%	0.226	4.844%
9	F	19.000	0.001333	0.001170	0.003174	1.00599E-04	9.6000E-03	0.001	0.008%	0.001	0.018%
11	Na	22.991	0.000206	0.000149	0.000491	1.28491E-05	5.3000E-01	0.007	0.059%	0.000	0.006%
12	Mg	24.320	0.007257	0.004978	0.017283	4.27965E-04	6.3000E-02	0.027	0.235%	0.014	0.293%
13	Al	26.980	0.000343	0.000212	0.000817	1.82257E-05	2.3100E-01	0.004	0.037%	0.001	0.018%
14	Si	28.090	0.003201	0.001901	0.007625	1.63461E-04	1.7100E-01	0.028	0.244%	0.011	0.227%
16	S	32.066	0.000927	0.000482	0.002207	4.14456E-05	5.2000E-01	0.022	0.188%	0.005	0.106%
17	Cl	35.457	0.000655	0.000308	0.001561	2.65043E-05	3.3100E+01	0.877	7.649%	0.004	0.090%
19	K	39.100	0.000154	0.000066	0.000366	5.63631E-06	2.1000E+00	0.012	0.103%	0.001	0.032%
20	Ca	40.080	0.360468	0.150065	0.858535	1.28995E-02	4.3000E-01	5.547	48.361%	4.325	92.503%
22	Ti	47.900	0.000111	0.000039	0.000264	3.32253E-06	6.0900E+00	0.020	0.176%	0.002	0.037%
26	Fe	55.850	0.001359	0.000406	0.003237	3.49084E-05	2.5600E+00	0.089	0.779%	0.039	0.837%
38	Sr	87.630	0.000209	0.000040	0.000498	3.42327E-06	1.2100E+00	0.004	0.036%	0.022	0.470%
40	Zr	91.220	0.000018	0.000003	0.000042	2.76471E-07	1.8500E-01	0.000	0.000%	0.002	0.048%
57	La	138.920	0.000001	0.000000	0.000002	1.06058E-08	8.9000E+00	0.000	0.001%	0.000	0.009%
58	Ce	140.130	0.000002	0.000000	0.000005	2.25440E-08	7.3000E-01	0.000	0.000%	0.001	0.022%
62	Sm	150.360	0.000000	0.000000	0.000000	1.76568E-09	5.6000E+03	0.010	0.086%	0.000	0.002%
63	Eu	152.000	0.000000	0.000000	0.000000	3.67641E-10	4.3000E+03	0.002	0.014%	0.000	0.001%
64	Gd	157.250	0.000000	0.000000	0.000000	1.68820E-09	4.9000E+04	0.083	0.721%	0.000	0.003%
90	Th	232.050	0.000000	0.000000	0.000000	5.72011E-10	7.5600E+00	0.000	0.000%	0.000	0.004%
92	U	238.070	0.000002	0.000000	0.000004	1.00358E-08	7.6800E+00	0.000	0.001%	0.004	0.081%
	SUM=	1788.47	1.000001	0.999999	2.381723	0.085966	5.8972E+04	11.471	100.0%	4.874	100.0%

Table 4 - An example of SNUPAR outputs.

> Reservoir characterization is typically done using rock properties derived from well logs, after calibrating with core. In core-log calibration, core analysis data is often considered as the "ground truth" even though the quality of core data depends on many factors such as test conditions and procedures[1].

Table 3 shows an example of the SNUPAR inputs. They require rock elemental chemistry analysis for mineral compositions and routine core analysis for matrix density and rock porosity.

With the inputs as shown in Table 3, SNUPAR performsneutron transport modeling and outputs nuclear parameters. Examples of Σ and Pef modeling are shown in Table 4. Similar modeling work was performed on the 99 samples, including limestone, dolostone, and anhydrite, studied previously[3] and the modeling results are plotted against FTIR mineralogy in order to determine MEP properties.

Figure 3 shows the modeled matrix density ρma, Fig. 4 Pef, Fig. 5a Σ, Fig. 6 ATNP, and Fig. 7 AENP. With these cross-plots, MEP properties have been determined and summarized in Table 2.

In Fig. 3, the modeled matrix grain densities (data points) are compared with the measured ones (the vertical bars)[3]. The agreements are good considering that any impurities in limestone samples will only make their densities higher in these carbonate rock samples whereas for dolostone, impurities can make the density higher or lower.

The modeled limestone Pef of 5.10 is almost exactly the same as that referenced in log interpretation chart books from the three major logging service companies[7,8]. The lower limit of dolostone Pef of 3.25 is only slightly higher than the often quoted value of 3.1, Table 2. The lower limit of Pef for the dolostone samples is picked as the dolostone Pef because any impurities (limestone or anhydrite) will only make dolostone Pef higher.

Using laboratory data as inputs, the modeled Pef for anhydrite samples are averaged to be 4.80; lower than often quoted value of 5.1. This reduction in Pef is probably related to anhydrite/gypsum transformation between tests in the laboratory. More details regarding anhydrite vs. gypsum are given in the Appendix.

It should be noted that Pef is not volumetric, in other words, Pef of a mixture is the mass weighted average rather than the volume weighted average of its components. Usually, petrophysicists use the volumetric photoelectric absorption coefficient U for reservoir lithology calculation.

$$U = \rho_e Pef \qquad U_b = \sum_{i=1}^{n} V_i U_i \tag{3a}$$

Where vi and Ui are the volume and U for each component in the bulk mixture including rock minerals and pore fluids.

For Arab-D limestone and dolostone in this study, the matrix Uma can be determined as Eqs. 3b and 3c and used for lithology calculation as Eq. 3d.

$$U_{lim} = 2.708x5.1=13.81 \tag{3b}$$

$$U_{dol} = 2.84x3.25=9.23 \tag{3c}$$

$$V_{lim} = \frac{U_{dol} - U_{ma}}{U_{dol} - U_{lim}} \tag{3d}$$

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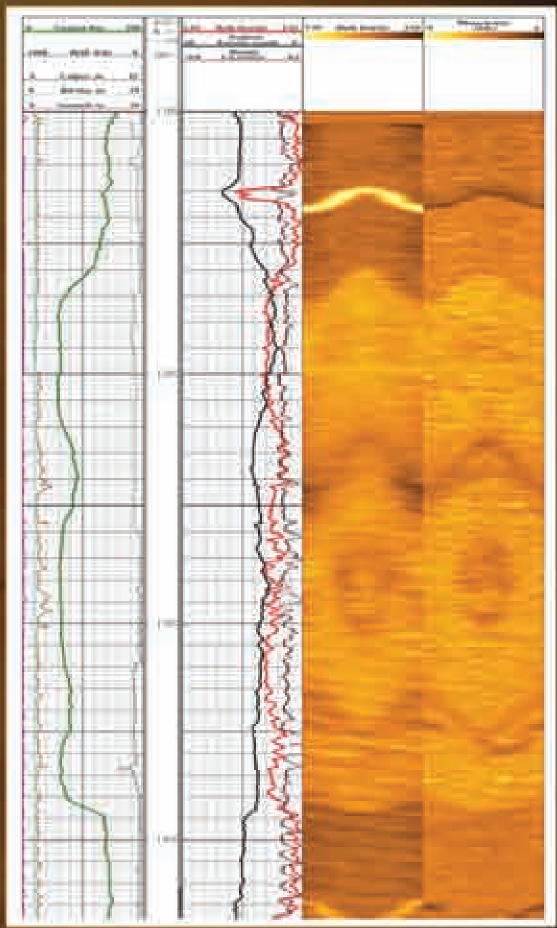

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Figure 5a - Modeled matrix sigma vs. FTIR mineralogy.

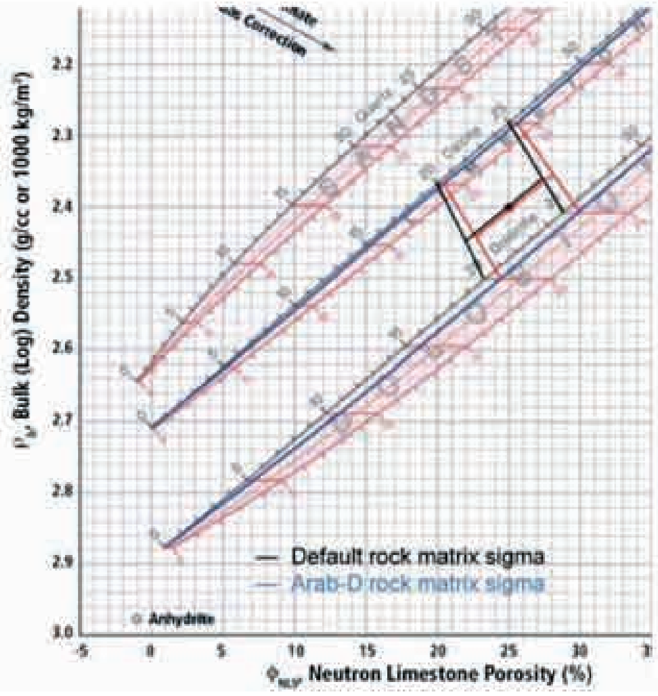

Figure 5b - Dependence of log interpretation for lithology and porosity on reservoir rock matrix Σ.

Reservoir specific MEP Σs are the most important aspect of this study since they directly affect the accuracy of logderived lithology and porosity. From Fig. 5a, the modeled data suggests Σlim = 8.15 and Σdol = 6.0 (considering that any impurities in the dolostone samples will only increase the modeled sigma). Without the reservoir specific MEP Σs, default values of Σlim = 7.1 and Σdol = 4.7 have to be used in log processing. Now with the newly obtained Σlim and Σdol, new DNCP charts for the Arab-D reservoirs can be generated for neutron tools as exampled by Fig. 5b for more accurate reservoir rock lithology characterization and porosity calculation.

Alternatively, the default DNCP charts can also be used for log processing if effects of MEP Σs on neutron log have been corrected[9]. To perform this environmental correction, reservoir specific Σs are required. Another approach is to calculate ATNP by using the default Σs, and then correct for the effect of matrix Σ, Fig. 5c for limestone and 5d for dolostone. In summary, one service company prefers correcting matrix Σ effect on neutron before DNCP chart for lithology and porosity. This approach may be the most logical since all log interpretation charts/models can be

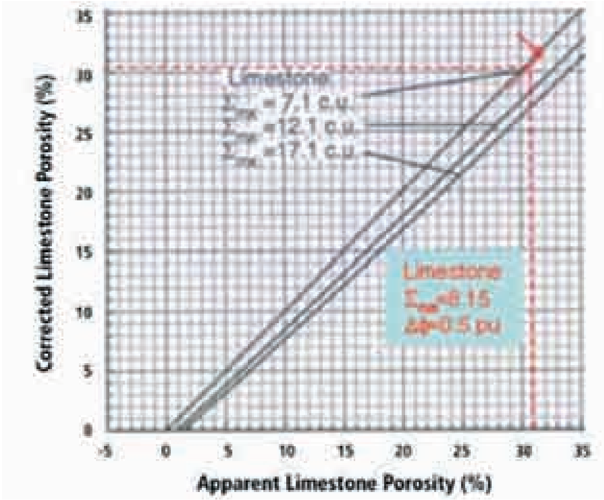

Figure 5c - Correction of limestone porosity due to effect of matrix Σ – Effect of neutron absorber in rock matrix on 2435/2438 CN logging tools (Baker Atlas, 1995).

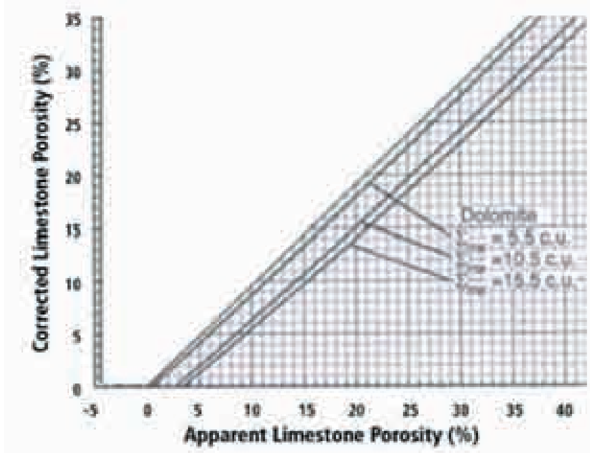

Figure 5d - Reservoir rock matrix Σ correction of dolostone porosity – Effect of neutron absorber in rock matrix on 2435/2438 CN logging tools (Baker Atlas, 1995).

kept identical after this Σ correction. Another service company prefers correcting the Σ effect during DNCP, Fig. 5b. This approach is the most intuitive of demonstrating the Σ effect and the impact on log-derived reservoir lithology and porosity if this effect is not account for. Lastly, the third service company prefers to correct the Σ effect after DNCP, Figs. 5c and 5d. This is the easiest approach to demonstrate the impacts of reservoir specific matrix Σ on log-derived reservoir properties, as illustrated in Fig. 5c for limestone and Fig. 5d for dolostone. All methods should produce similar results and all require reservoir specific Σs.

Since the determined Σlim and Σdol for Arab-D rocks are close to the default values, the effects of these small differences on the derived lithology and porosity may not be very large. But for giant reservoirs such as Arab-D, a small difference in the porosity unit (pu) such as 0.5 pu (i.e., Fig. 5c) can be

> Rock matrix may not be simple mineral mixtures. Impurities, such as those high neutron absorbers, can cause rock nuclear properties differing from that of pure minerals.

equivalent to a large quantity of oil. Thus, it still has significant impact on reservoir management.

It is noted that the lower limit of anhydrite Σ of 15.6 is higher than the often quoted value of 12, Fig. 5a. Data seems approaching to that of gypsum which is about 19, Table 2. Further investigations are required to fully understand the behavior of anhydrite nuclear parameters (Pef and Σ) even though it has minimum impact on the main objectives of this study which is to improve the accuracy of log-derived lithology and porosity in dolomitic limestone reservoirs. It is important however, to obtain representative anhydrite parameters since it is the best marker for log quality control in Arab-D reservoirs.

It is highly likely that part of the anhydrite powder samples may have been transformed to gypsum during/between tests by taking moisture from the laboratory environments. Laboratory procedures and sequences were documented[3] and more information on transformation between anhydrite and gypsum are provided in the appendix.

Matrix end point for neutron log is important for lithology and porosity interpretation. In addition, ATNP is often used as a gas indicator; errors in the expected MEP can result in misidentification of hydrocarbon type, particularly in lower porosity and carbonate formations. Since the neutron log is often the only measurement available in cased hole, it can be particularly important in older wells which does not have open hole logs.

> Use of pure mineral default log interpretation charts may result in errors in determined rock properties which could be significant, especially for giant reservoirs.

Matrix end point density, Pef, and Σ are rock properties and are independent of logging tools. Values of ATNP and AENP are mostly determined by rock matrix; but also, to a certain extend, dependent on the design of logging tools. Figures 6 and 7 are SNUPAR modeled ATNP and AENP, using correlating equations based on Schlumberger CNL tool, Eqs. 4 and 5. Data scatterings shown in Figs. 6 and 7 may be due to small amounts of water, H2O+, which were incompletely removed from the powder samples before analysis.

$$ATNP = 10^{\frac{\log\left(\frac{\sqrt{L_s^2 + L_d^2\left(c_1\sqrt{L_s} - c_2\right)}}{c_1}\right)}{c_2}} - c_3 \qquad (4)$$

and

$$AENP = c_4 e^{-(c_1 L_s + c_2)^{n}} \qquad (5)$$

Where Ls and Ld are neutron slowing down length and thermal diffusion length, respectively, and c1, c2, c3 and c4 are constants.

Note that AENP (energy from 0.025 to 1 eV) is a function of Ls only while ATNP (with a lower energy of about 0.025 eV) depends on both Ls and Ld, and Ld is a function of Σma. Therefore, unlike ATNP, AENP is insensitive to neutron absorbers existing in borehole or in formation, thus it provides a more accurate formation porosity measurement and extremely useful for cross-well correlations. Comparing to AENP, ATNP is more sensitive to gas, thus is a better gas indicator when compared to density/sonic logs.

The scattered data in Figs. 6 and 7 indicated that modeling tool responses is probably less robust than modeling rock intrinsic properties (Figs. 3, 4 and 5a) since several empirical correlations, such as Eqs. 4 and 5 were used. It is also possible that the modeled data is influenced by small amounts of water, H2O+, which were incompletely removed from the powder samples before analyses.

For comparison, results of Figs. 6 and 7 are summarized in Table 2. The difference between AENP and ATNP at the MEP is small, but it can be more significant in cases where Σma is more profound different than the often-quoted values[10].

Conclusion

Based on laboratory core and elemental chemistry analyses and SNUPAR modeling of Arab-D carbonates, the following are concluded:

1. Rock matrix nuclear properties such as density, Σ, and Pef are important parameters in log interpretation for reservoir lithology and porosity.

2. Rock matrix may not be simple mineral mixtures. Impurities, such as those high neutron absorbers, can cause rock nuclear properties differing from that of pure minerals.

Nomenclatures	
A	atomic weight
D	thermal neutron diffusion
L	neutron transport length
N	Avagadro's number
U	Volumetric photoelectric absorption coefficient
V	volumetric
Z	atomic number
ϕ	porosity
ρ	density
σ	microscopic capture cross section
Σ	macroscopic capture cross section

Subscript	
any	anhydrite
d	thermal neutron diffusion
dol	dolomite
e	electron
EN	epithermal neutron
gps	gypsum
lim	limestone
log	log
ma	matrix
s	neutron slowing down
TN	thermal

3. Use of pure mineral default log interpretation charts may result in errors in determined rock properties which could be significant, especially for giant reservoirs.

4. Matrix density, Pef, and Σ are obtained for Arab-D limestone and dolostone and should be used in routine log interpretation for accurate formation evaluation. The values are Σlim = 8.15, Σdol = 6.00, Peflim = 5.10, Pefdol = 3.25, Ulim = 13.81 and Udol = 9.23.

5. Chemically, anhydrite samples may not be stable under laboratory conditions, especially the powder samples obtained by crushing core plugs. Special handling of anhydrite samples in the laboratory is required to prevent them from transforming into gypsum which has significant different petrophysical properties.

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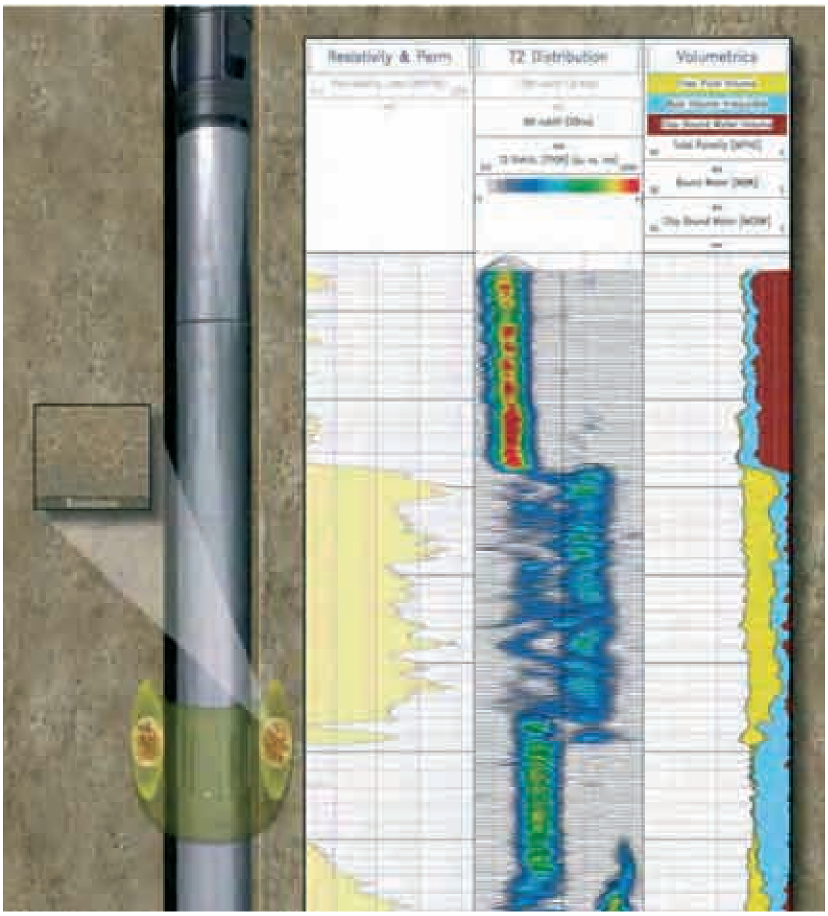
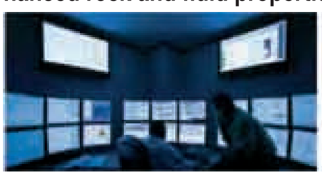
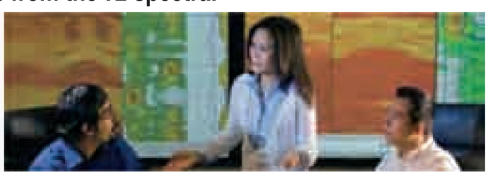
An Operator's understanding of a reservoir's petro-physical properties will drive critical decisions that impact both real-time operations and the long-term balance sheet. This is why INTEQ's accurate and timely answers regarding reservoir fluid volumes and properties prove so valuable to operators. Using MagTrak answers, they are able to achieve a comprehensive understanding of the down whole environment in order to optimize a well's ultimate productivity.



With the introduction of MagTrak advanced LWD magnetic resonance services, INTEQ is the first in the industry to deploy real-time T2 distribution, capturing the full potential of the measurements while drilling. The log above reveals a variety of information delivered at the well site, including porosity for reservoir storage potential, identification of zones with producible fluid, as well as enhanced rock and fluid properties from the T2 spectra.





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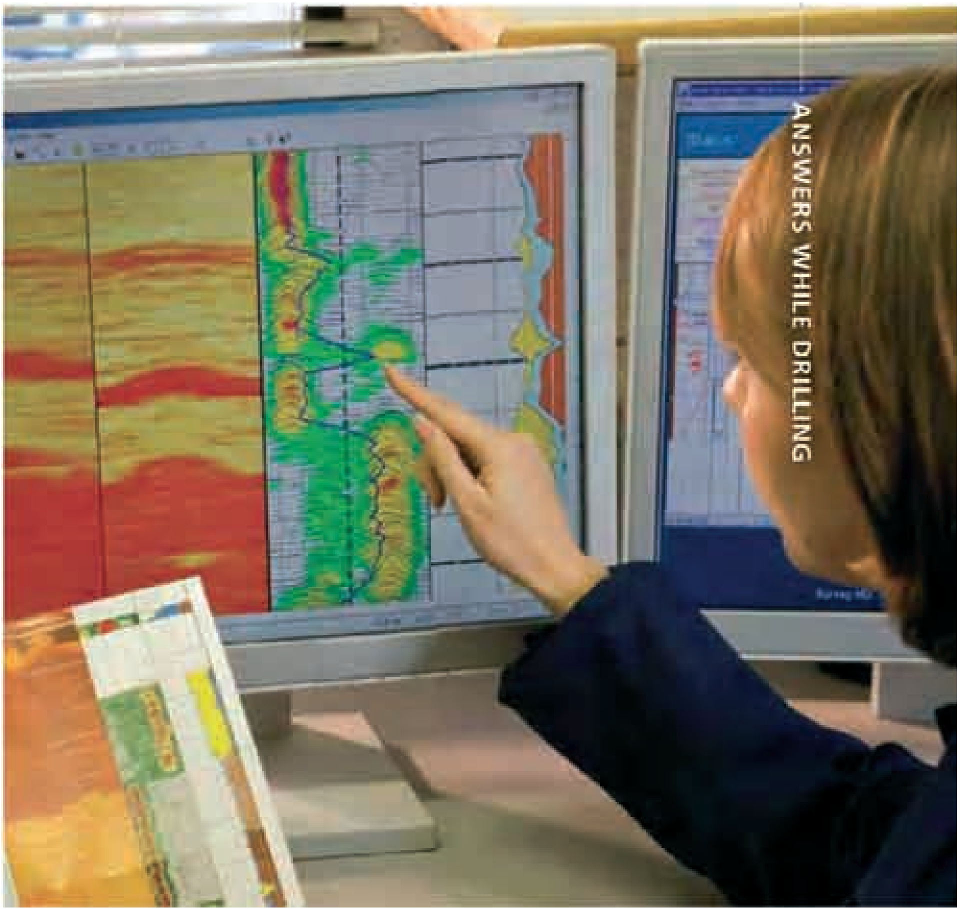


the system's ability to overcome the effects of down hole drilling vibrations to deliver uncompromised T2 Measurements.

Accurate T2 magnetic resonance logs

MagTrak magnetic resonance while drilling offers direct measurements of fluid-filled porosity, regardless of the complexity of the logging environment and without the need for a radioactive source - delivering valuable answers while drilling.

Whether the question involves estimating movable fluids in a shaley sand sequence, designing an enhanced completion strategy or determining the optimal 'sweetspot' for reservoir navigation, the MagTrak service can help deliver the answer. The real-time answers petrophysicists, geologists drillers and reservoir engineers need to make critical decisions with confidence. This confidence is based on reliable motion-insensitive measurements and superior vertical resolution.

TAR Detection Application – Saudi Arabia

The MagTrak was deployed in different scenarios in Saudi Arabia, ranging between high angle and extended–reach well profiles, and confirmed that the triple-combo, MagTrak and TesTrak (formation tester) combination can be used for effective and robust tar detection in real time application.

With MagTrak, INTEQ clients can make real-time and post-well decisions with assurance for improved:

• Direct measurements of fluid-filled porosity independent of lithology or radioactive sources for environmentally sensitive reservoir characterization

• Dependable estimates of moveable fluids in shaley sands and other complex lithologies for optimized reservoir drainage strategies.

• Intrinsic T2 Magnetic resonance data from the low magnetic field gradient design for reliable measurements.

Micro-Imaging Improves Wellbore Data Accuracy

Borehole images are widely used in geological, petrophysical, and geo-mechanical studies. This is because borehole imaging is a powerful tool which helps characterize the depositional setting of sedimentary rocks, delineate reservoirs, derive rock properties, and assess their potential to produce hydrocarbons. Optimizing reservoir recovery also requires reliable and precise geological and reservoir modeling.

By Rob Christie, Weatherford International Ltd.

Micro-resistivity imagers provide more accurate well-bore data. This can help to more precisely delineate geological structures such as folds, faults, or unconformities and fractures. They can also be used in geomechanical studies such as borehole stability and local stress determination, sedimentology and stratigraphic analyses for paleocurrent or depositional environments. Last but not least, they can also be used to integrate high resolution resistivity measurements into the petrophysics model. This enables a highly detailed evaluation of subsurface geology to be integrated with traditional petrophysical measurements.

Additionally, micro resistivity imaging offers continuous, high resolution in-situ rock measurements that are acquired cost-effectively and efficiently. Consequently, micro-imagers offer the ability to characterize the 'rock-fabric', image the borehole and provide a better overall understanding of the rock without coring.

Slim-hole logging

The latest generation of slim-hole diameter micro-resistivity logging tools show how advances in solid state electronics have led to improvements in reliability and operational efficiency as well as saving time and reducing costs. Development of Weatherford's new Compact Micro Imager (CMI) micro-resistivity tool enables E&P companies to gain high-resolution image data vital to successfully ascertain and interpret formation and well-bore characteristics. The tool's unique design, recording capabilities and deployment flexibilities allow such measurements to be taken in a variety of well-types. The tool is deployed on a special shuttle system which does not require wireline which lowers cost and risk.

As the tool can be deployed without wireline, it is not constrained by standard data transmission rates. Instead, high-resolution data are recorded to internal solid state memory chips similar to those found in USB sticks. The tool is deployed inside the drillpipe on a specially designed shuttle system which can pass through tortuous and highly deviated and horizontal wells without compromising borehole coverage. The shuttle is attached to the bottom of a conventional drillstring and consists of the logging tools, drillpipe, and mechanisms for retaining and releasing the tools. The logging string is housed inside the drillpipe at surface and remains inside until tripped to TD. There is no need for wireline. Data are acquired while the drillpipe is tripped out of the hole. In addition to the logging tools and surface system, the shuttle consists of a latching sub, running tool, messenger, circulating and landing sub, float valve, and mule-shoe.

Imaging the Geology

Batteries provide the power in wireless mode, and image data are recorded in time-domains to a dedicated flash-memory module. Merging this data with time-depth logs recorded by surface instrumentation (using techniques similar to LWD) generates depth based logs. As the high-resolution image data are recorded to flash-memory chips inside the tool sonde neither conventional wireline nor a surface winch system is required. Wellsite operations are simplified by replacing the traditional wireline unit with a small acquisition laptop computer.

For an improved wellbore image, each 5mm button on the tool measures a resistivity, and measurements are recorded every 2mm for a total of 500 samples per meter. These resistivity measurements are mapped to a false-color palette, and a high-resolution image of the borehole is generated. Images are oriented to north or the top of the borehole using three-axis accelerometers and magnetometers. The three-dimensional images are "unwrapped" into an industry-standard, two-dimensional view that can be plotted on paper. On the two-dimensional image, planar surfaces are represented by sinusoids that identify geological features such as bedding and fractures.

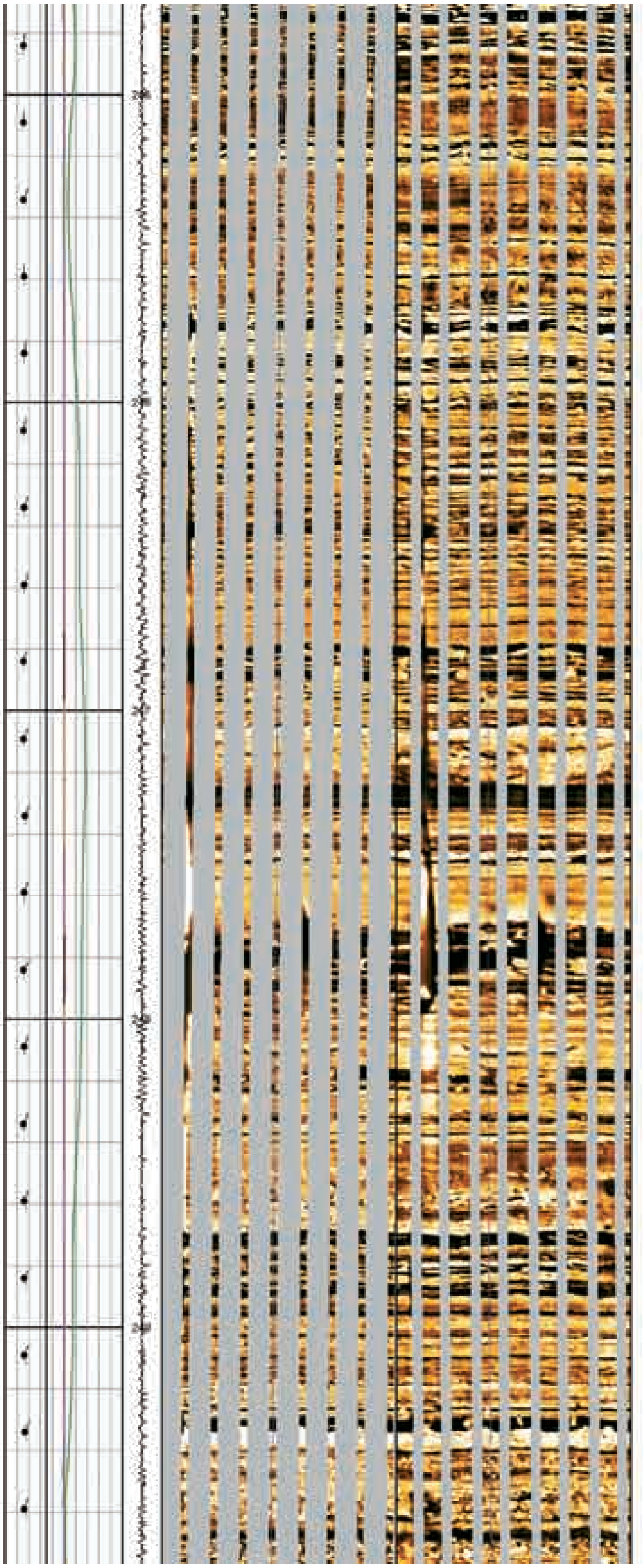
Two different types of images are typically generated—static and dynamic. The static image maps the resistivities over the entire log interval to the color palette. The dynamic image maps the resistivities to the color palette over a user-defined interval, usually about 1m. The dynamic image shows greater detail and resolution in zones of more homogeneous resistivity.

Identifying Operational Advantages

In addition to the wealth of detailed information obtained by the tool, several operational advantages were found by using the shuttle deployment system as opposed to traditional pipe-conveyed logging.

Speed Correction

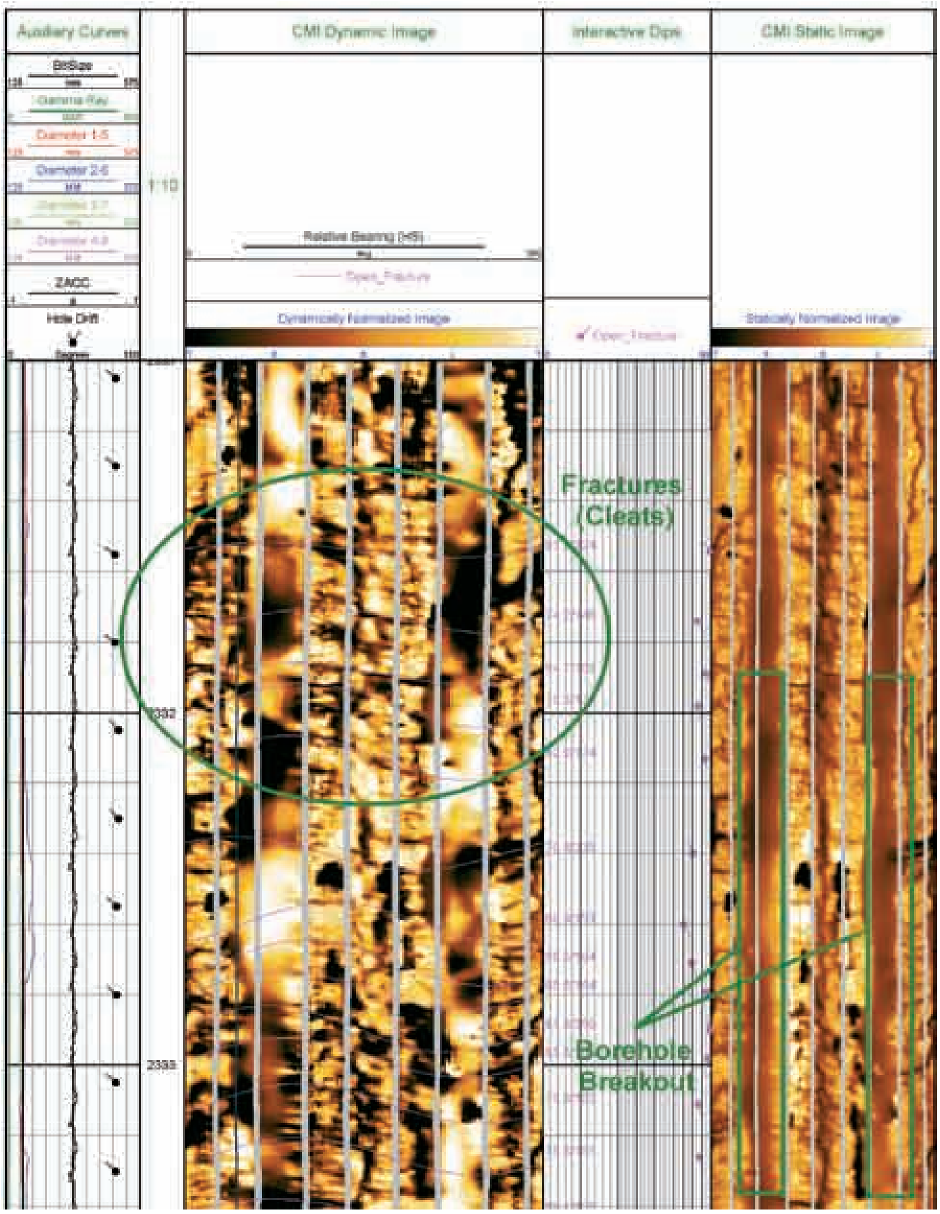
Whenever data are converted from time to depth, data loss occurs since not every time sample has a corresponding depth sample, depending on logging speed. High-resolution data recorded to a flash memory inside the tool allowed a unique time-domain speed correction to be developed. Speed correction is a critical component for imaging logs, which allows time-depth resolution. Stick-slip and pad-pad mismatch, the most common discrepancies resulting from irregular tool motion, are rectified with speed correction. The entire original time-domain data set allows speed correction to occur using



all available data, instead of the usual "abridged" depth-domain data. The result is a more robust correction and a better overall image.

Tool Protection

Housing the tools in a "garage" while running in the hole prevents exposure to washouts, bridges and other potential trouble spots. The shuttle system also enables the driller to rotate up to 60 rpm and circulate up to 40 bbl/min through the drillpipe while tripping in the hole. This is an important capability not available with conventional pipe conveyed logging. This feature enables the pipe to be worked past doglegs or bridges and allows circulation once on bottom,



Mechanical and Electrical Reliability

In contrast to historical pipe conveyed logging operations, the shuttle system does not use latches or wet connects—known to be unreliable elements. In conventional tool push logging, the wireline is pumped through the inside of the drillpipe until the pins on the latch physically engage with the wet connect on top of the tools. Any debris inside the pipe can prevent this physical latching. The wireline runs from the tool up through the inside of the drillpipe and exits through a side-door sub. From there the wireline runs to surface between the drillpipe and casing.

To keep the wireline from being physically damaged, the side-door sub (and the exposed wireline above it) must be kept within the casing. This configuration means the length of lateral logged cannot exceed the length of the casing if time-consuming multiple latches are to be avoided. The operator must then choose between risking wireline in open hole or drilling multiple-stage wells with intermediate strings of casing that greatly increases complexity and cost. Multiple latches degrade the physical and electrical connection and decrease the odds of getting a good latch with each subsequent attempt.

As the CMI uses a special shuttle system, the tools are tripped to TD, and pumped out of the bottom hole assembly without the need for any wireline or latches. The pipe is then pulled out of the hole in one continuous operation regardless of the length of the lateral which greatly increases both the mechanical and electrical reliability of the entire logging operation.

Rig Time Reduction

During initial logging trials in the field, this single, continuous shuttle logging pass significantly reduced rig time and the operator found the following improvements:

• Higher probability of getting better quality image data over the entire lateral from toe to heel.

• Higher degree of certainty in the completion of subsequent operations (such as getting a liner or casing in the hole) because the well is open for less time. This feature is particularly critical in lithologies that are inherently less stable such as coalbed methane.

• Fewer personnel on the rig floor, less equipment, and fewer operations, which increases safety.

Combining the latest micro-resistivity imaging tool with shuttle deployment has allowed the operator to realize

> Recent discoveries have shown that fractures in deep and tight rocks play an important role in the productivity of low-permeability formations such as coal seams that contain methane gas.

operational efficiencies and cost savings. The quality of data acquired has been at least as good as, if not better than previous generation technologies.

Optimizing Coalbed Methane Production

Recent discoveries have shown that fractures in deep and tight rocks play an important role in the productivity of low-permeability formations such as coal seams that contain methane gas. Since the fracture system that defines the coal seam determines production viability, it is imperative to understand the coalification process and characteristics of the resulting coal seams. Accurately locating and identifying these fractures, called cleats, has been a somewhat elusive task with conventional logging tools. Because cleats are below the resolution of standard measurements, using micro resistivity imaging allows features with a resistivity contrast that are 2mm and smaller to be identified, characterized, and measured.

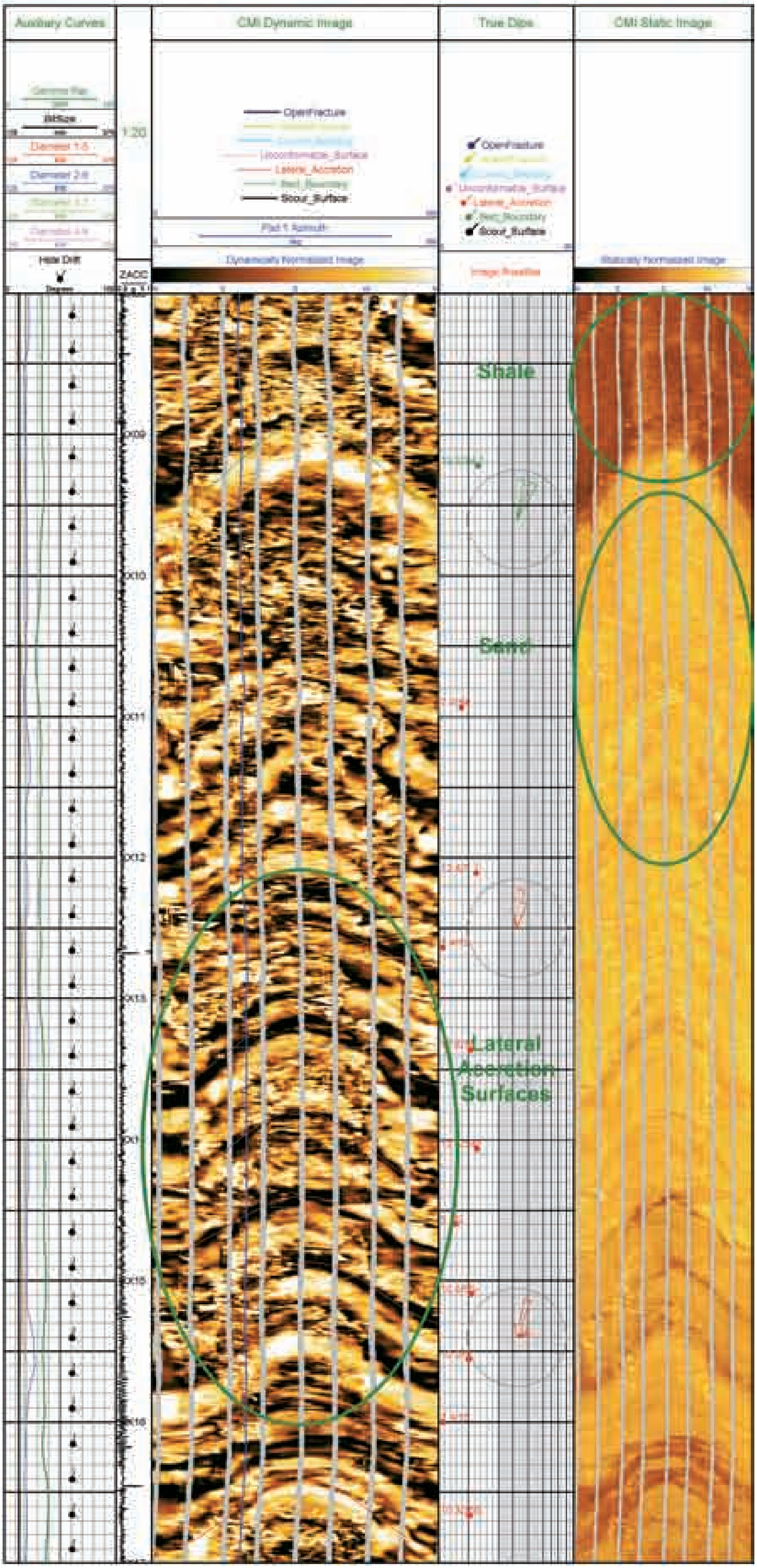
The coalification process, or coal genesis, begins when peat material becomes compacted and starts to generate heat from bacterial action. Upon further burial, coal takes shape in the form of lignite. With increasing temperature and pressure, the coal matures and drives off moisture and volatile gases, eventually transitioning to anthracite, the most mature coal. This dehydration and devolatilization causes the coal to "shrink" and create the natural fractures, or cleats, through which molecules of methane travel to the wellbore.

Unlike oil-bearing formations, coal itself is not permeable and the only way to access the methane lining the pore surface within the coal is through the cleats. Cleats are oriented perpendicular to the bedding and provide the primary conduit for fluid flow. Gas diffuses from the matrix into the cleats and flows to the wellbore. Because face cleat direction is typically more productive, it is important to intersect as many of these fractures as possible, which means drilling in a preferential direction to optimize production.

Coalbed methane has been a historical challenge because traditional logging methods do not work well. High-resolution density logging can tell where coal seams are located, but since the vertical resolution of these tools is typically about 18 inches, they give no indication of cleating, which occurs on a much smaller scale. With the latest suite of micro resistivity imaging tools, it is now possible to image the fracture system in a horizontal wellbore with great detail. Imaging fractures along a wellbore provides critical information, especially about their orientation (dip and strike) and density (fractures per meter). Once the fracture orientation and density are measured, the fracture system can be characterized along the entire wellbore length. The data can then be used to optimize completions by selecting intervals of maximum fracturing, correlating fracture patterns with subsequent production log data, verifying predictive seismic structural models, and quantifying the influence of local stress effects.

Improving Oil Sand Production Potential

The same imaging technology applicable in cleat location and characterization is proving to be a significant asset when characterizing oil sand play. Although conventional tools have identified some of the world's prolific oil sands, determining stratigraphic features such as paleocurrent direction point the way to more reserves. Being able to deploy these state-of-the-art tools using the Shuttle conveyance system has set the stage for imaging in horizontal steam-assisted gravity drainage (SAGD) production wells such as those being drilled in Canada. Understanding the depositional and transgressed environments of the oil sand is critical to optimizing operations. Micro resistivity imaging maps the sands to help determine where to drill, identifying permeable and impermeable shales to optimize steam injection and production in the laterals, and supplementing core data that suffer from poor recovery or are obscured by heavy-oil saturation.



Accurately imaging this meandering system of ancient point bars and channels is important to determining the optimal location and orientation of SAGD wells. Combining enhanced imaging with conventional logs, core, and seismic provides additional and often critical information that assists in the successful exploitation of subsurface reservoirs. Image logs can be used to determine the orientation of the old channels and identify bed boundaries, crossbedding, and lateral accretion surfaces. These new micro resistivity imaging tools provide unique insights through visual clues that are otherwise unavailable, even with core.

Conclusion

Borehole images have broad applications in geological, petrophysical, and geomechanical studies. Borehole imaging is a powerful tool to study the depositional setting of sedimentary rocks, delineate reservoir characteristics, derive rock properties, and assess their potential to produce hydrocarbons. Micro resistivity imaging offers continuous, high resolution in-situ rock measurements to be acquired efficiently and cost-effectively. Development of the new Compact tool enables E&P companies to gain high-resolution image data vital to successfully ascertain and interpret formation and wellbore characteristics.

Reservoir Nanorobots

Innovations and advances in nanotechnology, molecular engineering and quantum computing are opening up a new vista of applications in biotechnology, medicine, defense and material science, just to name a few. While much has been published on potentials and far-future applications of nanotechnology in these industries, however, relatively little or no attention has been paid to applying nanotechnology to address petroleum engineering subsurface challenges.

By Modiu L. Sanni, Rami A. Kamal and Dr. Mazen Y. Kanj

Is it feasible to develop intelligent nanorobots – 1/100th the size of human hair that can be deployed into the subsurface reservoirs, via injected wells, as "reservoir prospectors"? Can these nano-machines serve as our "eyes, ears and nose" in subsurface rocks with the ability to analyze reservoir pressure, temperature, fluid type, pore system and storing the information in a retrievable onboard memory or even transmit the data to the surface? Is such a proposition a "pie in the sky" or a potential reality? What are the potential limitations and possibilities? Are there fundamental issues that may hinder building such nanobots? What are the key "enablers" or "show stoppers" in moving from microbots to nanobots?

Unarguably, the development and use of reservoir nanorobots would have huge applications in exploration and field development, such as reservoir evaluation and delineation, well placement, reservoir monitoring, surveillance and management, thus leading to maximizing hydrocarbon recovery.

This article highlights the vision, the key components and development stages for intelligent reservoir nanorobots. It attempts to address and propose potential solutions to some of the challenges that may be encountered in developing subsurface nanorobots; such as size, means of mobility/ propulsion, power generation, telemetry, data storage and transmission, and potential downhole control of the device, etc. This article also outlines the value proposition for developing such nanoscopic machines for the petroleum industry.

Introduction

This article stems from the first ever Mentally Advanced Discussion (MAD) contest held during the technical weekly information exchange (TWIX) meeting held at the Exploration and Petroleum Engineering Center - Advanced Research Center (EXPEC ARC) in Saudi Aramco. The MADTWIX contest was inaugurated to generate out-of-the-box ideas ranging from short-term, implementable, to futuristic ideas that have the potential to become "game-changers" for exploration and production (E&P) operations.

Figure 1 - Artist's impression of nanorobots. The ultimate nanorobots may not look as shiny with blue-and-green Saudi Aramco colors, but will be a reality, (After Saggaf, M.M.).

> The nanorobot should be able to locate and quantify the fluid saturation within the accessed part of the reservoir. It may be interrogated to possibly change some reservoir properties.

The vision is to develop intelligent nanorobots that can be injected into the subsurface (reservoir) and possibly be steered from the surface. The device, Fig. 1, should be able to access pore systems, move through the pores, assess pore content and be able to store and transmit data relating to fluid flow and reservoir properties such as temperature, pressure, viscosity, relative permeability, pore throat size, porosity, permeability, etc. The nanorobot should be able to locate and quantify the fluid saturation within the accessed part of the reservoir. It may be interrogated to possibly change some reservoir properties.

To some, this is a ludicrous idea and an impossible dream that probably violates the law of chemistry and physics. In the words of Richard Feynman – one of the pioneers of nanotechnology, "The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom. It is not an attempt to violate any laws; it is something, in principle, that can be done; but in practice, it has not been done because we are too big[1]."

Nanotechnology

Nanotechnology is science and engineering at the scale of atoms and molecules. It is the manipulation of atoms, molecules and materials to form structures on the scale of nanometers (billionths of a meter), normally 1 to 100 nanometers[2, 3]. To put the scale into context, a nanometer to a centimeter is what the length of a human footprint is to the width of the Atlantic Ocean. An average human hair is about 80,000 nanometers in width!

The impetus for nanotechnology comes from the interplay of (a) a renewed interest in interface and colloid science, and (b) the development of a new generation of analytical tools such as the atomic force microscope (AFM), and the scanning tunneling microscope (STM). Combined with refined processes such as electron beam lithography and molecular beam epitaxy, these instruments allow the deliberate manipulation of nanostructures[3]. These led to some advancement towards the end of the 20th century. The 21st century ushered in demonstrable progress and applications in biotechnology, medicine, defense and material science[4].

Figure 2a - A flagellar motor, 30 nm to 40 nm in diameter, and yet can rotate as fast as 20,000 to 100,000 rpm, (After Namba, et al., Osaka University).

Figure 2b - Sensing capability enhanced bio-nanorobot concept, (After Mavoridis, et al.).

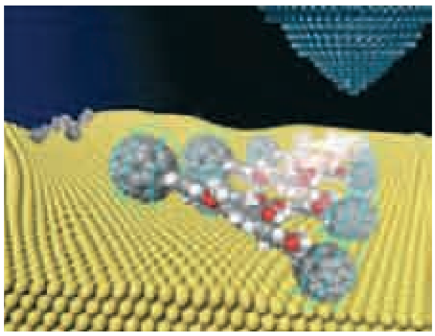


Figure 2c - The nanocar (3-4 nanometers wide). (Photo by T. Sasaki courtesy Rice U.)

Generally, nanorobotics centers on self-sufficient machines of some functionality operating at the nanoscale. The proponents of nanosytems and nanorobotics – Drexler and other researchers[5], opined that advanced nanotechnology, although perhaps

> Imagine the possibilities of mapping the formation pore-system network in real time? This will significantly impact our understanding of pore network modeling.

initially implemented by biomimetic means, ultimately could be based on mechanical engineering principles, namely, a manufacturing technology based on the mechanical functionality of these components (such as gears, bearings, motors and structural members) that would enable programmable, positional assembly to atomic specification. Drexler's analysis has been criticized by other scientists such as Richard Smalley[6] as very qualitative, impractical and that mechanosynthesis is impossible because of difficulties in mechanically manipulating individual molecules. Another set of researchers like Carlo Montemagno[7] thinks that future nanosytems will be hybrids of silicon technology and biomolecular machines.

These conflicting views not withstanding, current research findings[8, 9, 10] and progress on innovative materials and methodologies point towards the development of nanorobots with the use of embedded nanobioelectronics concept. Leaders in research on non-biological molecular machines, such as Alex Zettl and his colleagues at Lawrence Berkeley Laboratories and UC Berkeley[11], Constantinos Mavroidis et al., Rutgers State University of New Jersey[12], researchers at the NASA Institute for Advanced Concepts (NIAC)[13], Bahareh Behkan et al.[14], Tour et al., of Rice University[15] and many others have come up with molecular devices and non-biological devices that are potential building blocks for the envisioned nanorobots. Some of these include: nanomotors, molecular actuators, nanoelectromechanical relaxation oscillators, hybrid swimming microbots, nanoradio, etc., Figs. 2a – 2c.

It is pertinent to highlight that most of the pioneering works in nanotechnology are geared towards application in medicine, biotechnology, material science, defense and paint and textile industries. In fact, most of the research work on nanorobots is envisioned for potential use in medicine, drug targeting and delivery for treatment of medical problems such as tumors, arteriosclerosis, blood clots leading to strokes, etc. To date, very little effort (if any) has been made to apply nanotechnology to address E&P subsurface challenges. There has been no direct steer towards petroleum engineering and geoscience subsurface applications.

Description of a Reservoir Nanorobot

The proposed reservoir nanorobot will be about 500 nm wide – 1/100th the width of human hair, in order for it to be able to access and move through the reservoir pore systems. It should be deployable into the reservoirs, via new wells being drilled, or existing injection or producing wells. The nanorobot should have the ability to analyze reservoir pressure, temperature, fluid type, pore system, and stores the information in a retrievable onboard memory or even transmit the data to the surface. Ultimately, it would be nice to track its movement and possibly interrogate it from the surface for specific missions.

Value Proposition

If successfully built, the reservoir nanorobots will have tremendous applications in the following aspects of E&P operations, probably leading to an unquantifiable amount of dollars in savings and providing a new paradigm in reservoir in-situ sensing and intervention:

• Enhanced efficiency in drilling operations: Can you imagine a situation where real time downhole mud properties, formation stress and borehole stability data are being transmitted regularly without the big gadgets we use today? Can you envision these nanobots being sent ahead of the bit, collecting pertinent data for geosteering and well placement?

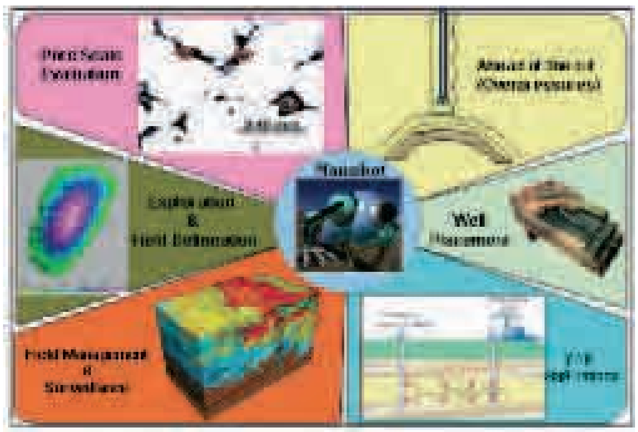


Figure 3 - Potential applications of nanorobots in solving E&P subsurface challenges. Endless possibilities!

> Some ongoing research efforts such as the Carnegie Mellon University's research on Microbots and Integrated Nano-Tool Carrier can serve as "foundation stones" providing valuable clues in formulating appropriate shapes and sizes for the nanorobots.

Figure 4 - Swimming microbots. Is it possible to recreate these at nano-scale? (Source: Carnegie Mellon University.)

• Prospect evaluation and delineation: Won't it be splendid to have all the relevant data for evaluating an entire prospect from only one well? Imagine sending nanorobots from a discovery well to find the edges of the reservoir and the fluid contacts for the field – completely eliminating extensive appraisal and delineation programs!

• Routine formation evaluation: Consider the possibilities of acquiring all pertinent geological and petrophysical data from a well even before the bit reaches total depth (TD). Can the nanorobot be able to acquire "true formation data" beyond the invaded zone, thereby eliminating mud invasion related uncertainties that have plagued petrophysicists for years?

• Reservoir monitoring and surveillance: Imagine the nanorobots being deployed to map thieve zones or high permeability – "super-K" zones, within the reservoir to enhance conformance control and water shut off operations. What about flood front monitoring and locating bypassed hydrocarbon far away from any existing well? Can they contribute to significant changes in I-Field applications?

• Enhanced oil recovery (EOR) applications: Similar to the current nanorobot development for drug delivery, can these bots be deployed to deliver surfactants and other injectants that can change formation wettability very deep into the reservoir for EOR?

• Downhole pore network modeling (PNM): Imagine the possibilities of mapping the formation pore-system network in real time? This will significantly impact our understanding of pore network modeling. Undoubtedly, the nanrobot cannot be the panacea or the silver bullet for all subsurface challenges, Fig. 3, but the possibilities are endless!

Key Components

In order for the nanorobot to function as desired, the following are key components and design attributes that should be considered:

• Size and shape
• Sensors
• Means of mobility/propulsion
• Power generation
• Data storage
• Telemetry and transmission
• Control and navigation

Obviously, there are several challenges to overcome if these are to be implemented at the nano-scale.

Size and Shape

The size and shape will depend on the intended function and operating environment of the nanorobot. The "near wellbore prospector" may be much different from "deep wellbore prospector" in size and shape. The first generation reservoir nanorobots may be a simple spherical ball like shape. Latter designs may be shaped like bacteria or other "crawlies" to enhance movement within different pore systems. A major design criterion is the minimum size or the minimum pore throat diameter that the nanobot can access without plugging or bridging the formation, causing formation damage thereby reducing the reservoir permeability. The shape factor can be determined based on the rock types and pore systems being targeted. Nuclear magnetic resonance (NMR) measurements and appropriate core-flooding experiments can aid in the determination of such minimum size.

> For the nanorobot to fulfill some of its functions, it must be capable of sensing different borehole and reservoir parameters.

Some ongoing research efforts such as the Carnegie Mellon University's research on Microbots and Integrated Nano-Tool Carrier can serve as "foundation stones" providing valuable clues in formulating appropriate shapes and sizes for the nanorobots, Fig. 4.

Sensors

For the nanorobot to fulfill some of its functions, it must be capable of sensing different borehole and reservoir parameters. Thus, it should be capable of sensing (a) reservoir fluid type, (b) reservoir temperature, (c) formation pressure, (d) basic petrophysical properties, (e) fluid analysis, (f) trajectory and position, etc. One or two sensors may suffice for the early prototypes. That will be several steps ahead of current smart tracers. The latter design may incorporate more of the desired sensors.

Means of Mobility/Propulsion

This is quite an important design consideration for the reservoir nanorobot. Early prototypes can be simple "ball like" robots without self-propulsion mechanisms. They may simply be injected into the reservoir with normal injection water and are allowed to navigate their paths through the reservoir following the natural path created by the injection water or the oil flowing naturally to the producers. Some of the potential means of propulsion are:

1. Propulsion by use of propeller: William McLellan's[16] 1/64" electric motor is a great example of what has been done at micro-scale. This may be scaled down to nanoscale in a foreseeable future. Petr Král[17] and his colleagues from the University of Illinois at Chicago designed molecular propellers with blades formed by planar aromatic molecules and the shaft is a carbon nanotube.

2. Propulsion by Flagellae: This is copying nature. Flagellum-driven bacteria are the smallest free motors in nature. Using a leg like or fin-shaped appendage similar to that of bacteria or paramecia to propel the nanobot is a potential option. Some works have been done in this regard by Bahareh Benkan[18, 19], Namba et al.[20] and Jon Edd et al.[21]. Jon's robot, at micro-scale, utilizes biomimetic synthetic flagella composed of multiwalled carbon nanotubes.

3. Propulsion by membrane: A rapidly vibrating membrane can provide the necessary thrust to propel a nanorobot. The work of Howse et al.[22] on "Self Motile Colloidal Particles" and that of the Mallouk research group at Pennsylvania State University[23] may have some applications for the reservoir nanorobot.

4. Propulsion by crawling, wriggling, rolling and wormlike or gecko like movement: Instead of floating and swimming in the reservoir fluid, the device could move along the pore system using any of the above techniques. Some of the work by Carnegie Mellon University on "Bio-Inspired Systems" and "Integrated Nano-Tool Carrier" may serve as building blocks.

5. Propulsion by nano-motors: A lot of research work has been done (and is still ongoing) on Brownian motors and nonbiological nano-motors that can be deployed to power nano-devices. Brownian motors are nano-scale or molecular devices by which thermally activated processes (chemical reactions) are controlled and used to generate directed motion in space and to do mechanical or electrical work.

For any of these propulsion techniques to be practical, they must each meet certain requirements:

- The device should be able to move through the rock pore system without being stuck, thereby causing bridging or formation damage.

- The device should be able to move even when not aided by downhole fluid flow. And must be able to move within the reservoir overcoming viscous and gravitational forces.

• The device should be able to move at a practical speed against the reservoir fluid flow (if needed). Early design may be limited to moving with reservoir fluid flow.

• Ultimately, the device should be able to change direction laterally and vertically.

Although, when it comes to moving through liquids, it is important to note that propulsion, momentum, gravity and many other familiar aspects of the everyday world change almost beyond recognition at the nano-scale where viscosity, surface interactions and Brownian motion rule. Some of the research work by Alex Zettl et al., UC Berkeley, Stoddat et al., UCLA, Namba et al., Oshaka University, Jim Tour et al., Rice University, Mavroidis et al., Rutgers State University of New Jersey and Roland Netz et al.[24], Technical University Munich, Germany, could provide the foundation for the envisioned nanorobots.

Power Generation
Another major requirement is power for the device. The intelligent nanobot will need power to perform its assigned operations and tasks. At the nano-scale, the power needed is probably low, probably tens to hundreds of pico-watts to even micro-watts, depending on the functions. Potential means of generating power for the nanobot are:

1. Power from fluid flow or counter-current motion.

2. Power derived from the reservoir temperature.

3. Power from friction with rock fabrics.

4. Downhole fuel cell generation from in-situ hydrocarbon.

5. Use of downhole recharge station.

Current research efforts by Fukushita et al.[25], Wang Zhognglin of Peking University, China, and the nanogenerator, developed by researchers at the Georgia Institute of Technology[26], Atlanta, Georgia, using an array of flexible zinc oxide nanowires hold some promises.

Data Acquisition and Storage
Data acquisition and storage are other key components for the nanorobot to fulfill some of its functions. Early prototypes with single or few data storage memory will be a step change. Quantum computing may help in the future nano-sized data storage.

Telemetry and Data Transmission
This will be a tough design function to be incorporated into these tiny wonders. Although recent findings by UC Irvine researchers[27], Zettl et al.[28] and Burke[29] who unveiled a working radio built from carbon nanotubes that are only a few atoms across, show some possibilities of transmitting data at nano-scale.

Control and Navigation System
Another desirable feature is the ability to control the bots from the surface. This is a nearly impossible proposition but who knows what can be discovered in the near future?

Key Challenges

The above design features are the ideal wish lists. Building any robot at nano-scale is not a mere technological feat! All the research findings and technological breakthroughs cited above are still in their infancy. It may take several decades if not half a century before the ideal reservoir nanorobot can be built. But we dare say it is possible! The other challenge that is yet to be fully understood and should be taken into consideration is the health, safety and environmental (HSE) impact of nanotechnology. The potential HSE risks of these tiny wonders to the ecosystem and especially humans via skin absorption, ingestion and inhalation, among other mechanisms, should be studied adequately and systematically.

Development Stages

Consequently, it is envisaged that the development of the reservoir nanorobot will be executed in phases, depending on research findings and technological breakthroughs regarding some of the components enumerated above. Like any typical technology development, each development phase for the nanrobot may be executed in three to four tranches. Tranch 1 is proof of concept; Tranch 2 involves laboratory demonstration; Tranch 3 is the field testing; while Tranch 4 is the actual field application. The possible phases are:

• Phase 1: Start with "simple Tracers." A simple spherical shape "dumb" nano-device that can be pumped down the well. This early prototype can be used to determine the optimal size and aspect ratio for later designs depending on the target reservoir pore system. A later version of this can serve as "smart tracers." Near wellbore applications may suffice at this stage.

• Phase 2: Add mobility or self-propulsion to the smart tracer. Include ability to move by itself with limited memory.

• Phase 3: Add sensors – textural and fluid analyzer. Simple pressure and temperature (PVT) analyses may suffice.

• Phase 4: Add visual sensor, capability for complex fluid analysis, textural and enhanced memory.

• Phase 5: Enhanced mobility and better telemetry.

• Phase 6: Improved telemetry and surface steering and navigation.

Leveraging Current Technology

The success of miniaturization in electronics and other industries holds some promises for near immediate applications in the upstream petroleum industry[30]. The last decade has seen tremendous growth in Microelectro - mechanical systems (MEMS) and recently Nanoelectro - mechanical systems (NEMS). Millions of MEMS de-

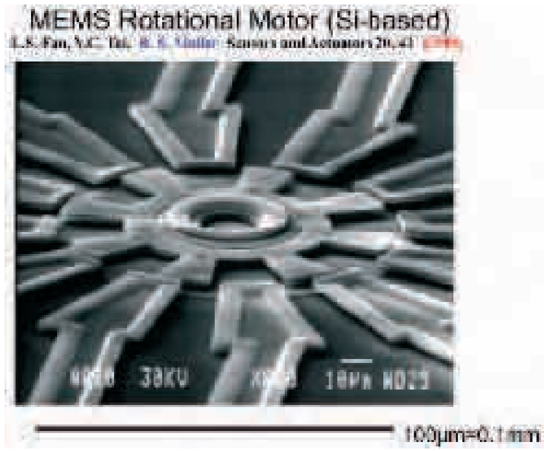


Figure 5a - The first MEMS rotational motor built in 1989 by R.S. Muller – 100 microns across! (After Zettl, et al.) Can this be made at a nanometer scale?

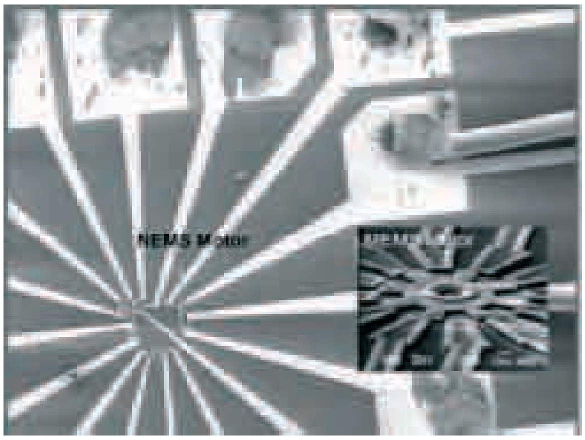
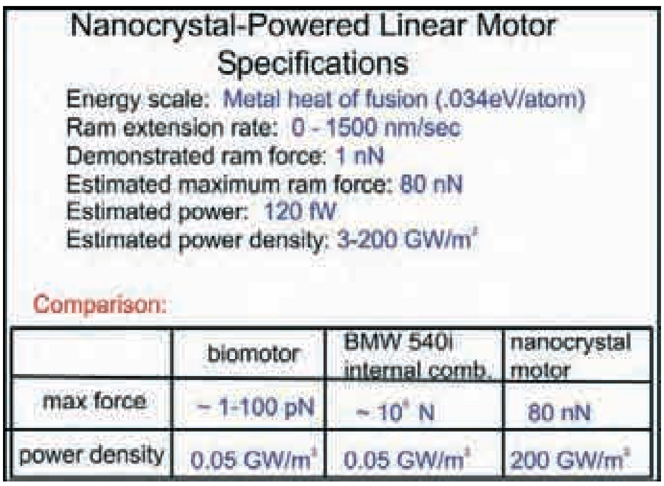


Figure 5b - Contrasting NEMS motor with previous MEMS motor. A scale-down of 1:1000 was achieved using different material. Learning from MEMS can be leveraged in the development of nanorobots, (Source: Zettl Research Group).



Nanocrystal-Powered Linear Motor Specifications

Energy scale: Metal heat of fusion (.034eV/atom)
Ram extension rate: 0 - 1500 nm/sec
Demonstrated ram force: 1 nN
Estimated maximum ram force: 80 nN
Estimated power: 120 fW
Estimated power density: 3-200 GW/m^3

Comparison:

	biomotor	BMW 540i internal comb.	nanocrystal motor
max force	~ 1-100 pN	~ 10^4 N	80 nN
power density	0.05 GW/m^3	0.05 GW/m^3	200 GW/m^3

Figure 5c - Comparison of nano-crystal powered (non-biological) motor with biomotor, (Source: Zettl Research Group).

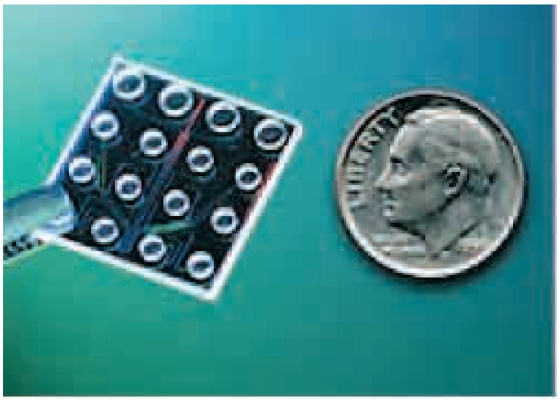


Figure 6 - Lab-on-a-chip device. Microfabrication makes it possible to create intricate designs of interconnected channels that are extremely small, (Source: Caliper Technologies).

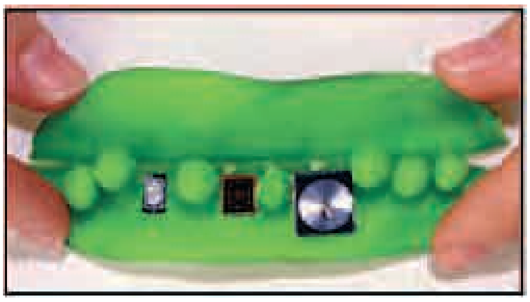


Figure 7 - Lab-in-a-pea-pod: Three principal components of Sandia's integrated micro chem. lab inside a snow pea pod. Shown from left to right are a surface acoustic wave sensor array, a pre-concentrator that collects chemical vapors for gas-phase analysis and a miniature gas chromatograph column, (Source: Sandia National Laboratories).

vices are being developed as miniature sensors, actuators and analyzers. Figures 5a – 5c shows an attempt by Alex Zettl et al., to scale down silicon based MEMS rotational micro-scale motor, first invented in 1989 by Richard Muller et al., to nanometer scale. One of the key lessons from their research is that it is indeed possible to create a nanoscale device, in this case a NEMS rotational motor, mimicking a MEMS device albeit using a different approach and materials.

Therefore, isn't it possible to leverage some of the progress made in MEMS, NEMS and microrobotics in developing reservoir microbots as a logical precursor to a "simple" reservoir nanorobot, for near borehole applications?

The reservoir microbots can borrow from the application of the "Lab-on-a-chip" (LOC) technology[31] also termed as "micro-total-analysis-systems" (µTAS). Lab-on-a-chip is one of the fastest growing technologies in the last decade. It has been successfully deployed in several areas such as DNA analysis, catalyst development and inkjet printing to name a few. Lab-on-a-chip tends to integrate several operations e.g., multistage chemical or biochemical analysis on a single chip, Figs. 6 and 7, at a size that can be easily deployed for near borehole applications. The goal of LOC is to bring the miniaturized laboratory to the sample instead of the sample to the laboratory[32].

LOC Applications

Mohanty et al.[30], enumerated several potential applications in E&P operations. Such as in-situ measurement of reservoir (dynamic) fluid properties, production allocation, formation stresses, pressures and borehole stability, formation damage assessment, mud rheology and mud logging, formation evaluation, etc.

Current Experiments

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 and not get caught in the pore throats[33]? After all, there is no sense in deploying these robots only to be caught in the pore throats around the wellbore, since this abrupt halt to their journey will mean not just the inability to retrieve them, but may also adversely affect the intrinsic permeability of the rock, thus damaging the reservoir.

Consequently, about 850 core plugs from the Arab-D reservoir in Ghawar have been analyzed to map the distribution of the pore throat sizes. The distribution is bimodal, as expected, but the important observation is that most of the pore throats are larger than approximately 500 nanometers. Thus establishing a target to which our miniaturization efforts should focus (actually, to avoid bridging the size of the robot will need to be less than this number).

Furthermore, we are currently conducting physical experiments 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 effluent is characterized using a Dynamic Light Scattering (DLS) device for particle size and distribution. Also, the end sections from the core plugs are analyzed for morphology, particle distribution and retention via environmental scanning electron microscope (ESEM) and energy-dispersive spectroscopy (EDS) – such that the size question can be answered empirically. Figure 8 is an ESEM image showing the distribution of the nanoparticles in one of the tested carbonate samples.

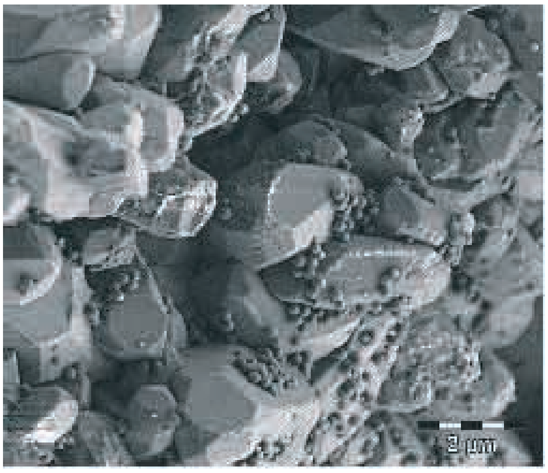


Figure 8 - This ESEM image clearly demonstrates the distribution of the nanoparticles in one of the tested carbonate samples.

In addition, the journey of the nanorobot through the pore structure will be simulated. In other words, the first milestone in the pursuit of the nanorobot dream would be answering the size question in three different ways: by observing the pore throat size distribution, conducting an empirical experiment of nanoparticle injection, and by modeling and simulation.

Conclusion

The value proposition enumerates the potential benefits of developing and deploying reservoir nanorobots in E&P operations. Unarguably, the envisioned reservoir nanorobots have the potential for becoming a "game changer" in formation evaluation, reservoir surveillance and monitoring, and reservoir management.

The technologies to create the ideal reservoir nanorobot are still at their infancy. The technologies to develop simple and practical microbots for near borehole applications currently exist. Lab-on-a-chip or µTAS is a "low hanging fruit" technology that can be harnessed and deployed for some basic reservoir and near bolehole applications in the immediate term (1-5 years). The learnings from the development and deployment of appropriate LOCs and microbots will contribute to realizing the dream for the ideal reservoir nanorobot in the long-term.

EXPEC ARC is conducting unique experiments and related research to pave the way towards realizing the dream for a reservoir nanorobot.

The E&P industry needs to actively steer nanotechnology breakthroughs for subsurface applications.

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A Successful Process for Em Mitigating Risk - from Geologi Development Plan Optimization

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Integrated reservoir studies aim at synergizing all disciplines to form a reservoir understanding and best strategy to field development. Handling uncertainty and risk using probabilistic approach is a challenge since it becomes quickly overwhelming.

This article describes the approach used to handle uncertainty and risk in the Saudi Aramco Event Solution process. This approach lies in between the conventional deterministic approach where the team agrees on one realization and the probabilistic approach where a whole family of realizations is covering all possible outcomes.

Here, throughout the process of understanding the reservoir, the team agrees on the most-likely value for all input variables, and set ranges of uncertainty for each of them. Testing the effect of these boundaries on the static models and OOIP, history matching quality or prediction strategy efficiency leads to discriminate the critical factors.

This discrimination helps to narrow down the number of uncertain factors and their ranges from one stage of the study to the next one and focuses on what really matters according to the study objective. The critical controllable factors are tuned to optimize production performances. Information plans are set to narrow down the uncertainty range on the uncontrollable factors.

Finally, a list of risks is stated for risk assessment. Potential risks are identified through four categories: level, probability, urgency and manageability, to which high, medium, and low values are assigned. Risks scoring 3 or 4 on the risk scale (meaning high in 3 or 4 categories) are flagged and mitigation plans are addressed.

This article presents an application of this process on a Saudi complex oil reservoir, which results in developing a clear understanding of the critical uncertainties, project risks, and the agreed development plan, information plan and mitigation plan.

Background

It is acknowledged that worldwide energy demand touches all aspects of today's energy dependent global society. Further, that while the demand for energy is clearly visible, the total solution to fulfill world energy demands has yet to be answered[1,2]. Nonetheless, within the framework of perceived controllable efforts, the value added potential to deliver accelerated hydrocarbon extraction at optimal recovery and cost is a key Oil and Gas Industry focus area towards world energy demands. Specifically, the potential to streamline field development decision process of impact to world energy demands with economic, technical and geo-political robustness is critical. In summary, the challenge faced now is to significantly condense the timeline to achieve increased production targets with large, expensive and highly dynamic commercial and technical uncertainties.

The range and form of technical and commercial field development and production strategy uncertainty is overwhelming. Uncertainty ranges include data acquisition, subsurface interpretation[3,4], economics[9,11] and international currency fluctuations to name but a few.

Starting in the 90s, major oil and gas companies engaged in the concept of uncertainty in field exploration, reservoir characterization[5] and development[4]. The scale, variety and complexity of uncertain factors from seismic

bracing Uncertainty and cal Understanding to of a Saudi Complex Reservoir

to economics, however, has deterred even the most determined to conclude a practical integrated uncertainty and risk modeling solution[6]. Indeed, most known uncertainty management techniques consider only two possible approaches, namely, a deterministic realization to reflect reservoir physics and flow mechanisms with low and high values for all variables including uncertainty boundaries. Secondly, a probabilistic technique that encompasses all uncertain factors ranges with lesser detailed attention on reservoir physics and understanding.

This paper describes the innovative Saudi Aramco Event Solution process[6] approach to jointly co-manage and model uncertainty and risk through an integrated static, dynamic and economic field development strategy process. This approach, that lies between a conventional deterministic and a fully probabilistic model approach, provides a range of qualified field development scenarios, under uncertainty and risk, including information and mitigation plans, in a reasonable timeframe (2–3 months).

Introduction

Among other challenges, enhancing the quality and shortening the timeline of complex reservoir management decisions remains a significant and overwhelming task in today's oil and gas industry. Balancing and resolving the demand for fast technically qualified commercial decisions is demanded. Furthermore, the concept to incorporate uncertainty in any component of a technical and commercial workflow unquestionably extends any study duration. Thus the need to shorten decision and cycle time between real time decisions and uncertainty, through an advanced integrated technical study is a key Saudi Aramco innovation and strategy to optimized field development decision.

The Saudi Aramco Event Solution[6] is a short, intensively collaborative event that compresses major decision cycles, to provide a clear and common technical understanding of the critical uncertainties, project risk, and agreed information and mitigation plans to accelerated field development decisions.

As compared to classical integrated reservoir engineering studies, an Event Solution study typically includes seismic and geology characterization, reservoir simulation, history match, field development, facilities and economics. Performed in 2-3 months duration, the Event Solution is characterized by a myriad of multiple parallel workflows and processes to assemble a rapid and integrated reservoir understanding towards the study objective. This includes uncertainty analysis and risk assessment to focus on what really matters to the study objectives. A team of 20 to 30 experts collectively work during the 2-3 month project duration, providing synergy of mind and direction to reach study objective and maintain consistency in each study discipline.

An exhaustive technical study involving hundreds of uncertain factors would significantly increase study duration without necessarily adding value to study results. Thus, the need is to judiciously include uncertainty analysis as a key study result without overburdening, mis directing and or falling short of value added study results.

In Event Solution, uncertainty is managed on a specific well-stated business objective aligned to company strategy. Subsequently, the team follows a pragmatic process where each team member assesses uncertainties within their respective study component analysis, with outputs rolled up and viewed as a study wide uncertainty assessment. Doing so, study uncertain factors and risks are re-assessed, narrowed down and qualified at each study process step, forming an improved understanding of uncertain factors impact on final study objective.

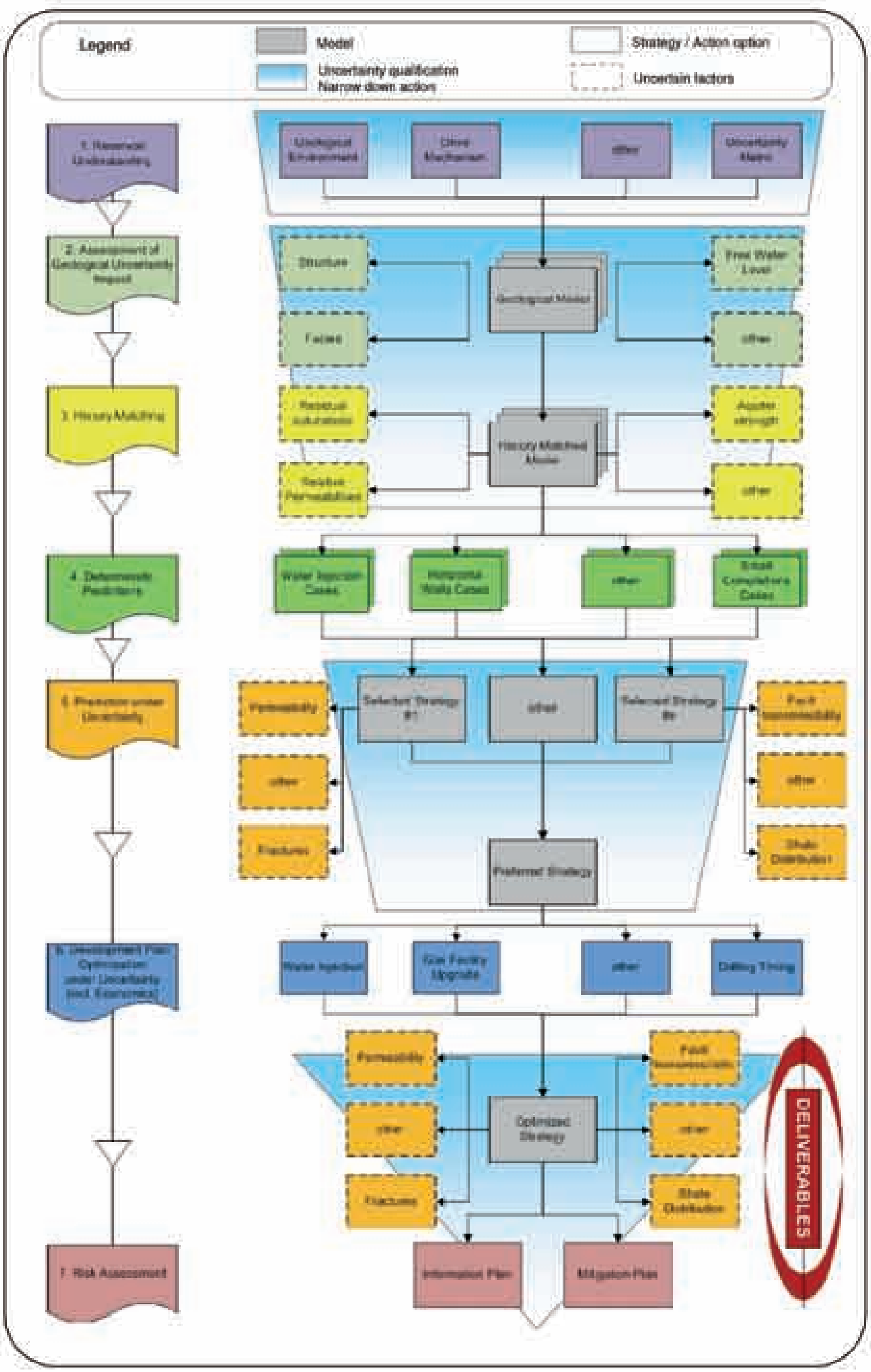

Figure 1 - Practical workflow for uncertainty and risk management in integrated reservoir studies.

Methodology and Workflow

1. A practical workflow to provide tangible study deliverables for real time decision making

The large number and complexity of uncertain factors generally discourages most from conducting integrated reservoir studies under uncertainty. The success of the uncertainty and risk workflow presented in this paper (Figure 1) does not solely rely on advanced analysis and technology, but more on an efficient and practical process that screens and narrows down uncertainty and risk ranges through integrated understanding, team synergy and clearly stated study objectives.

The Event Solution technical workflow[6] adopts a new reservoir study approach, gaining efficiency, understanding and cycle time reduction by:

- Identifying upfront the most important study objectives and fine-tuning these objectives as the study progresses

- Focusing the collective skills and team creativity to build a synergized reservoir understanding

- Conducting rapid semi-parallel workflows (all stakeholders engaged in different tasks at the same time)

Embracing uncertainty and risk from the Event Solution study onset becomes feasible with each technical team member expert seeing the relative contribution and direct impact of “his/her” uncertainty and risk

elements on the decision-driven study objective. Team members are not mandated to "go get results" on their respective study component, rather contribute to build and validate a qualified and rapid understanding of the key issues to "the Big Picture." Thus from the very beginning of each Event Solution study, the analysis process is fine-tuned and balanced between a conventional deterministic approach where the team agrees on one realization for each study variable, and a probabilistic approach where a family of realizations covering all possible outcomes are included.

The team, throughout the study steps agrees on most-likely (ML) values for all input elements, sets boundaries for these elements, and tests the effect of these boundaries on the outcome. Once the critical uncertain factors are identified through the different study steps, the team then mainly focuses on these elements.

As illustrated in Figure 1, through more detailed understanding, from step 1 to 7, uncertainties and risks are revisited at each of the below process step to narrow uncertainty range:

- Reservoir understanding
- Asessment of geological uncertainty impact
- History matching and its critical factors
- Prediction under uncertainty: Alternative development plans, including possibly different timings and economics

Indeed, uncertainty in itself is subjective when assigning boundaries to properties where full knowledge is lacking. Rather, as illustrated through the background arrow in Figure 1, uncertainty is based on all available data at the time, progressing to a more precise and less uncertain range as more data and understanding becomes available.

Event Solution study deliverables typically include:

- Optimized field development plan
- Estimates of uncertainty on critical study responses, e.g. plateau duration
- Evaluation of project risks, e.g. achieving plateau
- Time-sensitive information plan to reduce and mitigate qualified project risk.

2. Reservoir Understanding: on the necessity to see "the Big Picture" upfront

The key element of success of this methodology is to consider uncertainty and risk upfront and fine tune it as the process progresses and not to "map" uncertainties or risks on a deterministic understanding, or only consider them at the final stage. The initial understanding of the reservoir should fully encompass uncertainty and risks, as highlighted in section 1, Reservoir Understanding of Figure 1.

Conventional studies typically handle uncertainty at study conclusion where the identification of risk is often too late in the study cycle. In Event Solution, to avoid spending time on detailed study factors or mechanisms of no or little impact to study objectives, each team member works in parallel on several tasks, regardless of his/her discipline, to facilitate a better view of the full reservoir understanding including uncertainty and risk. Each day, study results are rolled up and summarized for review and discussion. As this routine continues, the entire team synergizes on a common reservoir understanding of "The Big Picture," including notion of uncertainty and risks.

This understanding phase is critical in the uncertainty and risk management process, where a rolled-up view of the candidate uncertain factors and project risks is first set in a qualified Uncertainty and Risk matrix.

The uncertainty matrix lists uncertain factors, as well as their possible most-likely value and range or boundaries, as framed through current field understanding. Although at this early study stage, all uncertain factors are considered only as notion and according to their potential expected impact on static, dynamic, project timing and economics. The risk matrix rolls-up the possible less desirable outcomes, relative to the stated study objective, ranging from changes in reserves, plateau duration, recovery, capital investments and economics.

3. Geological Uncertainty Assessment on Reservoir OOIP and Dynamics

Following data gathering and initial reservoir understanding steps, the initial static geological model is built and an estimate of OOIP is conducted (section 2 of Figure 1). As previously mentioned, through the uncertainty matrix the team provides Most-Likely (ML) figures for static factors as porosity, saturations, fluids contacts, etc., according to the initial reservoir understanding. Since ranges for each factor have been debated, discussed and concluded among the team / all stakeholders, and stated in the uncertainty matrix, an uncertainty analysis for the static models and thus OOIP is initiated[5,7].

A generic static uncertainty matrix is carried forward in each project as a preliminary startup check list. Within this check list each factor associated with oil in place has an unknown component. The concept of including these entire factor ranges to history matching and prediction is neither efficient, nor necessary. Rather, the whole purpose of static uncertainty analysis is to continue the process of narrowing down factors ranges and select only those factors of significant impact on volumetric results.

The generic static uncertainty matrix consists of the following components at their initial condition:
- Structure & Thickness
- Facies
- Porosity
- Permeability
- Water Saturation

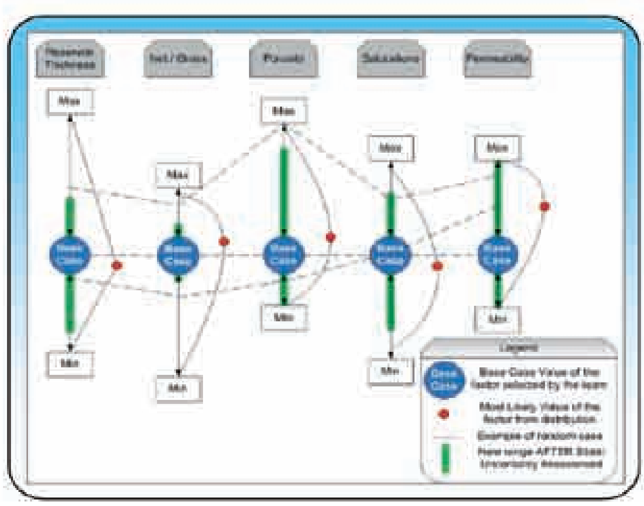

Figure 2 - Geological uncertainty assessment.

- Fluid Contacts (Free Water Level & Gas Oil Contact)
- Formation Volume Factor

During the modeling of these properties, several underlying factors can be considered as uncertain. For instance, for facies modeling, porosity, permeability or water saturation, well data blocking methodology, proportions, histogram distribution, modeling methodology, e.g., SGS simple krigging, directionality, variogram model type, zonal modeling, etc., can be involved in the uncertainty analysis.

Each reservoir being specific, the impact of uncertain factors has to be analyzed accordingly. For example, if compartmentalization exists an analysis is conducted for each compartment. In each compartment, the uncertainty range on say, the free water level is again dependent on the quantity and quality of available data in this specific compartment.

As illustrated in Figure 2, according to the range of uncertainty of each factor, hundreds of nested simulations are performed to determine both:

- The potential impact on OOIP figures,

- The main contributors to OOIP uncertainty, among all uncertain factors. These factors are then qualified as critical factors to volume assessment.

After OOIP assessment, critical static factors to volume uncertainty are determined. Some static uncertain factors, however, which do not impact OOIP figures, might impact fluid flow dynamics. To efficiently handle these static factors, a screening of geological realizations through mechanistic/conceptual/streamline models is conducted. Doing so, critical static factors which can

lead to different types of flow are identified in a reasonable simulation time. In the case presented in this paper, due to the complexity and size of the Saudi reservoirs, a classical full field simulation model analysis is not practically feasible. At the end of this "dynamic impact" screening step, representative geological realizations are identified.

The "static part" of the uncertainty matrix which was initially used as a guideline for this step is thus fine-tuned highlighting critical factors and narrowed-down ranges. This analysis determines which factors are critical and which will remain as uncertain in the matrix for the simulation model history match. Static factors that are not critical and not expected to have an impact on the history match or prediction are narrowed down to a most likely (ML) figure, when carried forward to the history match and prediction.

4. History Matching under Uncertainty

The main purpose of history matching is to calibrate the simulation model to historical performance data. It is extremely important to see the history match process as a mean to achieve reliable production forecasts and not as a distinct goal in itself.

According to the reservoir understanding phase and geological uncertainty assessment, the uncertainty matrix has been updated. Among all factors in this matrix, the history matching step will involve:

- OOIP critical factors with their narrowed uncertainty ranges

- Static factors that might have been non-critical for OOIP but will have dynamic impact (variograms, fractures, fluid paths, …)

- Dynamic factors which might affect the production during historical period

For each of the possible representative geological realizations, a full detailed history matching will be performed. This history match process is performed through an assisted history match approach[8] to permit the handling of a large number of factors. Typically, history matching starts with investigating and testing the impact of hundreds of factors. Paying attention to factor selection with respect to their likelihood to impact the results lowers the potential to blindly consider all dynamic factors. For instance, even if from a reservoir understanding perspective, relative permeability curves are seen as uncertain, they might not be included in the history match if the reservoir is in an early development phase, still produced under depletion. This process focuses on achieving not only the "Most Likely" history match but as many other equiprobable matches as possible (section 3 of Figure 1).

The history matching process aims to calibrate the simulation models to historical data while preserving the understanding in terms of reservoir dynamics and initial geological realization[10]. Thus all changes applied to factors during the history match are carefully parameterized to preserve data consistency (well data for instance). To ensure that the geological understanding remains captured during the history match, a post-processing step is proposed. Updated properties are analyzed from all discipline point of views, avoiding for instance the use of regional multipliers which drastically impact the prior property distribution heterogeneity. The match quality is analyzed on a well by well basis following three criteria:

- Acceptable match: historical performances are captured

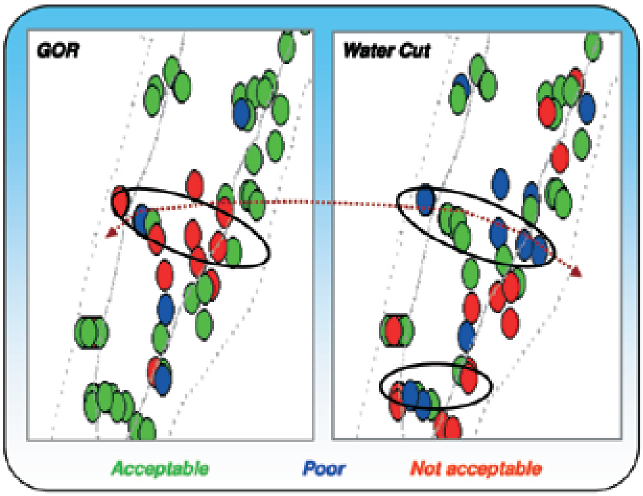

Figure 3 - History matching analysis process.

- Poor match: historical performances are not fully captured, however the physics of the reservoir drive mechanism is characterized (e.g. water is produced through the simulation model, but a delay in breakthrough or a mismatch in quantity is observed)

- Non-acceptable match: the physics is not captured; the current model needs to be updated in this neighborhood

Doing so, as illustrated in Figure 3, the match quality is reviewed from an areal point of view, providing more insights on possible need for new characterization, or for missing geological features (e.g., path identified where water cut match is non-acceptable could suggest the presence of fracture/fault clusters).

This post-processing is critical since it allows all team members to be involved in the history matching process regardless of their disciplines. The insights and suggestions to enrich the parameterization are thus fully consistent with all aspects of the prior reservoir understanding both from simulation and geological view points.

As a result, uncertain factors are characterized into two groups:

- Critical factors to match history

- Non-critical factors to match history

The ranges of uncertainty on the critical factors to history match are narrowed to a ML value to honor historical data. The non-critical factors need to be carried with their uncertainty ranges to prediction. Indeed, the non-critical factors ranges might have been narrowed down, but not enough to be fully characterized by the available data.

Again, the uncertainty matrix is updated as a guide to production forecasts and field development strategy optimization. More importantly, through the post-processing analysis, areas of bad data match, due to lack of information or bad understanding are identified. This information is critical and is carried forward towards prediction with uncertainty ranges since the associated forecast figures will have to be taken with caution in these problematic areas (the model being known to be non-accurate from history in these areas).

5. Development Plans under Uncertainty

Once the history matching process is performed and the uncertainty matrix is updated with narrowed intervals for uncertain factors, prediction forecast simulation is initiated.

Depending on the size of the simulation model and number of factors, uncertainty analysis can be very time-consuming. To streamline the process, deterministic analysis of the field development strategies is introduced (section 4 of Figure 1). The idea is to design simulations to test various development strategies such as areal or flank water injection; gas injection; water alternating gas injection; well type (vertical / horizontal / multilateral), spacing and orientation; facilities upgrade; production rates and timing tactics, etc.

Here, it should be noted that only the most likely reservoir/fluid model realization is considered to assess the performance of each proposed development strategy alternative. Analysis results are compared according to project objectives: maximize recovery, maintain a specified production target rate with maximizing plateau duration, do not exceed water / gas production limit, etc. Based on this comparison, the outlier cases, i.e., cases that are clearly unattractive, are discarded, and study effort focuses on the remaining promising strategies. A detailed uncertainty analysis is then conducted on the identified preferred development strategies.

Let us now focus on detailing the uncertain factors that are involved at this stage (section 5 of Figure 1). These factors can be categorized in three groups:

• Factors with only ML values (no or limited uncertainty):

- Uncertain factors that were identified as non-critical in the static modeling and OOIP step, and were expected to have limited effects on both history match and prediction

- Critical uncertain factors for history match that were narrowed down to the ML value.

• Factors with narrowed down range of uncertainty:
- Uncertain factors that were identified as critical to the OOIP estimates with their uncertainty range
- Uncertain factors involved in the history match process which were not narrowed down enough according to historical production data
- Uncertain factors characterized through history match process, but only in the vicinity of existing wells and are still considered uncertain in regions where there are no wells

• Factors with its initial wide range of uncertainty:

- Uncertain factors that were not tested in either the OOIP or the history match process, which could impact long term recovery and that, do not impact history (for instance residual oil saturation to water flood for a reservoir produced through depletion during history and for which water injection is planned since aquifer size and strength are very limited).

Typically, at this stage of the study, the number of uncertain factors ranges from 10 to 20. This number was reduced from typically 50 to 70 factors at the study beginning. Rather than running random simulations for such a number of factors, experimental design techniques are utilized to screen critical factors for each alternative development strategy. This process step involves "screening experimental designs"[12] (first order orthogonal design, fractional factorial, placket-burman), which requires a small number of simulations to assess the sensitivity of each factor. Indeed the control of the number of simulations is critical since in the case of mega fields, simulation computing run time is typically in the order of days rather than hours, even while providing significant computing power cluster resources.

This prior screening stage aims to keep a reasonable number of uncertain factors for development strategy optimization. Many levels of optimization can be considered. At a well level, optimization of placement, type (vertical, slanted, horizontal and multi-laterals), spacing, and completion type (tubing size, equalizers, etc.), including smart tools are tested. Driving mechanism and production performances, among others, injection to production ratio, reservoir depletion pressure level, maximum oil rate per well, maximum injection rate per well, production facilities limits are analyzed.

The impact of each of these controllable factors must be qualified and optimized in face of the critical uncertain factors for each development strategy alternative (section 6 of Figure 1). At this stage, study process aims to combine controllable factors with uncertainty, highlighting the clear benefit of narrowing down uncertain factors through the previous steps.

Here experimental design and proxy based approaches are of first importance since the analysis is no more qualitative (ranking impact) but quantitative. Experimental designs are, at this stage, more simulation consuming (second order designs, ccf, latin-hypercubes[12]), since the level of details in the proxy model is higher (interactions of factors, quadratic to non-linear impacts).

Beyond informative simulations through experimental design that optimally cover the uncertainty domain, the uncertainty analysis has to be tied to project objectives. At this stage, economical evaluation is often required. Classical development strategy optimization focuses on

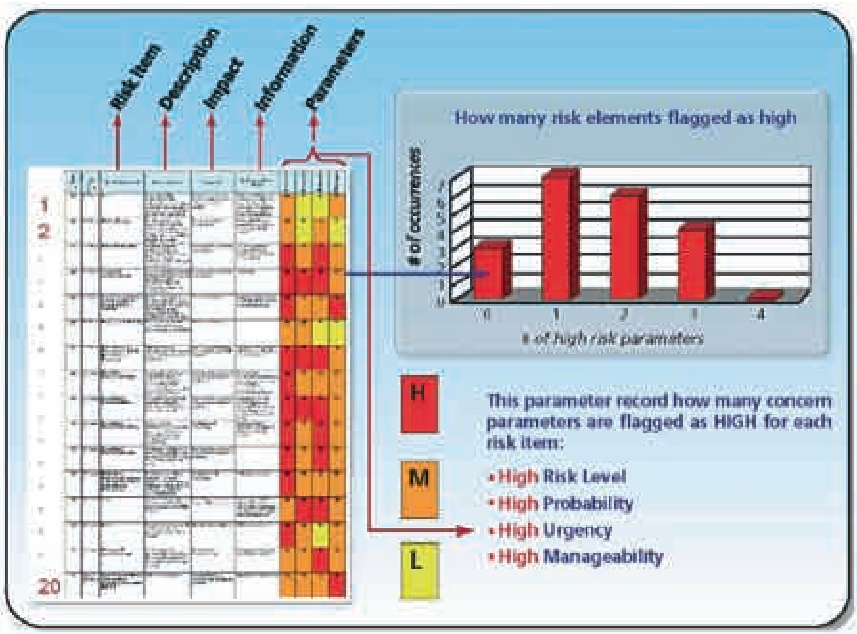

Figure 4 - Project Risk scoring.

increasing production or recovery. Some of the alternatives considered involve considerable investments (complex wells, production facility upgrades, etc). Thus, an optimal strategy in terms of production does not necessarily translate as an optimal economic design.

Proxy based models, coupling production and economics[11], are useful for understanding the influence of each factor through Pareto charts. This analysis is translated to project risk or potential. A detailed 3D analysis of the fluid movements (sweep efficiency, moveable oil at different time steps, etc.), according to the critical factors change, is then helpful to design an information plan and optimize mitigation actions.

The most robust plan facing uncertainty is selected as the final development plan and corresponding information plan and risk/mitigation plans are developed.

6. Risk Assessment, Information Plan & Mitigation Plan

As an introduction to this paragraph, we would like to differentiate between uncertainty and risk. A project risk is the chance that some of the study objectives will experienced an unexpected bad outcome. For example, a shorter plateau duration than expected, a lower recovery, etc. Risk is thus a translation of the uncertain framework, but relative to the base case realization[9].

For instance, saying that from the most pessimistic case to the most optimistic case we observe 5 years discrepancy in plateau duration describes uncertainty on plateau duration but does not qualify risk on it. On the other hand, if we believe from understanding step that our base case realization for plateau duration is 10 years, and that the most pessimistic case is 6 years less, and most optimistic case is 1 year upside, we actually qualified a risk project.

Risks, once identified and quantified, can be handled through actions. Project risks are listed and quantified as high, medium or low referenced to four categories: risk level, probability, urgency and manageability. The risk that scores 3 or 4 on the risk scale (meaning high in 3 or 4 categories) is flagged and mitigation plans are then addressed. This process is presented in Figure 4.

For these risks, the critical factors, which explained underlying uncertainty, are analyzed to understand and design the mitigation action required. Mitigating the risk can be by either through obtaining more information on the uncertain factors that are causing the uncertainty or by changing/modifying the production strategy to accommodate these uncertainties (i.e., water injection to accommodate the uncertainty in aquifer strength).

Finally, the process is completed by staging out through time, the development plan, the information plans, and the mitigation plan (section 7 of Figure 1).

Application to a Saudi Complex Reservoir

1. Case Study - Presentation & Challenges

The reservoir under study is a massive fractured carbonate that is in the order of 45 km long and 10 km at its widest. The reservoir is an elongated anticline with a

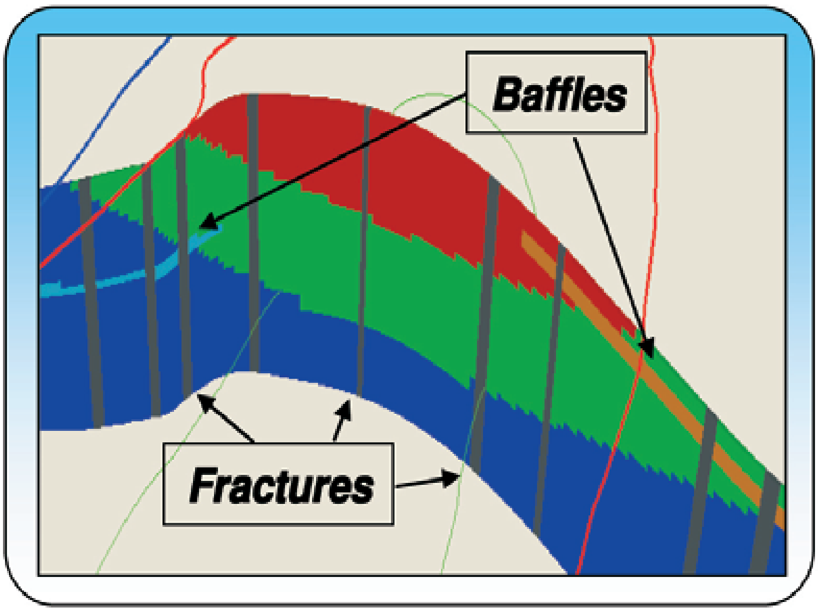

Figure 5 - Study Case: Mechanisms understanding.

large STOOIP. The reservoir is a saturated reservoir with a gas cap. The oil rim is bounded by a significant gas cap that provides effective and strong pressure support and good vertical sweep to the well completion depth. The peripheral aquifer is known to be large in volume but with poor permeability, in particular on the east flank, and unlikely to offer any effective pressure support with limited oil sweep in the flank. The reservoir permeability quality is modest and declines in magnitude to the flanks and the south of the reservoir. The reservoir has been developed with three hundred 3 km multi-lateral horizontal wells aligned along the structure and completed in the middle of the oil rim.

2. Case Study - Reservoir Understanding

Several key challenges were to be addressed during the study to maximize plateau length and recovery. Field challenges to fully develop the reservoir are considerable but so is the prize. Examination of the well histories had indicated that well completions that penetrated fractures brought early gas and water. The control of gas movement was essential to well longevity and in turn enhanced recovery.

Field performance to date has seen low levels of water production and a slow, steady increase in gas-oil ratio (GOR) above the solution GOR.

With respect to current understanding, well performances in terms of gas and water movement are dictated by common factors such as:

- Areal placement: wells placement in the oil rim or under the gas cap

- Drawdown: directly linked to changes in permeability or facies, to the well-reservoir contact, and to the off take rate

- Well standoff to gas and water fronts

These 3 classical factors, however, cannot explain the performance of all the wells. Indeed, field specific non-common factors appeared to play a significant role in well production profiles. For instance, some early breakthrough can be explained by fracture characterization. On the other hand, detailed log analysis concluded the presence of very thin geological lenses that prevent or at least dramatically impact vertical fluid flow for both gas from the gas cap or water from the aquifer. These geological lenses (baffles) and their respective areal extension can significantly impact fluid movement preventing gas and/or water arrival, depending on baffle standoff with respect to well placement, as illustrated in Figure 5. A more detailed characterization of critical water and gas saturation as a function of facies change is also considered to be critical to specific well performances. Furthermore, potential communication with other reservoirs, through fractures or matrix, is considered as a possible uncertain factor at this stage of the reservoir understanding.

As a summary, the initial uncertainty matrix involves: free water level, facies change through porosity, permeability and water saturation modeling, fracture density

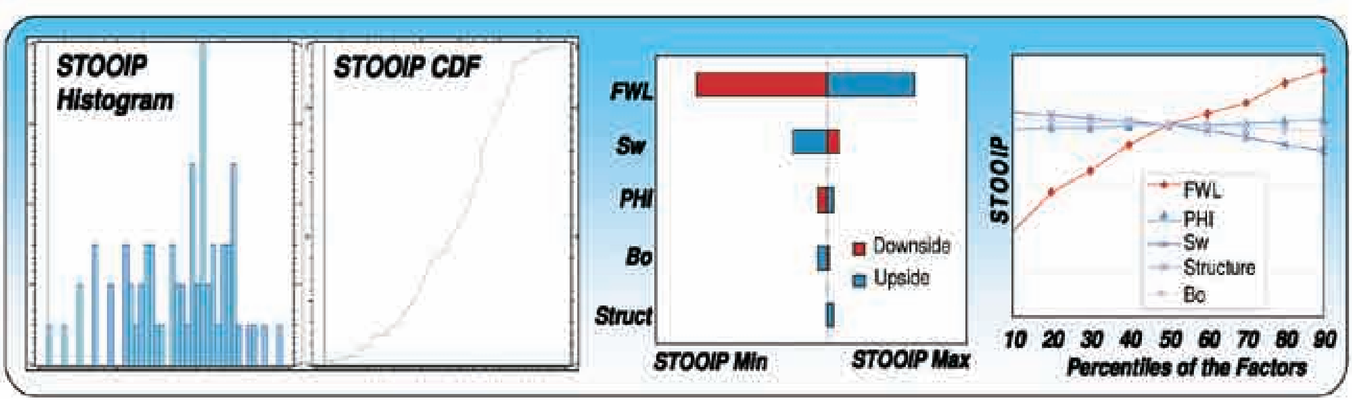

Figure 6 - Study Case: OOIP uncertainty analysis results.

characterization, baffle extension, relative permeability to gas and water, aquifer strength and potential communication with other reservoirs.

Among these factors, the ones which can affect volume calculation are taken through static modeling and OOIP uncertainty analysis.

3. Case Study – Geological Uncertainty - OOIP Critical Factors

Uncertain factors, namely water saturation model Sw, free water level FWL, porosity Phi, reservoir structure and formation volume factor Bo, are simultaneously manipulated within their respective uncertainty boundaries, providing a range of OOIP or STOOIP according to a 60 million cells geological model.

Figure 6, illustrates the histogram or probability distribution function (PDF) plot of volume with column height representing the number of realizations within each case. This plot indicates the realization probability in a given volume interval.

The STOOIP cumulative distribution function (CDF) presented in Figure 6 represents the cumulative number of realizations (vertical axis) per volume (horizontal axis). This plot illustrates the percentage of realizations for which the obtained volume is below a given value.

The number of realizations required to establish the STOOIP distribution is determined by the stabilization of three STOOIP attributes that are continually recalculated within each new realization: Mean, Variance, $P_{90} - P_{10}$. These attributes once stabilized indicate that the full range of STOOIP distribution has been captured.

At this juncture it is necessary to determine critical factors in terms of largest impact to STOOIP changes.

The Tornado and Spider charts, illustrated in Figure 6, present the impact of each parameter on STOOIP when all other factors are held at their respective P_{50} value.

Figure 6 illustrates that the range of uncertainty in FWL and water saturation are drastically impacting the changes in STOOIP. Thus, these two factors are carried forward to history match to translate the possible range of uncertainty in STOOIP. The other factors (Bo, Structure, etc), are considered as unlikely to impact the dynamic behavior of the reservoir. Those factors that clearly do not influence STOOIP variations are set to a most likely value for the subsequent study steps.

4. Case Study - History Matching under Uncertainty

An upscaled 7 million cells, dual permeability – dual porosity (DPDP) model was used for the history match, with an average 10 hour simulation run time on a multi-processor, multi-node cluster.

A comprehensive methodology has been developed in which the possible range of variation for each relevant factor is tested during the history matching process.

In this study and as captured in the uncertainty matrix, some 70 factors describing possible uncertainty on permeability, fractures, baffles, FWL, relative permeabilities, etc were modified to achieve a historical performance match. It is noted that a number of factors were modified according to region and/or rock type. Typically, permeability was consistently modified for each facies within the boundaries of the original conceptual information. Furthermore, since 'hard' data was used to build the original permeability model, such as cores or image logs (FMIs) a weighted 3D property - based on kriging of these data - was used to constrain possible changes in permeability. Thus, as illustrated on Figure 7, at well location, the weighted multiplier respects the

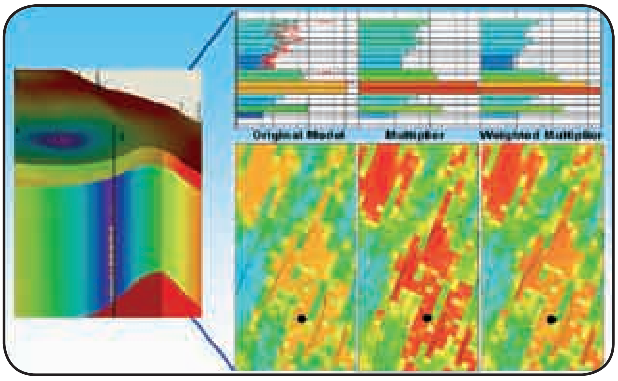

Figure 7 - Study Case: Permeability range of variation during history matching – constrained to hard data

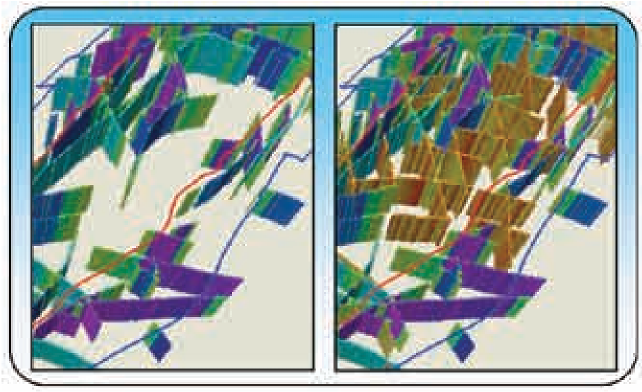

Figure 8 - Study Case: Fractures range of variation during history matching – constrained to hard data.

original information and permits a degree of progressive modification with increased distance from well. This design rigor to 'hard' data is critical to develop a history matched with respect to the conceptual geological knowledge and existing field data.

The methodology to manage fracture uncertainty realization is also critical. We present an innovative approach to continuously modify fracture distribution while respecting all available field data. Indeed, shifting from one fracture realization to another leads to completely different results. Hence using discrete fracture with an assisted history match process is not acceptable. The Event Solution utilizes a probability of fracture existence based on available field data (FMIs, mud losses, pressure transient tests, etc.) to model a possible range of fracture realizations from factual well location data as illustrated in Figure 8. Thus, this fracture probability property is used as a continuous factor to truncate realizations and describe the range of possibilities.

As a result of the history match, a narrowed range of possibilities from the original 70 factors is established. In particular, fracture distribution network was characterized with high confidence, as it was identified as a critical factor to match historical field performance. The FWL was also clearly identified in a very narrow range to match current water production. Likewise, critical water saturation as well as relative permeabilities were defined. Analysis excluded possible inter-reservoir communication through fracture and or matrix.

On the other hand, even with a narrowed range, permeability remains uncertain, as well as baffles extension. These narrowed uncertain factors were thus used to study development strategies under uncertainty.

5. Case Study - Development Plans under Uncertainty

A fundamental issue for field development was to apply the appropriate recovery scheme to maximize reservoir sweep and ultimate recovery. This was undertaken in a two stage process with the initial focus on technical recovery (areal / vertical sweep, tight rock recovery, pressure depletion, gas and water injection, EOR). Subsequently, practical and economic consideration (availability of injection fluids, impact on NGL recovery, project profits, net present value NPV) review was lead.

Reservoir recovery factor at the end of the history period was less than 2%. Therefore, much of the reservoir behavior remains unknown and only "performance insights" and "uncertainties" around controllable and non-controllable factors are carried forward from history match under uncertainty to prediction. The process of deterministic prediction involves taking the "best" history match under uncertainty and conducting a range of development scenarios to maximize the stated objective function (recovery factor, plateau length, revenue, NPV).

During history, well life was clearly controlled by explicit well limits (minimum economic oil rate, maximum producing water cut and GOR) and explicit higher field limits (field gas and water handling). As field limits are reached the recovery action was to close on the worst performing wells. Thus, the appropriate gas and water handling limits, and timing, through the prediction phase was a key challenge to superior cumulative production.

The base-case field development populated the underdeveloped reservoir areas with additional multi-lateral

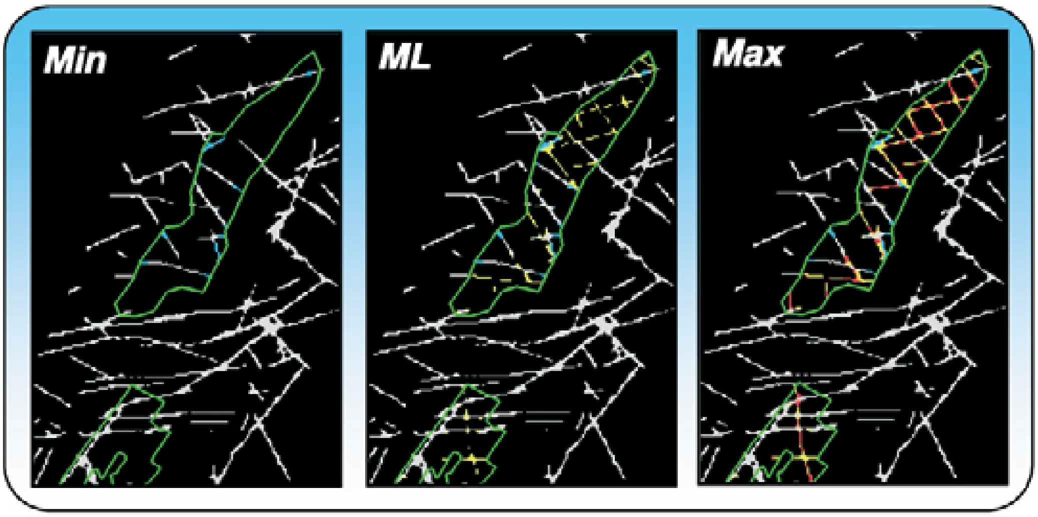

Figure 9 - Study Case: Fractures range of variation during prediction – regions with no information.

horizontal wells and continued to recycle produced gas (inject the produced gas into the gas cap as a pressure maintenance scheme). Deterministic prediction insights with reference to this case lead to the realization that field gas handling constraints were an impediment to well longevity with high oil rate wells being shut-in due to the field producing GOR limit being exceeded. Furthermore, oil in large sections of the reservoir below the horizontal wells was unproduced. The weak aquifer was not capable of sweeping this oil to the wells. A water injection scheme was implemented and made a significant impact in recovery in the lower reservoir sections. Substantial oil volumes, however, remained unswept in poor quality rock of < 10 mD. These areas were considered as EOR target areas for miscible gas injection or water-alternate gas injection schemes. Deterministic predictions defined parameters in areas such as improve well performance, increase reservoir sweep, balance off-take and gas / water injection and eventually maximize recovery.

There are numerous non-controllable factors which impact reservoir performance and innumerable controllable factors which optimize recovery. The affect on recovery factor and plateau length of non-controllable factors such as permeability, fractures, baffles extension and residual oil can be quantified by running a series of predictions under uncertainty. The impact of controllable factors such as field fluid handling constraints, water injection strategies and gas recycling can be tested through a series of predictions under uncertainty with optimization. These simulations will deliver at the end an optimized development plan under uncertainty with clarity on risk and critical uncertain factors.

An experimental design for 6 factors: fracture network, baffles extension, baffles in new areas, permeability, sorg and sorw, was considered. Looking at main effects, interactions two by two and quadratic terms, the analysis required 29 full field simulation runs. These runs target 50 years of simulation, which translates in 40 to 50 hours of running for each simulation under parallel clusters. The objective of this analysis is to understand the impact of the 6 factors, their interactions 2 by 2 and their quadratic effects on plateau duration, recovery, GOR and WC.

The fracture realization was modified to assess fracture realization impact on prediction performance. To respect consistency with history match, the realization remains unchanged near the existing producing wells (history match critical uncertain factor), and is modified in areas where wells do not exist. These regions are highlighted in green, in Figure 9, and from the minimum realization to the maximum one, the density of fractures is changing.

Based on vertical well log data, baffles were mapped; however, uncertainty remains on baffle extension. Thus, baffle extension was modeled and modified (Figure 10) with uncertainty (red regions Figure 11) for areas without wells. Permeability distribution was the fourth factor included in uncertainty analysis. To analyze the impact of permeability uncertainty on reservoir performance, a multiplier ranging from 0.75 to 1.75, as characterized through history match and based on the uncertainty ranges from available data, was applied. It is important to note that the multiplier does not modify permeability where existing data is available e.g. cores and or FMIs. Thus, as during the history match, the weighted 3D property is used to correct the multiplier (Figure 7). Hard data is preserved and changes are applied where information does not exist. Finally, uncertainty on residual oil saturation to gas and water is considered.

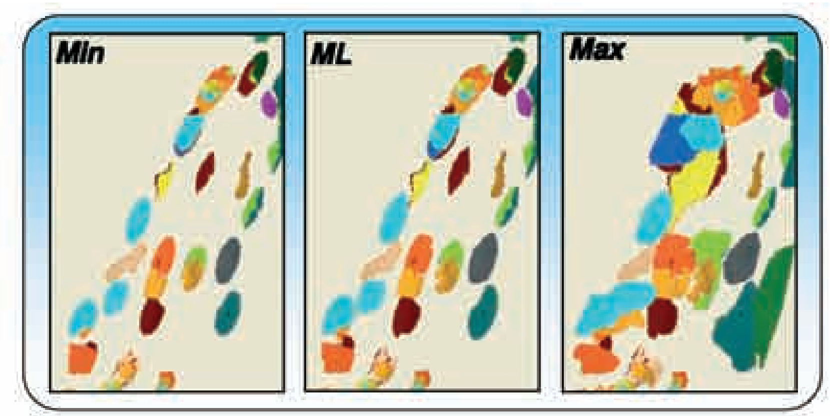

Figure 10 - Study Case: Existing baffles extension range of variation during prediction.

As illustrated in Figure 13, uncertainty analysis on the 6 factors: fracture network, baffles extension, new baffles, permeability, Sorw and Sorg resulted in a discrepancy of 7 years in terms of plateau duration. The time at which the maximum field gas handling capacity was reached is also affected by uncertainty, changing the timing to facility upgrade within a 5 year range. The factors critical to explain these discrepancies are the horizontal permeability and baffle extension. These factors, according to how they translate in project risks would be subject to an information plan.

6. Case Study - Risk Assessment, Information Plan and Mitigation Plan – The added value

According to uncertainty analysis results, risk assessment has been handled. Basically, knowing a 7 year difference in plateau duration exists, the risk qualification is to analyze this range of uncertainty with respect to the base case forecast. As illustrated in Figure 12, the plateau duration assessed as the base case (illustrated in blue) is close to the lower plateau range. Here, the risk assessment is a 7 years potential with very limited risk, since all changes in the uncertain factors extends plateau duration beyond the base case scenario. In such a case, a better understanding of the factors that influence plateau variation may add value to field understanding, but is not critical to mitigate study risk to plateau duration.

The risk in terms of determining the timing to upgrade the gas handling facilities, however, as illustrated on the right of Figure 12, is high. Indeed, the base case figure implies facility upgrade as one of the earliest investments. Thus the setting of a relevant information plan on facility upgrade factors (i.e. permeability and baffles extension) is critical, since it will allow applying better decision in terms of timing for investments.

Conclusions

Integrated reservoir studies under uncertainty are generally not pursued and or discarded as a consequence of an overwhelming and often suffocating perception / reality of un-managable study complexity and time.

The successful uncertainty and risk assessment workflow described in this article (Figure 1) does not rely only on advanced techniques and tools but mainly on an efficient and practical process, to screen study factors and narrow ranges, through integrated understanding, team synergy and clearly stated study objectives.

A practical workflow was provided to study uncertainty effectively in a reduced study cycle time. This workflow was also presented through a case study. As an example of this workflow, the Giant Saudi field case presented in this paper was completed in 3 months. Study deliverables included an optimized development plan detailing smart completion design and clarity on critical field development factors of business decision significane with an associated information and mitigation plan.

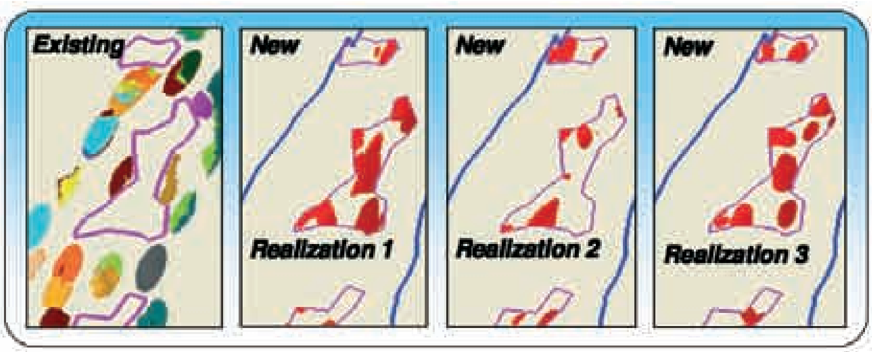

Figure 11 - Study Case: Baffles realizations range of variation during prediction – regions with no information.

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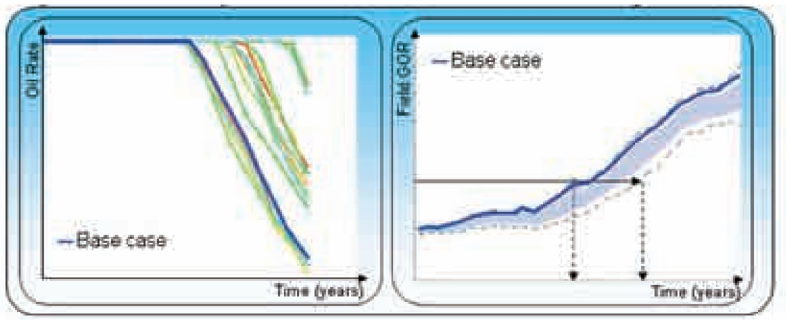

Figure 12 - Study Case: Risk assessment for plateau duration and timing for gas handling facilities upgrade.

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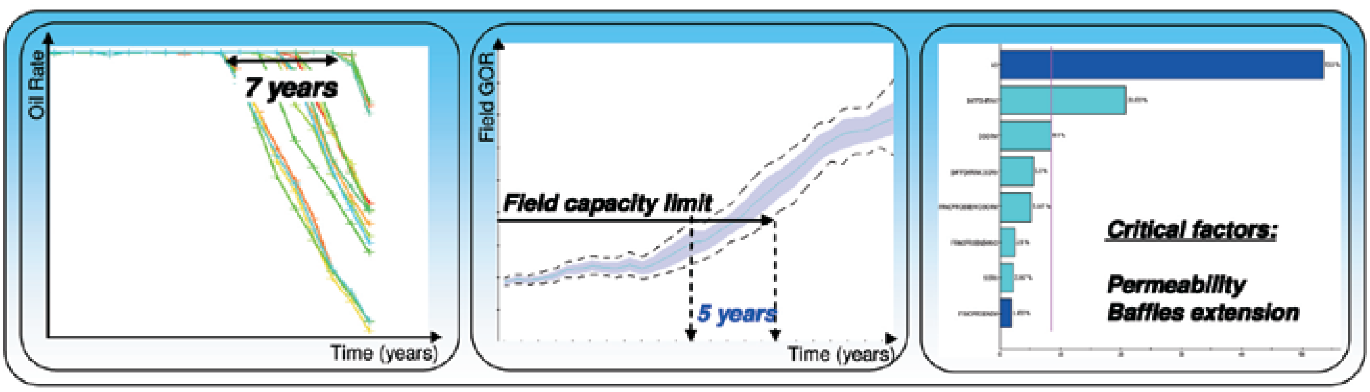


Figure 13 - Study Case: Production forecasts uncertainty analysis results.

They Built Aramco

First Saudi Board Member

Abdullah Al-Tariki

Engaging, dynamic, courageous and outspoken, Abdullah H. Al-Tariki is widely remembered as a world figure in the politics of oil and energy.

A Saudi native, Al-Tariki originally came from Zilfi, the son of a camel owner who organized caravans between Saudi Arabia and Kuwait. At an early age, Al-Tariki was noted for his intelligence and was sent to schools in Kuwait and Cairo. He later earned a scholarship to the University of Texas, where he studied chemistry and geology.

Al-Tariki was responsible for many firsts in Saudi Arabia. He was one of the first American-educated Saudis and is believed to be the first Saudi trained in both chemistry and geology. At 35 years of age, his role with the Directorate of Oil and Mining Affairs was to process petroleum statistics from Aramco and provide these to the Royal Family with his analyses.

In 1954, he became director general of Petroleum and Mineral Affairs. In 1959, Al-Tariki was the first Saudi elected to Aramco's Board of Directors. Upon creation of the Ministry of Petroleum and Mineral Resources in 1960, Al-Tariki was appointed the first oil minister.

Al-Tariki was pivotal in supporting both the nationalization and the Saudization of the company.

Among his other accomplishments, Al-Tariki was instrumental in the founding in 1960 of the Organization of Petroleum Exporting Countries (OPEC), and in his later years, served as an oil consultant and an activist in Arab affairs.

Bridging the Gap

Abdul Aziz M. Shalfan

Abdul Aziz Muhammad Shalfan joined California Arabian Standard Oil Company (Casoc) in 1934 as Employee No. 4 and continued to work, declining retirement for nearly 49 years, until his death in 1983.

During his lengthy tenure with the company, Shalfan served a variety of functions within the organization and a key role in the Public Relations Department. Shalfan worked at the Aramco Oil Exhibit and quickly developed a strong reputation for his warm and engaging treatment of exhibit visitors.

Originally from the Najd, Shalfan as a young boy was brought to Bahrain where he encountered two Western geologists in pursuit of oil. Although quite young, Shalfan offered his expertise as a native of Saudi Arabia, to accompany the gentlemen in their exploration efforts. Such began his adventures in the search for oil, and led Shalfan ultimately to the well called Dammam No. 7, where Max Steineke and his geological team reached their goal for commercial oil discovery in 1938.

Shalfan experienced first-hand this momentous period in history, important both for the Kingdom of Saudi Arabia and the world. Describing the rapid pace of transformation within Saudi Arabia as a result of discovering oil, Shalfan proclaimed, "We have gone from nothing to everything."

To Teach is to Learn

Fahmi Basrawi

With only a sixth-grade education, Fahmi Basrawi began an exciting journey with Aramco, obtaining a job as one of the first teachers at the company's Jabal School in Dhahran.

A resident of Jiddah who worked as a clerk in the local police station, Basrawi responded to an ad for Aramco employment. Because he could read and write Arabic he was quickly hired. He was told he was going to be an English teacher! Basrawi did not actually know English, but he soon taught himself the language, learning as he went, only a lesson or two ahead of his students.

At the time Basrawi taught at the Jabal School, there were 3 or 4 teachers and over 100 students. His work was cut out for him, and he quickly found himself to be a natural teacher with a penchant for organizing youth sports and field trips. Basrawi remembered teaching Ali Al-Naimi for two years during his time at the Jabal School. Al-Naimi, he recalled was a very prepared student.

Following his years at Jabal, driven by his own educational goals, Basrawi attended college in Beirut. He was among the first group of Aramco students to study in Lebanon. He later returned to Dhahran for a job in the company's government relations division.

Basrawi is also well known as a personality on Aramco Television, where he hosted educational programs for 17 years. Through this programming, women in the Eastern Province in Saudi Arabia learned to read and write during an era when there were no schools for girls. He later hosted a popular quiz show where Aramco contestants competed on the subjects of math, history, geography and religion.

One of Aramco's important pioneers, Basrawi reflects back on his time with Aramco and thinks it is wonderful that the Saudi employee of today has even more opportunities for education than during his era.

"Ohligers' team did not see themselves as "pathfinders" but rather as just men who were there to work."

Getting the Job Done

Floyd Ohliger

Surprisingly Floyd Ohliger, who was present during the very early days of Aramco, would have been reluctant to consider himself a "pioneer." In Ohliger's eyes, the true "pioneers" of the company were the early geologists, including Max Steineke and others. Ohliger said in a 1983 interview with "The Arabian Sun" that his team did not see themselves as "pathfinders" but rather as just men who were there to work.

Educated in petroleum engineering at the University of Pittsburgh and Stanford University, Ohliger's began his career in the oil fields of Venezuela and Colombia. In 1934 he was approached by Standard Oil of California (Socal) about working in Saudi Arabia. He jumped at the chance, and immediately headed to al-Khobar, where his first assignment as a petroleum engineer was to oversee construction of a pier and supervise the unloading of equipment. He went on to hold many positions with Aramco, developing a strong reputation for "getting the job done." One of Ohliger's more interesting jobs was with Government Relations, where he had frequent contact with King Abdul Aziz. The two men developed a very positive, respectful relationship and Ohliger reflected fondly on his close interactions with the King. Additional positions Ohliger held included resident manager, general manager, vice president and chairman of the Aramco Board of Directors. He retired from Aramco in 1957 and subsequently returned to the United States with his family.

On the 50th Anniversary of Aramco, Ohliger returned to the Eastern Province and other areas in Saudi Arabia, met with management and toured the new Exploration and Petroleum Engineering Center (EXPEC). He commented to "The Arabian Sun" during that return visit to the Kingdom that his work and time with Aramco brought him a "satisfaction more inward than anything else." He also talked about the overwhelming transformation of the Kingdom in the years he had been away and said the developments "for the country as a whole, including Aramco in the last 10 years, have been greater than all the preceding years." Much of the transformation was the result of a highly successful oil industry built through the hard work of Aramco's early pioneers, and Ohliger, whether he would admit it or not, played a significant role in this success.

"Davies's vision, professional skills and persistence were instrumental in the uncovering of vast petroleum reserves in the Gulf."

Early Explorer, Dedicated Leader

Fred Davies

Spanning a 37-year career in the oil business, Fred Davies was one of Saudi Aramco's earliest pioneers and geologists. Originally from Aberdeen, South Dakota, Davies studied engineering at the University of Minnesota before serving in World War I. He became a geologist in the United States and started his career in the oil business at the California Oil Company in Texas.

It was 1934 when Davies visited the Arabian Gulf on his first trip. On behalf of Socal (Standard Oil Company of California) and its subsidiary Bapco, Davies worked with the team that located the first wildcat well in Bahrain. Based on this discovery and his superior instincts, Davies recommended efforts to obtain a concession agreement in Saudi Arabia. He was convinced of the Kingdom's great potential for oil exploration.

This instinctual knowledge led to a tremendous future for Davies with the company, including his presence in 1939 when King 'Abd al-'Aziz turned the valve that permitted oil to flow onto the first export tanker at Ras Tanura. Davies' career with the company flourished after the momentous entrance of Saudi Arabia into commercial oil production.

Davies' career path included president of Casoc (California Arabian Standard Oil Company); Aramco vice president of Exploration and Production; executive vice president of Aramco; and eventually CEO and chairman of the board. He served on the senior leadership team during the season that Aramco relocated its headquarters from New York to Dhahran. He relocated his family to Dhahran and resided in the Kingdom for the remainder of his Aramco career.

In a display of honor, Aramco's first floating storage vessel was named the "F.A. Davies." Liston Hills, president of Aramco at the time, described Davies as a man "whose vision, professional skills and persistence were instrumental in the uncovering of vast petroleum reserves in the Gulf."

Pioneer of Saudization

Frank Jungers

He held what Fortune Magazine called "One of the Most Delicate Positions in all Industry."

Undisputedly a key figure in the company's history, CEO Frank Jungers oversaw momentous growth during his time with Aramco. Originally from North Dakota, Jungers was educated in Oregon and Washington State in engineering. He served in the U.S. Navy and then immediately went to work for Standard Oil of California in San Francisco. It was 1947, and Jungers was just 23 years of age when he was sent to Saudi Arabia for the first time. He was immediately given a permanent assignment in the Kingdom to work on a construction project. He quickly developed a reputation for maintaining very positive relations with the Saudi workforce. This is the reputation that Jungers carried with him throughout his career and an attribute that made him a great success with the company.

Unlike some of the earlier pioneers who built the company and its facilities from the ground up, Jungers joined a going concern, and worked hard to enhance and improve its operations. The course had already been laid out by his predecessors. Jungers, however, faced equally daunting challenges, as he was running Aramco during an era of massive change.

A natural problem solver, Jungers was tapped early on for managerial roles in Ras Tanura and then in Dhahran. In his desire to communicate better with his Saudi workforce, Jungers became fluent in Arabic. In 1971, Jungers was appointed as President of Aramco and served as Chairman of the Board and CEO from 1973 to 1978. During his time of senior leadership, Jungers oversaw the creation of the Kingdom's Master Gas System, the negotiations surrounding the Saudization of the company, and the OPEC oil embargo. A key figure during a critical time, Jungers today is recognized for his 30 years of service with Aramco and his dedication to the growth and professional development of the Saudi workforce during his tenure.

Senior Arabist, Superior Scholar

George Rentz

"Senior Arabist" is one of several titles bestowed upon Dr. George S. Rentz, Jr., during his tenure with the company.

Originally from Pennsylvania, Rentz's interest in Arabic culture occurred while teaching in Syria in 1932 at the age of 20. In his three years there, Rentz developed a profound love for the Arabic language which he pursued after returning to the United States. Rentz attended the University of California at Berkeley. He was studying classical Arabic and Near Eastern history at Berkeley when World War II broke out. He left the university to run the U.S. Office of War Information in Cairo.

In 1944, Rentz was invited to Jiddah by Karl Twitchell, an American mining engineer who was instrumental in the signing of the Concession Agreement in 1933. With his superb command of the Arabic language, Rentz was recruited as a translator for a mere 9-month opportunity, but went on to serve 17 years with Aramco.

With his comprehensive grasp of the language and culture, Rentz provided a critical role in Aramco's Government Relations Department. He also served as chief of the Arabian Research and Translation Division, and supervisor of Arabian Research. Rentz established high standards for Arabic translation and research. He is also recalled for his contributions to a series of Aramco handbooks detailing the history of Saudi Arabia, the petroleum industry and of Aramco itself.

Like other Americans who served with Aramco, Rentz was able to return to Dhahran later in his life to see how the country had changed. At the age of 71, Rentz was struck by the size of the buildings and the overwhelming accomplishments of the company. Rentz's contributions in research, scholarship and service were a significant part of that success.

Geologist and Icon

Max Steineke

Chief geologist from 1936-1946, Max Steineke arrived in Saudi Arabia after 13 years as a Socal (Standard Oil Company of California) geologist with experience in Alaska, Colombia and New Zealand. Steineke is described by author Wallace Stegner in his book Discovery!, as "Burly, big-jawed, hearty, enthusiastic, profane, indefatigable, careless of irrelevant detail and implacable in tracking down a line of inquiry, he made men like him, and won their confidence." The early pioneers agreed, and Steineke was highly respected by both his American and Saudi colleagues. Despite their limited communication in broken Arabic and English, Steineke developed a close friendship with chief guide, Khamis ibn Rimthan. The two worked side by side for many years in the early exploration days.

Steineke is well known for his efforts at Dammam Well No. 7, which in 1938 produced oil in commercial quantities for the first time in Saudi Arabia. With no promise of success – and previous unsuccessful drilling attempts – the teams kept drilling at Steineke's urging, which led to the discovery that ultimately transformed the Kingdom. It was no surprise that Steineke was awarded the prestigious Sidney Powers Memorial Medal in 1951, the highest honor for a petroleum geologist. Steineke's perseverance and commitment to Aramco give him a very special place in both the company and world history.

> "The daughter of a Saudi diplomat, Husseini's experience with education occurred outside the Kingdom, first in Rome, Italy, where she attended Marymount High School and subsequently at the University of Damascus in Syria."

First Saudi Female Professional

Najat Husseini

Aramco's first Saudi female employee with a college degree, Najat Husseini holds a significant place with pioneers in the company's history. The daughter of a Saudi diplomat, Husseini's experience with education occurred outside the Kingdom, first in Rome, Italy, where she attended Marymount High School and subsequently at the University of Damascus in Syria.

It was 1964, and Aramco had not yet hired an educated Saudi woman. Husseini, determined to put her education to work, applied to the company. Aramco lacked a precedent in this matter and sought special permission from King Faisal, a great supporter of women's education, to hire Husseini.

Upon gaining approval, Husseini took part in a health education outreach program where she contributed directly to Aramco's communities. With other Aramco employees, Husseini traveled and educated Saudi families on personal care, health practices and sanitization. Her impact on Aramco and its female work force – as well as on the improved health care of the surrounding communities – has left a lasting mark on the company.

The Legacy of a Lifetime

Nassir Al-Ajmi

"I wasn't looking for a career. I was looking for a living", Nassir Al-Ajmi says in a 2007 interview about his 42 year experience with Aramco. Al-Ajmi represents a remarkable story of a humble teenager who started his path at Aramco as an auto-mechanic trainee in Dhahran in the 1950s. Eventually, Al-Ajmi grew to occupy the role of Executive Vice President, leading the company through its evolution to a state owned enterprise in 1988.

Al-Ajmi is honored as one of the most successful leaders in Saudi Arabia, in transitioning a company and a Kingdom from the pre-oil discovery era to industrialization and growth. With his leadership skills shining through at an early age, Al-Ajmi was selected by Aramco for an out-of-Kingdom education in Lebanon and the United States. He completed a high school degree in Beiruit, and a University degree at Milton College in Wisconsin. Upon returning to Aramco, Al-Ajmi took on several leadership roles within the company and was ultimately sent for further advanced education at Columbia University and Harvard University. With his education, ambition and determination, Al-Ajmi served in the roles of Vice President, Senior Vice President and an eventual election to the Board of Directors. Colleagues describe Al-Ajmi as hard working and always available.

Al-Ajmi is currently retired, and is a published author of "The Legacy of a Lifetime". In a 2007 interview, Al-Ajmi recounts his experience in the early days of Aramco. He provides thoughts on the future of Aramco and says he hopes to see managers who are able to grow and learn beyond what the founders were capable of. In speaking to a group of new engineers at Aramco, Al-Ajmi tells them he is glad to not be competing with them. "That's the kind of organization that we hope to maintain in Aramco", Al-Ajmi says, "…as a generation leaves, they leave people better than themselves".

Geologist, Engineer and Photographer

Richard Kerr

After working with Shell Oil in Mexico and Canada, Richard Kerr was approached with an opportunity to travel to Saudi Arabia in 1933. Because of his expertise in geology, Kerr was asked to provide aerial geological reconnaissance for Standard Oil of California (Socal).

Kerr and colleague Charles Rocheville ordered a Fairchild 71 airplane and began their aerial journey. There were no roads in Saudi Arabia at that time, nor any maps or communications tools to help them find their way. Kerr and Rocheville relied on markers left by other explorers who dug trenches in the sand, filled them with gas and set them on fire to leave blackened messages and words to other travelers. Kerr studied, sketched and photographed the Arabian terrain, and played a great part in the development of the country's maps. Today, many of Kerr's photographs remain in Aramco's historical archives.

After his first airborne mission, Kerr returned to Saudi Arabia for permanent employment with the company from 1937 – 1950. Described by colleagues as 'insatiably curious', another important accomplishment Kerr made is the design of a low-pressure sand tire for desert driving. He received recognition by the U.S. Secretary of Defense for this contribution which enabled longer distance driving in desert areas and made greater exploration efforts possible in Saudi Arabia.

Kerr's later years with Aramco were spent in the New York office where he hosted many associates from Aramco and Saudi Arabia. His lasting marks as an Aramco "pioneer" were the innovative contributions borne from his spirit and dedication to the country and company.

Deep Desert Oil - The Shaybah Field

Saudi Aramco heightened its profile as a world-class engineering and construction organization with a presentation before the prestigious Construction Industry Institute recently. The presentation, entitled The Shaybah Story: Oil From Deep in the Desert, was given at the organization's annual conference in Minneapolis.

Abdulrahman F. Al-Wuhaib, then vice president, Project Management, and currently vice president, Ras Tanura Refining, reported on the series of construction accomplishments before an attentive gathering of some 500 Institute members representing 83 companies. Assisting him in a panel presentation and discussion that followed were four key members of the project team. They included Nadhmi Al-Nasr, manager, Shaybah Development Projects Department; Abdullah M. Okab, manager, Shaybah Producing Department; Rudy Ionides, project director, Overseas Bechtel, Inc.; and Hamid Amin, area general manager, Consolidated Contractors International Company. J.G. Palmer, quality coordinator, Project Management, served as moderator.

The Construction Industry Institute is a research organization with an all-encompassing mission: to improve the quality, safety, scheduling, competitiveness and cost-effectiveness of the engineering and construction process. Established in 1983 to develop a national research center for construction, it consists of a consortium of leading owner companies and contractors who join together to find better ways of planning and executing capital construction programs.

Al-Wuhaib saluted the construction industry organization in his presentation, giving credit to the national forum for planning, engineering and construction techniques developed and fostered by the organization. He indicated that the techniques had strong influence particularly in team building and schedule compression, two important areas that played a major role in the successful completion of the Shaybah program.

The Shaybah presentation marked the first time that Saudi Aramco has appeared on the annual conference agenda. Saudi Aramco has been a member of the Construction Industry Institute, through ASC, since 1992, and has participated on a number of research teams over the years.

Abdulrahman F. Al-Wuhaib presented the Shaybah story to the Construction Industry Institute.

"Picture yourself, a project manager, sitting in a nice cool office in the headquarters building," said Al-Wuhaib, as he began his presentation. "Suddenly the boss stops by and says the company needs to develop a grassroots oil field in Shaybah, one of the hottest and harshest environments on earth. It is 340 miles from the nearest town. Vehicular travel will take four days over sand dunes. No problem, you say. It will be a challenge, but it can be done.

"Just after the front-end engineering is underway, the boss comes back and says your schedule is cut by 25 percent—a whole year! You have a total of three years to start production. Now this is a real undertaking."

Al-Wuhaib challenged his audience: "How would you manage and execute a project this big, in such a remote and harsh environment, in only three years?"

The Shaybah team, he said, actually built Saudi Aramco's largest oil production plant in this extremely short time frame.

> Success was achieved through the combined efforts of a committed team of employees, contractors and suppliers, from the president of Saudi Aramco to the welders in the field.

The first steps in Shaybah presented a picture of overwhelming challenges—all to be overcome.

"Success was achieved through the combined efforts of a committed team of employees, contractors and suppliers, from the president of Saudi Aramco to the welders in the field. One team, with one vision and one mission—that was Shaybah."

Panoramic view of the project

Using slides as he spoke, Al-Wuhaib took his audience through a scenario that has become familiar to many in Saudi Aramco acquainted with Shaybah's background and development. He covered the project scope, the obstacles faced, and explained how the project team met a myriad of challenges.

A map showed Saudi Arabia, the pipeline network and fiber optic cables, and the Abqaiq Plants and mammoth gas/oil separation plants (GOSPs) and related facilities. His audience saw scenes depicting the local topography, large salt flats surrounded by sand dunes towering 700 feet, and viewed pictures of early construction work where bulldozers leveled the imposing dunes to make way for men and machines.

"The desert environment has been undisturbed for thousands of years," Al-Wuhaib explained, "and the project team felt that its protection had to be one of their top priorities. Environmental impact assessments were conducted to minimize and mitigate potential harm to this delicate landscape, and all of our protection measures were enforced throughout construction.

"As you can see, the terrain is starkly beautiful, but treacherous and unforgiving. With temperatures sometimes reaching 135 degrees Fahrenheit, anyone unfortunate enough to get lost in this environment would most likely pay with his life. The location is 340 miles from the nearest town, 240 miles from the nearest road. Until the new road was finished, surface travel took four days, men digging out stuck vehicles and sleeping on sand dunes under the stars—nice in winter but a different story in summer."

The team faced extraordinary difficulties, Al-Wuhaib said, with transportation, equipment maintenance, and worker safety, health and morale. His rapt audience chuckled when he explained that even sand and gravel for concrete had to be imported because none of the local sand was suitable.

Biggest hurdle

But of all the challenges, Al-Wuhaib said the schedule presented the biggest hurdle. Six months into front-end engineering, management requested that the completion be advanced. The plan called for startup only 30 months later. According to Al-Wuhaib, not everyone in the company believed it could be done.

The steps the project took to meet the challenge were team building and schedule optimization, concepts promoted by the Construction Industry Institute, and strong management and teammember commitment.

An integrated project team structure was developed whereby members of Project Management and Operations and other involved organizations became members of a single team. This approach worked well as it streamlined communications and approval procedures and greatly expedited the progress of the work.

A major milestone was reached when the access road was completed, allowing much easier and speedy access to construction and operations sites.

Transportation achievements were legendary during the development of Shaybah. Every capital item, as well as all expendables, had to be transported deep into the desert.

The availability of pipe when and where needed was an indispensable part of the Shaybah story.

The availability of pipe when and where needed was an indispensable part of the Shaybah story.

Crude-handling facilities designed to process 500,000 bpd.

A city grows from the desert as the Residential/Industrial Complex takes shape.

Access by air was also indispensable. Runway and hangar facilities tie the desert operations into everyday schedules.

Shaybah GOSP-2 pipe rack under construction.

> "Upper management communicated its commitment to complete the project on time to all Saudi Aramco organizations and explained its importance. Members of our team were committed to success, and everyone worked overtime regardless of his role, to ensure that the schedule was met. You never heard the words, It's not my job."

A second innovation was to expand the team concept to all stakeholders in the project. The team not only included such routine members as design and construction contractors, but also team members' families, turnkey suppliers, and local officials and agents.

Each and every stakeholder was impressed with the importance of the project and his role in it, which was key to establishing commitment. "The commitment had to come from the top," Al-Wuhaib explained, "and it did. Upper management communicated its commitment to complete the project on time to all Saudi Aramco organizations and explained its importance. Members of our team were committed to success, and everyone worked overtime regardless of his role, to ensure that the schedule was met. You never heard the words, 'It's not my job.' "

Al-Wuhaib went on to explain numerous other innovative approaches— such as early release of bid packages, unique tran portation arrangements, Customs clearance assistance and compression of commissioning and startup—that contributed to the successful and timely completion of Shaybah. But underlying them all was team building, the members working together as a team to meet the aggressive schedule.

As a result, Al-Wuhaib said, the team effort accomplished:

• On-time completion with start of production just three years after the start of front-end engineering and only 18 months after start of construction;

• Less than 3 percent change orders;

• Capital expenditures well under the original budget; and

• Proven methods of organization and schedule improvement that are being used on other projects in Saudi Aramco.

In closing, Al-Wuhaib told his audience that the word "Shaybah" in Arabic means "gray-bearded, or old man." Most of our project team members, he said, now feel that they have earned this title.

KAUST: Building Wisdom's New House

Saudi Aramco is no stranger to mega-projects, but in 2007, the company undertook a building program of a different kind: a $10 billion, world-class research university tha is the brainchild of King Abdullah. The new university, to be located in Thuwal, Saudi Arabia, on the western Red Sea coast north of Jiddah, will usher in a new era of scientific discovery and achievement that will benefit not only the Kingdom but the entire world.

The King Abdullah University of Science and Technology (KAUST) builds on the tradition of the Arab golden age of knowledge, when from the 8th to 11th centuries, scholars of Baghdad's Bayt al-Hikma, or House of Wisdom, preserved and enlarged on Greek and Roman discovery, anticipated and informed Renaissance scholarship, and made seminal contributions to geometry, physics, optics, medicine, logic, engineering and other fields. As wisdom's new house, KAUST is chartered to bring the world to Saudi Arabia on one campus to explore and develop solutions that will transcend national boundaries to serve the world.

The university will be international in scope, open to men and women of all nationalities and faiths, creating opportunities for top minds to address common global issues and problems. Initially, KAUST will focus on four interdisciplinary research clusters: energy and the

KAUST, envisioned by King Abdullah as both "a source of knowledge and a bridge between people and cultures," is being built on the premise that a global institution with global partners can exert a global impact.

> It is true that KAUST's physical campus represents a mega-project, but Saudi Aramco's participation is the result of more than the company's success with giant construction projects. For nearly 75 years, the company has been the Kingdom's international model, with 65 nationalities working together to help meet the world's energy needs.

environment, biosciences and engineering, materials science and engineering, and applied mathematics and computational science. The university, in collaboration with the world's foremost research and academic institutions, will recruit top students globally to pursue master's and doctoral degrees and conduct research. KAUST's Innovation Center, a key element of the university, will link researchers and industry to drive economic growth and create jobs. These goals of forming a knowledge-based economy, supporting scientists and their work at national and international levels, and benefiting the world through research and economic development will be achieved through partnerships and collaborative agreements with leading universities and research centers around the globe.

In addition, KAUST's $20 billion endowment will place the university in the upper echelon of the world's top-funded institutions of higher learning.

It is true that KAUST's physical campus represents a mega-project, but Saudi Aramco's participation is the result of more than the company's success with giant construction projects. For nearly 75 years, the company has been the Kingdom's international model, with 65 nationalities working together to help meet the world's energy needs.

Leadership in Community Enrichment

In a major, unprecedented undertaking at the direction of the government, Saudi Aramco is developing the King Abdullah University of Science and Technology (KAUST), a world-class graduate research university that promises to usher in a new era of scientific and technological discovery. This unique cooperative research complex is intended not only to advance academic knowledge and strengthen and diversify the economies of Saudi Arabia and the region, but also to contribute to global economic and social advancement by producing generations of leading scientists, engineers and technologists to find solutions and innovations benefiting all humankind. In June, the KAUST website (www.kaust.edu.sa) and logo were launched, and on October 21, KAUST's groundbreaking on the Red Sea coast north of Jiddah took place before 1,500 dignitaries from around the world.

We started preliminary engineering on the Saudi Aramco Cultural Center, a planned multistory public complex commemorating our 75th anniversary in 2008 and supporting King Abdullah's vision of a knowledge-based society. In addition to housing a library, learning facilities, a media center and an auditorium, the center will host a variety of cultural events.

In 2007 Saudi Aramco took many steps to create jobs and boost the domestic economy, including procuring two contracts for the construction of 65 new offshore oil and gas production platforms and structures. In addition, a new yard in the Dammam Port area will allow offshore fabrication to be done in Kingdom for the first time, capturing jobs in construction, procurement, housing, transportation and other areas that previously were foreign-sourced.

Reliable energy supplies far into the future

Saudi Aramco is continuously seeking new oil resources, as well as expanding production through efforts including the two largest single increments in its history (Khurais and Manifa), and expertly managing its existing portfolio of some 100 fields to maximize recovery. And as the world's oil supplies become more challenging to produce, Saudi Aramco is taking the lead in developing technologies to produce conventional oil reserves more efficiently.

Crude Oil

Not long ago, Saudi Aramco President and CEO Abdallah S. Jum'ah issued a challenge to the wider oil industry: Find enough new resources to add 1 trillion barrels to world reserves over the next 25 years. That challenge began at home. Saudi Aramco is leading the strategic development charge to help ensure reliable energy supplies far into the future. Saudi Aramco is continuously seeking new oil resources, as well as expanding production through efforts including the two largest single increments in its history (Khurais and Manifa), and expertly managing its existing portfolio of some 100 fields to maximize recovery. And as the world's oil supplies become more challenging to produce, Saudi Aramco is taking the lead in developing technologies to produce conventional oil reserves more efficiently.

This 10-year, Kingdom-wide capital program includes an exploration strategy that aims to replace reserves to match our annual crude oil production and add at least 5 trillion standard cubic feet of non-associated gas reserves per year. The program includes drilling and seismic activities to generate prospects and improve imaging in support of finding both oil and non-associated gas. Some of the capacity added by these major crude oil increments will offset natural decline, and the remainder will expand our maximum sustained production capacity, which by the end of 2009 will reach 12 million barrels per day (bpd).

These efforts to discover new resources and add to reserves for years to come are just one reason Saudi Aramco is the world's cornerstone for crude oil.

Our mega-project slate is geared to ramp up production in response to the growing global need for energy. Collectively, these strategic increments alone will match the daily oil production of some oil exporting countries.

Two Days, Two New Oil Discoveries

Success stories for 2007 included two new oil discoveries, both located in the Eastern Province southeast of Ghawar, the world's largest onshore oil field.

The first, Mabruk, struck on April 26, is the first discovery in the Hadriyah reservoir south of Ghawar.

The Mabruk-1 well flowed 5,600 bpd of Arabian Heavy oil with 2 million standard cubic feet per day (scfd) of gas. Under normal production conditions, the well is expected to flow at a higher rate. The following day, on April 27, the Dirwazah field was discovered in the Unayzah reservoir. The Dirwazah-1 well flowed 5,569 bpd of Arabian Light oil with 2.8 million scfd of gas.
Mega-Projects: Production Success Stories

Saudi Aramco's ambitious capital program achieved many milestones during 2007 toward construction of crude oil increments. Since 2001 through the scheduled completion of Manifa in 2011, the company will have built more than 4 million bpd of oil production capacity and 3.3 billion scfd of new gas-plant output.

Mega-projects, generally defined as programs exceeding $1 billion in value, are not big news just for their size or cost. Their impact also is huge. Major crude increments will add the following amounts to Saudi Aramco's oil output capacity: Khurais, 1.2 million bpd; Manifa,

"To put the grand scale of this expansion program in perspective, consider that the collective capacity these increments represent is equivalent to the daily oil production of some exporting countries."

900,000 bpd; Khursaniyah, 500,000 bpd; and Shaybah, 250,000 bpd. While Nuayyim does not qualify as "mega," at 100,000 bpd, it will add significantly to production capacity.

An unprecedented number major of crude oil increments were in progress during the year: Khursaniyah is near completion, and Shaybah, Khurais, Nuayyim and Manifa are under construction.

To put the grand scale of this expansion program in perspective, consider that the collective capacity these increments represent is equivalent to the daily oil production of some exporting countries.

Khursaniyah: The Khursaniyah Oil Production Facilities project neared completion at the end of 2007, with facilities slated to come on-stream in 2008. The plant has the capacity to process and stabilize 500,000 bpd of Arabian Light crude. All gathering and distribution pipelines, and communication and industrial support facilities were commissioned in 2007. The integrated Khursaniyah Gas Plant (KGP) designed to process the associated gas will be commissioned with a first-time distinction: a 100-percent Saudi workforce.

Khurais: The Khurais program, the largest integrated project in company history and the largest industrial project in the world, is on track for facilities completion in 2009.

Natural Gas

Discoveries and Expansions

Saudi Arabia's expanding domestic economy and industrial enterprises depend heavily on Saudi Aramco's natural-gas reserves. Current use is at the highest level in the history of our gas program. To meet this demand, Saudi Aramco is working hard to find reserves and build its production and distribution capacity. Total gas production average was 8 billion scfd at year-end. Saudi Aramco plans to increase gas capacity to 13 billion scfd by year-end 2011.

Saudi Aramco's exploration efforts were rewarded with the discovery of two significant gas reservoirs in 2007, both located in oil fields originally discovered in 1967. Karan-7, an extension of our largest gas field, Karan, is located six km south of Karan-6, a 2006 reservoir discovery. Gas also was discovered at the Jana-6 offshore well.

Gas Cornerstones

The Karan Gas Field Development Project will provide offshore platforms and pipelines for the production of 1.5 billion scfd of gas by 2012. Associated gas from Khursaniyah will be processed at Berri Gas Plant until the new Khursaniyah Gas Plant is completed. Scheduled to begin operations at the end of 2008, the new plant will process 1 billion scfd of associated gas from Khursaniyah, Abu Hadriyah, Fadhili and neighboring fields.

The Hawiyah NGL Recovery Plant, on track for start-up in third-quarter 2008, will process nearly 4 billion scfd of sales gas to yield 310,000 barrels of natural gas liquids. The NGL products will be used as feedstock for the Kingdom's expanding petrochemicals industry, creating thousands of job opportunities for Saudi citizens. Approximately 379 km of related pipelines and two pump station upgrades were completed in November 2007, and are ready to deliver the NGL products to end users.

Another component of the project, the expansion of Ju'aymah Gas Plant, is set for startup in second-quarter 2008 and will fractionate additional NGL products. The last part of the program, the Hawiyah Gas Plant Expansion, will process an additional 800 million scfd of non-associated gas.

The integrated Khurais program will dehydrate and compress 450 million scfd of gas, and the Manifa Oil Field program will produce 120 million scfd of gas by third-quarter 2011.

The expansion of Yanbu' Gas Plant will increase ethane and NGL processing by 185,000 bpd, and will support the strategic aim of growing feedstock supply to industries at the Yanbu' and Rabigh petrochemicals complexes. The Master Gas System Eastern Region Expansion Project, funded in July 2007 and slated for completion in 2010, will expand the MGS distribution system with 215 km of 56-inch pipeline parallel to existing lines and increase capacity by 30 percent.

Innovations and Breakthroughs

Saudi Aramco has developed new drilling practices that led to drilling horizontal wells targeting separate layers and improving access to gas reserves. As part of this process, we also developed clean drilling-fluid designs in 2007. An added benefit of this latest fluid development is a much lower cost.

The mystery of black powder, a corrosive nuisance that clogs and damages control valves, parts and pipelines and whose origin has stymied the industry for years, was solved when Saudi Aramco's Research and Development Upstream Program completed a two-year study and presented its findings in Norway in 2007. The company's scientists determined that black powder results from the gas components of oxygen and moisture; they also identified the culprit's punishing properties, which include tiny particles of metal, sand, dirt, hydrocarbons and elemental sulfur. The team worked closely with the Pipelines Department to isolate black powder's origin and composition, and Southern Area Labs contributed to the breakthrough by conducting gas analysis.

The Oil Curtain - An excerpt from the Hydrocarbon Highway

The Oil Curtain neatly symbolizes resource sovereignty and separates the Hydrocarbon 'haves' from the 'have-nots'. It has led to the major part of proved global oil reserves being booked by National or State Oil Companies. To illustrate the change of ownership, in 1971 NOCs held 30% of total reserves while IOCs held 70%. Today NOC have increased their share to 93% while IOCs hold 7%[1] - what caused such a dramatic reversal in fortune?*

By Wajid Rasheed

Since the early 1900's the importance of oil in financial, political and strategic matters has been bubbling up to the surface. Eventually, this led to a pressing need for producing states to control Oil. Mexico was first to 'shut' the Oil curtain by nationalizing its oil assets and forming the wholly state owned Pemex (Petróleos Mexicanos) in 1938[2]. By 1960 resource sovereignty had fully matured into a global force and the Central Bank of Oil[3] - OPEC (Organization of Petroleum Exporting Countries) was created.

OPEC's central message was clear; oil was too important to leave in the hands of foreigners[4]. It would seek to regulate 'oil-rents' and end arbitrary payments from foreign oil companies. OPEC's thinking was shaped threefold. Firstly, deals favored foreign oil companies and foreign governments, not producing states. Foreign oil companies also controlled an outward flow of profits which were often the greater part of producing countries' GDP. Generally, beneficiaries were foreign governments either directly through shareholder dividends or indirectly through taxes. Secondly, foreigners took vital political decisions affecting the sovereignty of producing countries. Oil production, foreign exchange earnings through oil sales, and ultimately, national debt were unilaterally dictated by foreign oil companies. Lastly, the military and naval campaigns of the Second World War combined with the utility of oil in general transportation left no doubt that oil was a primary strategic asset.

Producing countries were united; the old deals had to be undone. New deals would treat territorial owners of resources and the international oil companies as equals.

Modern National oil policy has come full circle (see Figure 1). It has evolved from seeking equal treatment to maximising royalties to stipulating local content to

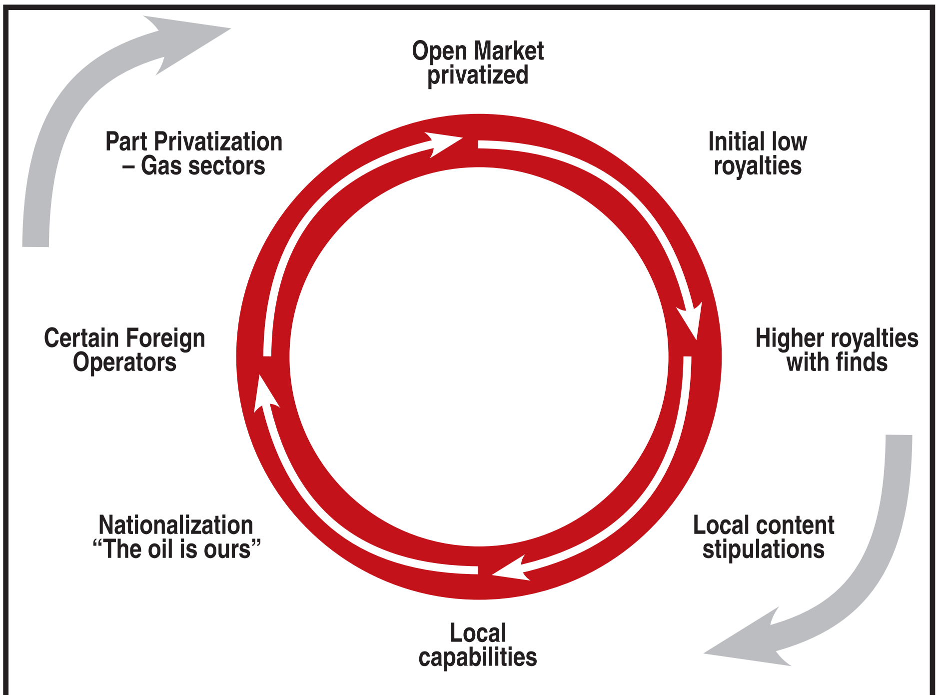
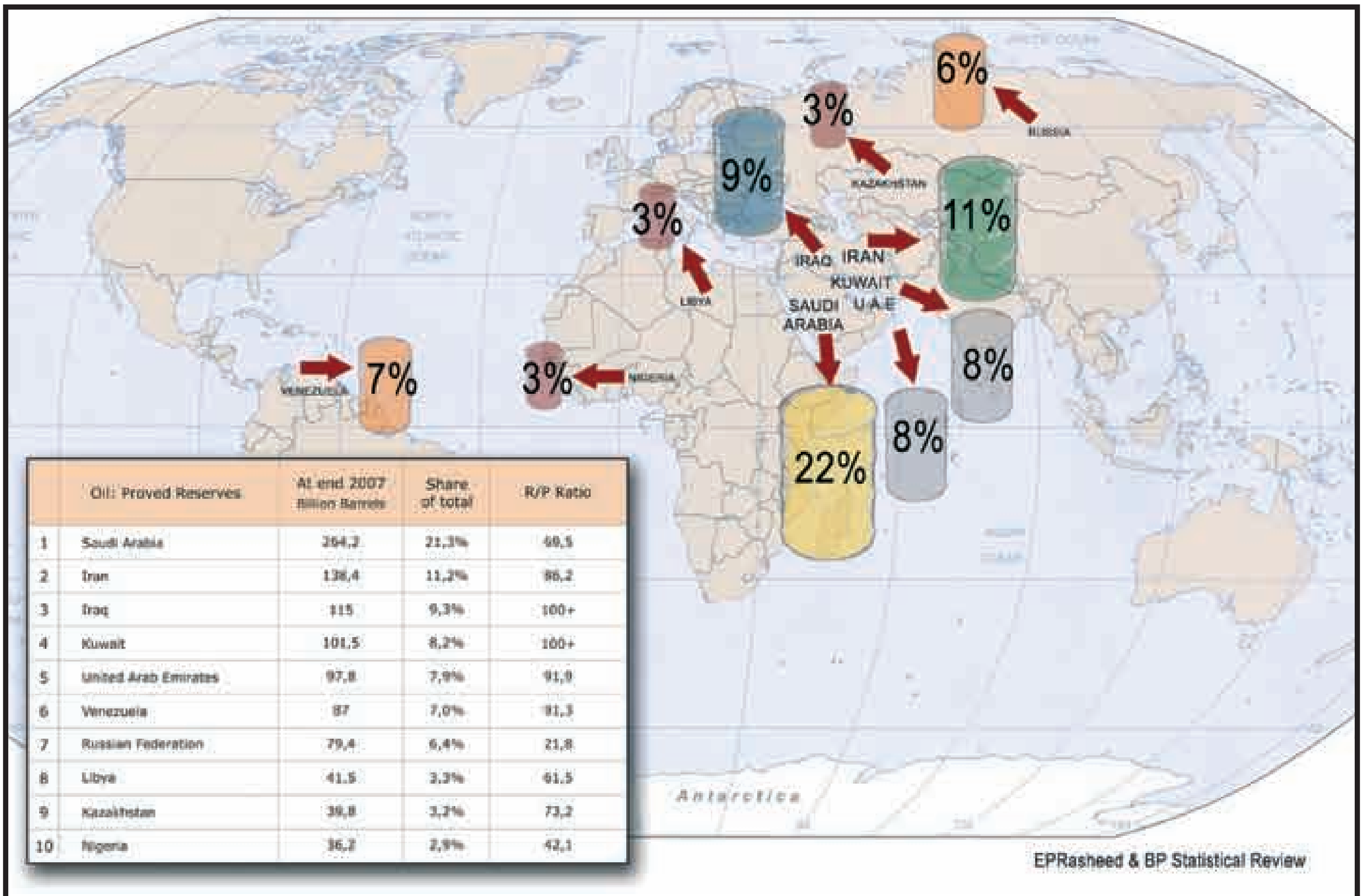


Figure 1 - Oil and Gas Nationalization has come full circle from seeking higher royalties to partial privatization.



	Oil: Proved Reserves	At end 2007 Billion Barrels	Share of total	R/P Ratio
1	Saudi Arabia	264,2	21,3%	69,5
2	Iran	138,4	11,2%	86,2
3	Iraq	115	9,3%	100+
4	Kuwait	101,5	8,2%	100+
5	United Arab Emirates	97,8	7,9%	91,9
6	Venezuela	87	7,0%	91,3
7	Russian Federation	79,4	6,4%	21,8
8	Libya	41,5	3,3%	61,5
9	Kazakhstan	39,8	3,2%	73,2
10	Nigeria	36,2	2,9%	42,1

Figure 2 - Top Ten Global Oil Reserves 2007.

full re-nationalization and now to partial privatization for Gas developments.

New Seven Sisters

Nowadays, OPEC decisions get as much ink as those of major central banks[5]. Yet beyond the paparazzi flashes and news-wire headlines, how important will OPEC and NOCs be for future oil supply? Realistically, the production of OPEC and certain NOCs will be vital for several generations to come. To understand that reality, simply look at (see Figure 2) the top ten reserve holders worldwide: Saudi Arabia, Iran, Iraq, Kuwait, UAE, Venezuela, Russia, Libya, Kazhkstan and Nigeria. Seven of these countries - the first six and Libya - are all OPEC members.

To see how important these new Seven Sisters[6] are to future oil supplies, consider the reserves to production column (Figure 2) to see how many of today's top ten global reserve holders are likely to be producers in the EIA Energy Reference Case year of 2030[7].

At that time, I will be 60 years old and probably writing about the world's next 25 years of oil production. But more to the point of todays' top ten reserve holders Russia would have dropped off the list while the new seven sisters and OPEC would still be producing away. If you are wondering where are the other current major producers? Canada has 22.9 years, the US has 11.7 years and Mexico has 9.6 years of oil reserves left at current production rates. Upshot: OPEC and the new Seven Sisters will grow both home and abroad. NOCs may not become global household brands but they have set the trend that restricts IOC access to oil, and lately, the dividing line between the two is not so clear.

Fuzzy Logic

The fuzziness between private and state oil companies stems from the NOCs that have 'gone global'. On the one hand for certain companies the logic and returns of going global are compelling; add new production and export 'home-grown' technology. Yet, on the other hand there is the risk of sudden nationalization. Once well-heads, fields, pipelines and refineries are built, they cannot be dismantled and sent back 'home'. In the event of political change or a major dispute the Oil company's bargaining power is effectively reduced. Any share it may have of production can only be sold off to the state concerned – which becomes a question of expedient valuations rather than ownership.

Corporate Social Responsibility

CSR has grown to encompass the building of local capacity that may export technology and know-how, the saving and investment of oil profits into non-oil related industries but essentially it means enfranchising locals in most aspects of the oil company's business either locally owned or managed.

The politics of revenue distribution can be a potential minefield for Oil companies. They must satisfy the powers that be – state governments—and reconcile the valid needs of local groups whether these are communities that have right-of-way over pipelines or those that living in the state that produces oil or gas. If there are competing ethnic groups or a self-perpetuating elite with poverty stricken masses then the oil company is sitting on a time-bomb. Paradoxically, it is the case sometimes that even that if Oil companies keep locals happy and build local industries, the government may still nationalize.

Setting Ethical Standards

Why do oil companies set ethical standards? Mainly due to past problems with 'corruption' and the lack of transparency which had savaged the reputations of IOC. IOCs learnt that they were being targeted by savvy lobbyists and environmental activists which could negatively impact their image and share price globally. This coupled with anti-corporate demonstrations even led some IOC to publish sensitive figures regarding tax payments abroad made to foreign Governments in regard of operating agreements. Further, some Oil companies aligned themselves to protecting human rights by joining the UN World Compact. Legislation such as Sarbanes Oxley in the USA, with its emphasis on due diligence has tightened up and defined the limits of ethical behaviour for companies acting abroad, and this influence has permeated the industry as a whole which generally has high levels of corporate governance.

What actually constitutes a National or State Oil Company? It is worth focusing here to see what distinguishes the NOC from the IOC. Is it 100% state ownership? Or just a state majority? What if the company floats on the world's stock markets and has private shareholders yet retains a State majority? Yes to all.

The distinction depends on whoever holds 51% or more of voting shares and controls overall decision making power. If the majority shareholder is a Government or State, the company must answer to them, therefore such a company is defined a National Oil Company. The opposite applies also. If the company's 51% voting majority is privately held or listed it would be defined as an International Oil Company.

Shareholder distinctions shed light on the responsibilities of each company too. NOCs have a strong responsibility to steward oil wealth to meet the needs of a given nation and its population in a sustainable way. IOCs focus primarily on maximizing returns, social responsibility is important also but not to the same degree as NOCs. Most people in the industry accept that profits must be balanced with social responsibility. Private shareholders generally accept this too. Corporate Social Responsibility (CSR) programs within IOCs are abundant and this type of social spending does raise investors' eyebrows as long as returns are healthy. Part-privatized NOCs fall into this category also. Just how much social responsibility is deemed healthy depends on the shareholders. (See boxes above)

We speak your language

Notable NOCs such as Petrobras and CNPC operate well beyond their home territories. Both companies not only retain majority government stakes but also raise capital using a canny combination of state finance and international financial markets to develop domestic and foreign reserves. But where they really excel is by competing internationally for capital and upstream acreage and applying their unique technologies and know-how.

Accessing reserves or holding on to them is the producer's top challenge. Consumption is a given. Subsequently, finance, human resources, technology and processed can be acquired.

NOCs go global

Naturally then it is a 'no-brainer' for NOCs with global ambitions to compete for foreign reserves and production. Entering this competition makes sense for those NOCs such as Petrobras or CNPC that have limited reserves or high production costs at 'home' or where they can export 'home-grown' technologies abroad. It does not make sense for the new Seven Sisters who have abundant domestic reserves at relatively low production cost. In the latter it makes more sense to stay 'home' and develop national reserves. But where do the IOCs fit into all of this?

> In the corporate cost-cutting that ensued, locations and operations were rationalized. Many IOC's consolidated their international operations in Houston. RD, technology activities and technical disciplines were seen as unnecessary fixed costs that could be more profitably outsourced.

Original Seven Sisters

A decade ago the price of a barrel of oil languished at US $10. This triggered 'mergeritis' and reformed the original Seven Sisters - a term coined by the Italian oil tycoon Enrico Mattei[8]. The original Seven were Exxon (Esso), Shell, BP, Gulf, Texaco, Mobil, Socal (Chevron) - plus an eighth, the Compagnie Francaise Des Pétroles (CFP-Total). During the 1990's the new 'Prize' for these companies was finding synergies and economies of scale. Management consultants were set the task of merging these great disparate entities and Analysts evaluated the mergers in terms of restructuring and costs.

In the corporate cost-cutting that ensued, locations and operations were rationalized. Many IOC's consolidated their international operations in Houston. RD, technology activities and technical disciplines were seen as unnecessary fixed costs that could be more profitably outsourced. At that time, only a handful of voices questioned rationalization; it made sense financially and operationally. Ironically, this would strengthen the oil curtain and return to haunt IOCs.

Outsourcing Technology

As operators and well profiles became leaner, service companies grew. They were required to contribute more value than ever before; to reduce well cost and optimize performance. IOCs contracted out technical niches such as Directional Drilling or Reservoir Modelling as well as entire technical disciplines such as drilling or reservoir management. With the advent of outsourcing 'in-house' services became the 'in-thing'. Simultaneously, service companies commercialized projects that IOCs cast off.

As the industry consolidated, Houston emerged as its capital city and its downtown skyline became synonymous with the global oil business. Today Houston represents the oil consumption capital of the world. The oil production capital lies elsewhere. Characterized by a modest skyline and towering reserves, Dhahran takes that title. Moscow becomes the natural gas production capital and Doha that of LNG. Almaty, Baku, Bushehr, Lagos, Macae, Maracaibo are other emerging oil cities as the industry realigns. The combination of oil technology as a commodity, ascendant oil prices and the realignment of cities has strengthened the oil curtain. Ironically as oil production technology becomes freely available on the market so access to oil reserves becomes more restricted.

Metamorphosis of IOC

In the old days, IOCs conferred access and monetized oil reserves. IOCs alone had the technology, capital and know-how to tap the wealth of an unknown hidden natural resource. Naturally, they bargained hard and got the lion's share. Those 'old ways' show that oil reserve holders used to recognize IOC as equals, perhaps, even as holding the upper hand as the IOC was required for revenues to be realized[9].

Even before the Oil Curtain, some IOCs noted that the pool of accessible oil reserves would one day shrink. Progressive IOCs repositioned themselves for the future; some seeing 'beyond petroleum' others shut out by the 'Oil curtain'. However, this does not imply the fall of IOCs. Some are perfectly adapted to evolve and there is

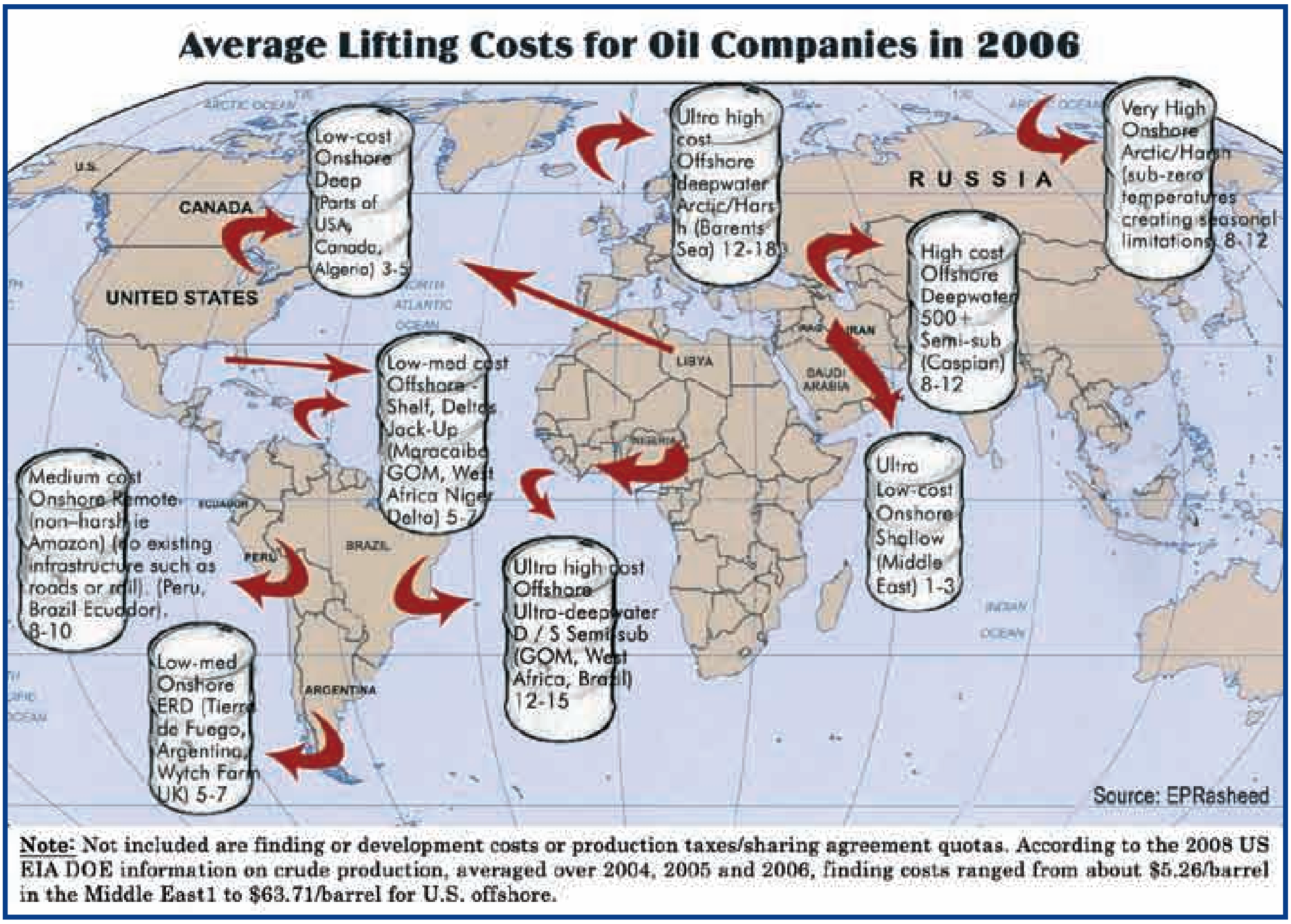


Figure 3 - Costs for Oil Companies

still a healthy global EP environment for them to adapt to.

The drawback is that this environment of extreme EP has high replacement costs as margins are squeezed by technical challenges (See Figure 3). Extreme EP opportunities exist in ultra-deepwaters, Arctic, Unconventionals and in a dazzling array of Gas-related technologies. These include LNG (Liquefied Natural Gas) which mobilizes and commercializes stranded reserves as well as 'Bio-Gas' which is renewable through biologically produced methane. And in Compressed Natural Gas (CNG), Liquefied Petroleum Gas (LPG) that provide fuel for the transport and power-generation sectors. Capping it all, Gas to Liquids GTL offers high quality gasoline fuel. Of the original seven sisters most have already adapted to Extreme EP environment. Going further BP has distinguished itself in LNG and Solar power, Shell in GTL and Hydrogen.

Undoubtedly IOCs face increasingly challenging operations – extreme EP. Additionally there are a wide-ranging set of challenges such as decommissioning, booking new reserves in a narrowing opportunity base, a lack of EP technology as a differentiator and environmental lobbyists. But perhaps, most of all, nationalization and resource sovereignty, has made business more difficult.

Despite this IOCs retain refineries, retailing networks, brands, and direct access to international consumers. Certain IOCs for example BP and Shell have continued to be early adopters of new technology. That is praiseworthy because by supporting innovative new ideas and signposting applications[10], these IOCs have significantly contributed to many EP innovations ie rotary steerables and expandables across the industry. Those IOCs took risks to prove tools down-hole and the benefits have been reaped by all types of oil company.

References

Credit should go to BP for compiling the Statistical Review of Energy. Regarding country and global data the issue is that ultimately, all collating organizations must rely on country export/reserves data and to an extent each others data. The statistics therefore incorporate OPEC / OGJ / Non OPEC data and so

Saudi Aramco

Considered by many to be the world's largest oil company and the world's largest NOC, Saudi Aramco controls 1/4 of all world hydrocarbon reserves and plays a vital role in fuelling Saudi Arabia's socio-economic growth. In this context, Saudi Aramco routinely evaluates its development decisions on a combination of corporate and national contributions. For example, a petrochemical project with a Japanese Chemical company contributes at both these levels by seeking to transform the Rabigh Refinery in Saudi Arabia into an integrated refining and petrochemical complex. The evaluation showed that although Rabigh would be profitable, it was not the most profitable investment opportunity that Saudi Aramco was considering. However, what Rabigh provided was "the most combined value to the company and the nation". The national component means that Saudi Arabian society will benefit from the foreign investment, the new jobs created and additional revenues. The corporate component means that Saudi Aramco will extend its petroleum value chain, upgrade oil processing and making its portfolio more profitable.

In the area of key performance indicators Saudi Aramco's approach is to use IOC yardsticks in order to be best-in-class in areas such as finding and lifting costs, corporate governance and financial discipline.

PdVsa - Venezuela

For Venezuela's PdVsa sustainability is stated as being central to its existence. Its' definition of sustainability considers oil and gas resources from both a production and consumption perspective. PdVsas' stated policy is to regulate production of oil and gas so that EP is optimized while certain blocks are conserved for the benefit of future generations of both consumers and producers. Its central belief is that because Oil is a finite natural resource, producing countries must exercise the sovereign right to regulate production levels so that benefits accrue to current and future generations of indigenous people. PdVsa also sees its role as educational and to show consumers that oil is not a commodity that operates according to free market rules. PdVsa recognizes that stability should exist in the market but this can only occur if there is political, economic and particularly social stability. It also asks consumers to consider whether they are consuming energy in an efficient way. For PdVsa sustainability must include policies of integration that allow poorer countries to have access to oil and gas. This has been the reasoning behind the Petrocaribe initiative by which Venezuela supplies 200,000 bopd to more than 20 of the smallest countries of Latin America and the Caribbean under special financing. For Pdvsa "unrestricted access to (the) energy is not the same thing as sustainable access". The company views the current model as consumers demanding unrestricted access to natural resources but not allowing resource holders to improve the socio-economic standing of their people. According to the company this model is characterized by infrastructure bottlenecks resulting from decades of under-investment caused mainly when IOC held unrestricted access to reserves. PdVsa's view is that sustainability of access must mean that poor countries should be able to access sustainable energy sources.

on. The approach has been to check regional or local data sources but to use the BP SR 2008 as a reference point - see pages 6 and 8 for Global Proved Reserves and Production respectively.

1. Rasheed Wajid, Hydrocarbon Highway 2009 – Table of NOC and IOC Reserves Comparison 1971-2008.

2. The seeds of Nationalization had been sown by Mexico in 1934 when it led a hostile takeover of the shareholdings of foreign oil companies operating in Mexico creating Pemex in 1938 - the first 'Nationalized Oil Company'. It can be said that BP or Anglo Persian was the first National Oil Company but this was taken over by the British government from British shareholders rather than foreign ownership. Mexico was followed by Venezuela and Iran who nationalized their hydrocarbons.

3. OPEC Bulletin 2008 - 7 Undoubtedly, production is one end of a transaction; refineries and consumers are needed too.

4. OPEC: Origins & Strategy 1947–1973 Editor: A.L.P. Burdett.

5. Undoubtedly, every move made by OPEC is watched by the major newswires who have assigned some of their brightest minds to cover the decisions that usually come out from the Austrian capital. The wires cover these events pursuing the heads of delegation and hanging on

Petrobras

'The oil is ours' reads a sign as you leave Rio de Janeiro on the road to the oilfield city of Macae. That sign is not a historic throwback or juvenile street graffiti, but a modern official billboard paid for by the Brazilian Government. Its' nationalistic message is that oil, and oil wealth, are too important to be left to foreigners and external market forces. The tightrope that Petrobras must walk is balancing the interests of two very different kinds of shareholders. The Brazilian government still owns a majority 51% of ordinary shares while the remainder is held privately. This kind of balancing is ultimately made easier because from both a medium and long term perspective, Petrobras is in an enviable position. It has helped the country reach self-sufficiency and added reserves, while growing its operations in the international arena, especially the US.

- Reserves (SEC criterion): 11.7 billion barrels of oil and gas equivalent (boe)
- Productive Wells: 14.194
- Production Platforms: 109 (77 fixed; 32 floating)
- Daily Production: 1.918 barrels per day (bpd) of oil and LPG
- 382.000 barrels of oil equivalent of natural gas per day

China National Petroleum Corporation (CNPC)

CNPC, China's flagship oil company plays an important role in China's oil and gas production and supply. Its' oil and gas production account respectively for 57.7% and 78.3% of China's total output. CNPC is also a global player with EP projects in Azerbaijan, Canada, Indonesia, Myanmar, Oman, Peru, Sudan, Thailand, Turkmenistan, and Venezuela.

CNPC has bet heavily on R&D to increase EP production and reduce risk in complex basins. It has developed solutions to improve recovery factor as well as reduce development costs. It has a strong sense of innovation and has technologies in reservoir characterization, polymer and chemical-flooding. Other technologies include high-definition seismic, under-balanced drilling, ultra-deep well drilling rigs and X80 high-tensile steel pipes. According to the company, by the end of 2007, CNPC had acquired 7,010 patents out of its 9,693 patent applications.

It holds proved reserves of 3.7 billion barrels of oil equivalent.

- Oil production: 2.75 million barrels of crude oil/day
- Gas production: 5.6 billion cubic feet/day
- Oil reserves: 3.06 billion metric tons
- Gas reserves: 2,320.1 billion cubic meters

any word or gesture in the same way celebrities are pursued by paparazzi.

6. The "New Seven Sisters" - 11th March 2007, the Financial Times redefined the "New Seven Sisters": as the most influential and mainly state-owned national oil and gas companies from outside the OECD. They were: Saudi Aramco (Saudi Arabia), JSC Gazprom (Russia), CNPC (China), NIOC (Iran), PDVSA (Venezuela), Petrobras (Brazil) and Petronas (Malaysia). In terms of Oil reserves the major reserve holders are more influential than Gazprom, CNPC, Petrobras and Petronas who are influential in their own rights ie Gas, Technology and Internationalization respectively. A variant exercise would be to use market capitalization for top ten NYSE listed Oil companies, organizations such as Petrobras and CNPC appear.

7. EIA World Energy Reference Case Oil Consumption to 2030 Annual Energy Outlook 2008 (AEO2008).

8. Sampson, Anthony; The Seven Sisters. New York: Bantam Books, 1976.

9. Rasheed, Wajid; Brazil Oil and Gas 2006 Issue 4 – Black Blessing.

10. Rasheed, Wajid; Harts E&P Issue 30 2004 - Small Companies and Tangled Thickets.

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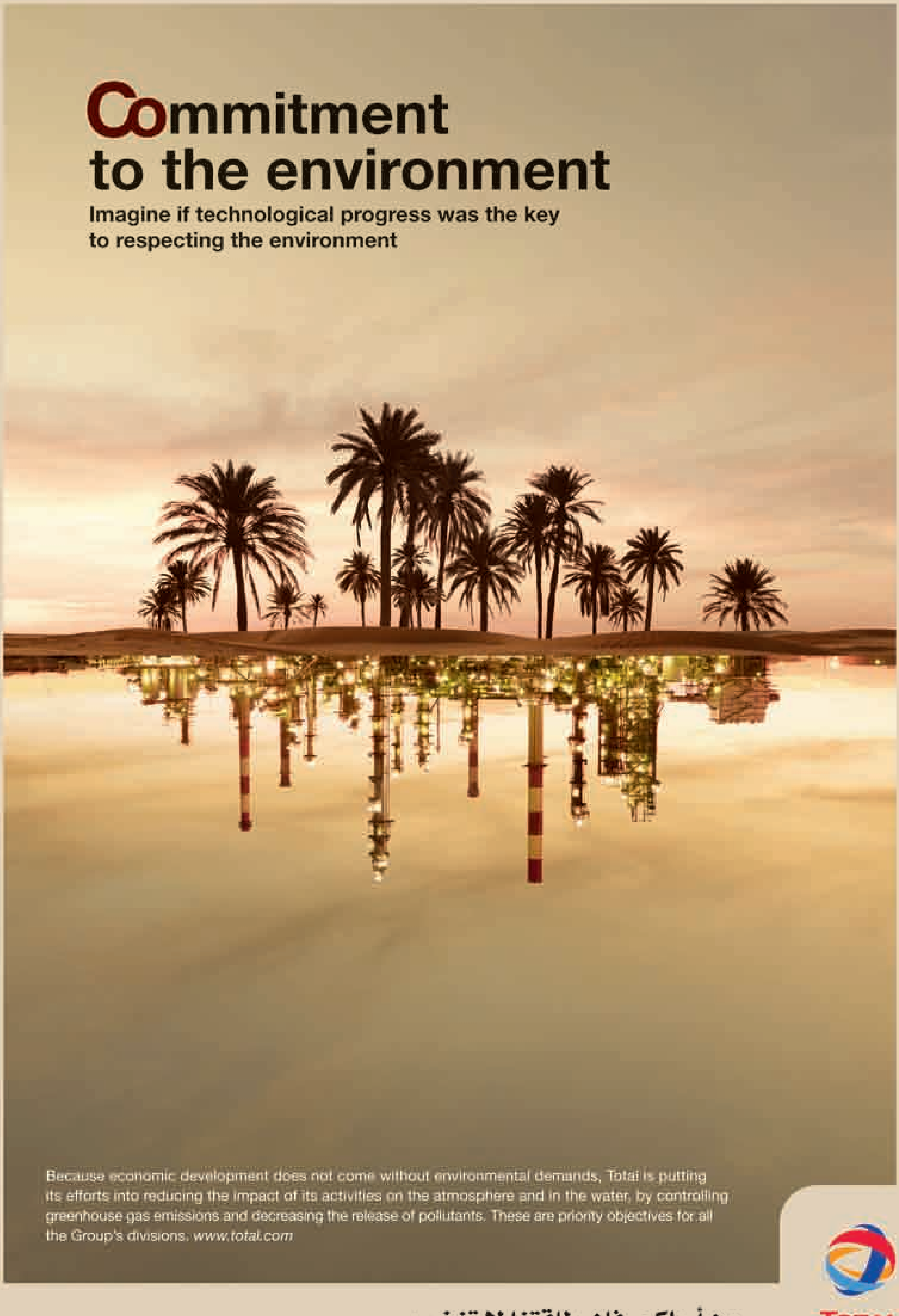

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