A Periodical of Saudi Aramco

Winter 2018

dimensions INTERNATIONAL

SAUDI ARAMCO'S NEWEST TEST VEHICLE

DRIVEN TO INNOVATE

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The Saudi Arabian Oil Company, also known as Saudi Aramco, was established by Royal Decree in November 1988 to succeed the original U.S. concessionary company, Aramco. The Aramco concession dates back to 1933.

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About the cover:
Saudi Aramco's newest test vehicle in its Octane on Demand lineup is the 2018 Ford Raptor, significantly boosting engine performance and efficiency.

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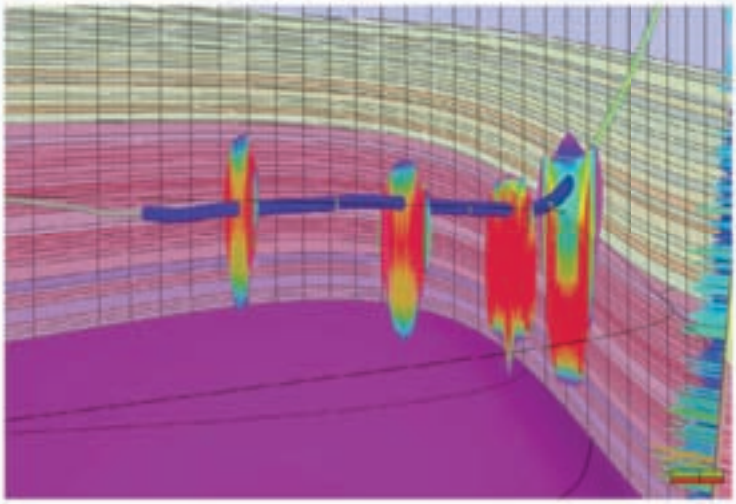


departments

EXPEC ARC'S i-Quest

TRAVELS TO SILICON VALLEY

BY JUDI D. OTTMANN

Left: (L to R) Bader Alromaih, a Ph.D. at Stanford University; Ahmed Al-Eidan, chief technologist in the Strategic Technology Analysis Division with EXPEC ARC; and Mustafa Al-Ali, a chief technologist in Geophysics Technology with EXPEC ARC, greet one another during the recent i-Quest event in California's Silicon Valley. *Above*: The day before the i-Quest forum, EXPEC ARC honored a select group of company-sponsored graduate students attending U.S. universities for their outstanding academic achievements. Those recognized, sitting in the front row, are, from left, Ahmed Al-Rashed, Tariq Al-Mubarak, Ibrahim Al-Atwah, Abdulmohsen AlAli, Omar Al-Dajani, and Mohammed Al-Majid. They are joined by Ali A. Al-Meshari, EXPEC ARC manager, third from left, back row.

Saudi Aramco's ongoing quest for new technological breakthroughs recently led the company to California's Silicon Valley — considered a global nexus of innovation and opportunity.

A team from the Exploration and Petroleum Engineering Center – Advanced Research Center (EXPEC ARC) headed up the mission, hosting a tech forum aptly called "i-Quest," to seek out and collaborate with entrepreneurs on the use of artificial intelligence (AI)/machine learning and data analytics in the upstream petroleum sector.

Over the past few years, EXPEC ARC has conducted several i-Quest forums, going to tech hot spots around the world to find something new and different to enhance oil and gas exploration and production. This initiative is supporting the company's efforts to not only solve today's operational industry challenges, but also help write the next chapter on energy sustainability.

"We are seeking out disruptive technologies that will take us further, that will truly result in a 'quantum leap'

Weichang Li, a petroleum engineering consultant at Aramco's Houston research center, presents on the significant impact that AI/machine learning could have in such domains as seismic data processing, production monitoring, and drilling efficiency.

in upstream capabilities and efficiencies," said Ali A. Al-Meshari, EXPEC ARC manager.

A MEETING OF THE MINDS

The i-Quest forum was conducted over two days in Menlo Park, California, located in the hub of Silicon Valley. More than 70 people participated, including representatives from EXPEC ARC, Aramco Services Company (ASC), and Aramco's Houston research center. They joined Silicon Valley tech leaders — company owners, CEOs, scientists, investors and university professors — specializing in AI/machine learning, data analytics, and computational methodologies.

EXPEC ARC International Advisory Council members were also on-site, as well as Saudi Aramco-sponsored students, including those attending Stanford University, located nearby. The forum's first day featured a general session of tech presentations followed by a second day of individual meetings between EXPEC ARC and potential partners to discuss collaborative opportunities.

Al-Meshari officially opened the forum with welcoming remarks.

"We are honored to meet you here, in Silicon Valley, to collaborate with the best minds in research to help solve some of our industry's toughest challenges," Al-Meshari told the audience. "We see huge potential in the use of artificial intelligence to extract deeper value from the data we collect and store on our field operations. We are excited about the possibilities to enhance our decision making capabilities and break new ground."

He said EXPEC ARC has a number of research projects underway addressing data management and usage. "Even small gains in this area could lead to significant operational improvements," he added.

Weichang Li, a petroleum engineering consultant at Aramco's Houston research center, gave a presentation on the significant impact that AI/machine learning could have in the energy industry. He specifically illustrated opportunities where domain experts and computer scientists could work together to apply these new breakthroughs and improve, for example, seismic data processing, interpretation, and well log analysis, production monitoring and optimization, drilling efficiency and risk mitigation, and source rock characterization and crude oil assay analysis.

SILICON VALLEY PRESENTATIONS

Invited speakers talked about their new inventions and processes in AI/machine learning that are setting new standards in big data management, interpretation, and modeling — where computers are capable of producing results that, quite literally, go beyond human capability.

The experts generally agreed that the oil and gas indus-

try has done an exceptional job collecting and storing data over the decades, but its value has not been fully optimized. Vast quantities of information have been captured and stored, they said, but these data sets are spread across numerous business spheres, operational areas and domains — and often not shared. This makes it virtually impossible to extract the deep value "hidden" within the data without the application of AI/machine learning.

AlphaX Decision Sciences was one of the presenting companies, with chief operating officer Aruna Viswanathan talking about her company's development of "predictive and prescriptive" AI software and cloud computing solutions that can work on any platform, with built-in cybersecurity and privacy measures designed to help accelerate the pace of AI adoption in the oil and gas industry. Ram Shenoy, Ph.D., one of the company's board members, talked about the use of machine learning and data analytics for pinpoint precision in seismic imaging, allowing geoscientists to easily zoom in on exactly what they need to see within the seismic data cube — for greater accuracy and faster results.

Professor Biondo Biondi, with Stanford University's Department of Geophysics, presented on the impact of machine learning algorithms and hardware on computational seismology to improve outcomes. He posed the question: "Is machine learning a revolution or transformation?"

The answer is both. Machine learning, he said, is opening up new, "revolutionary" data intensive processes for drilling and well optimization — and also leading the radical "transformation" of old data intensive processes for seismic imaging and reservoir modeling — which, he added, are "computational hungry."

He further said the commercial success of machine learning is rapidly driving computer platforms and architectures across multiple industries.

Another presenting company was EMOTIV, with Kim Old, vice president of Corporate Development, who allowed the audience to explore the mysteries and "untapped" powers of the human brain. She gave a talk on contextualized neuro-informatics, and her company's development of advanced brain sensors — capable of measuring electroencephalography patterns — to help

Nasher BenHasan of EXPEC ARC provides a demonstration, showing how the brain's energy waves can literally "pilot" an object. He put on an EMOTIV Insight headset to command an unmanned aerial vehicle — seen hovering beside him. The device took flight using machine learning and recognition of brain patterns.

gain insight into the cognitive and emotional states of people in real time for learning and safety applications.

She conducted a demonstration at the forum showing how the brain's energy waves can literally "pilot" objects — with event organizer Nasher BenHasan of EXPEC ARC serving as a volunteer. He put on an EMOTIV Insight headset to command an unmanned aerial vehicle, which took flight using machine learning and recognition of brain patterns.

i-Quest proved to be a great learning experience for Jumanah Al Kubaisy, a Saudi Aramco-sponsored graduate student at Stanford University. She is working on her master's degree in computational and mathematical engineering.

"I really enjoyed listening to the presentations, which allowed me to see how classroom theory is actually applied in the real world," she said. "I particularly liked the presentations on seismic imaging, and how machine learning is offering geoscientists a new generation of tools to enhance their decision making capabilities."

EXPEC ARC INTERNATIONAL ADVISORY COUNCIL

Several members of the EXPEC ARC International Advisory Council (IAC) — composed of leaders in the global scientific community — participated in the i-Quest forum. They were: IAC chairman Larry W. Lake, who is with the Department of Petroleum and Geosystems Engineering at the University of Texas at Austin; professor Albert P. Pisano, dean of the Jacobs School of

> This company is always in the market for new ideas, sourcing new partners and looking for collaborative opportunities. The use of AI/machine learning in the management, and use of big data is a turning point in the oil and gas industry. It's great to see Saudi Aramco staging events such as i-Quest, and I'm excited to see what happens next.
>
> — PROFESSOR LARRY W. LAKE

> I am so proud of Saudi Aramco and its quest for excellence; and honored to be a part of this organization. I think there is an old saying: "You are known by the company you keep." I am constantly and wonderfully surprised at the bold steps Saudi Aramco is willing to take to stay out in front — to not just follow a standard, but set it.
>
> — PROFESSOR ALBERT P. PISANO

Engineering at the University of California San Diego; professor Pulickel Ajayan, with the Department of Materials Science & NanoEngineering at Rice University in Houston; and professor Jean M.J. Fréchet, senior vice president of Research, Innovation, and Economic Development at the King Abdullah University of Science and Technology (KAUST).

The council members expressed their thoughts about i-Quest and the emerging field of AI/machine learning, saying that they are excited about Saudi Aramco's foray into this powerful new arena to maintain the company's position as a world leader in technology excellence.

The day prior to i-Quest, an official IAC meeting was held where EXPEC ARC provided updates on the latest research projects underway, and engaged advisory members in discussions on future plans and initiatives. Additionally, EXPEC ARC honored a select group of company-sponsored graduate students attending U.S. universities for their outstanding academic achievements, presenting each of them with an EXPEC ARC Young Researcher Award.

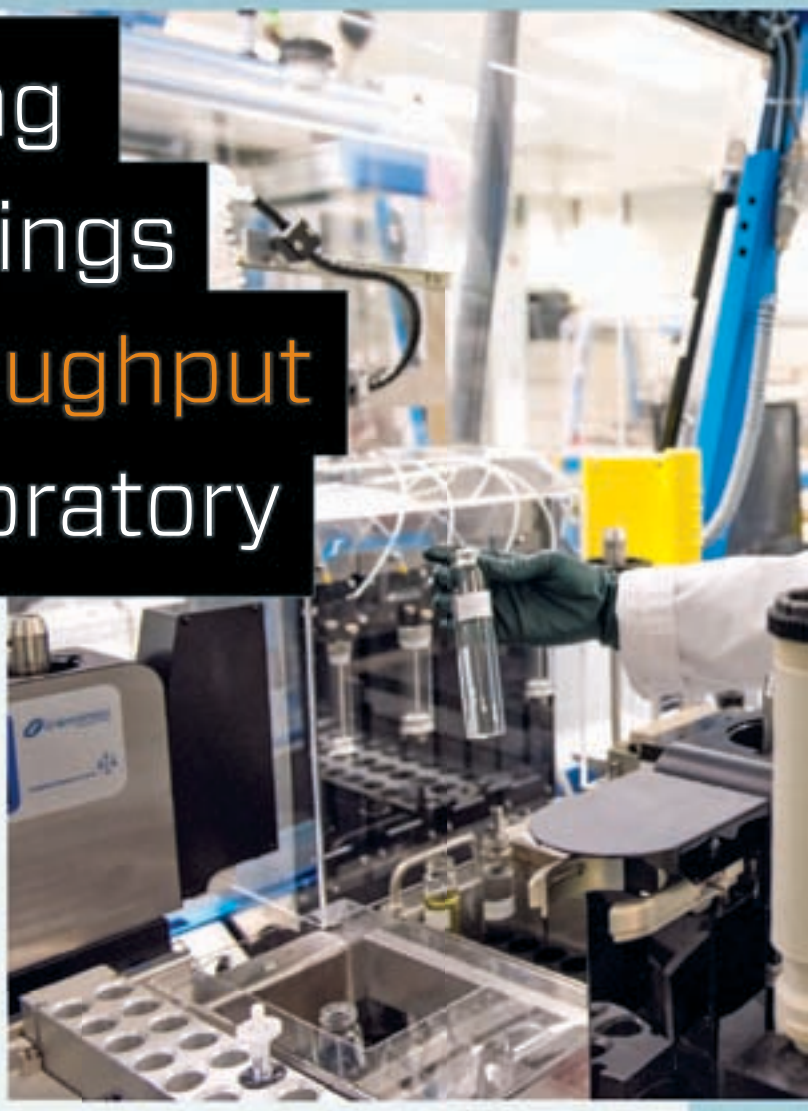
FUTURE OF I-QUEST

EXPEC ARC is planning additional i-Quest forums in the future. "We want to continue the mission to seek out technological breakthroughs — both around the world and within our own research centers," Al-Meshari said. "It's important to develop these partnerships and create synergies that fortify Saudi Aramco's important role as a global technology leader."

> Oil and gas exploration is a data-driven science, so it's great to see Saudi Aramco moving further into the realm of AI/machine learning. There are definitely some exciting, eye-opening developments in this field, with potential to change the dynamics in the upstream sector.
>
> — PROFESSOR PULICKEL AJAYAN

> To remain on the leading edge of innovation, it is important to seek out and connect with tech leaders across diverse sectors and disciplines. The i-Quest forum has provided a solid platform for that. It's great to see the Saudi Aramco EXPEC ARC team working to collaborate with Silicon Valley entrepreneurs who have developed breakthroughs in AI/machine learning that could solve upstream challenges.
>
> — PROFESSOR JEAN M.J. FRÉCHET

Fast Forwarding Research Findings with High-Throughput Research Laboratory



BY Janet E. Pinheiro

Saudi Aramco's new High-Throughput Research Laboratory (HTR-Lab) in Dhahran — the first of its kind in the Middle East — is accelerating cutting-edge discoveries into advanced chemicals technologies. Rather than the more traditional testing of one catalyst at a time, the lab uses purpose-built robots and high-throughput reactors to simultaneously test multiple research outcomes. The HTR-Lab is one component of Saudi Aramco's significant preparation for the production of high-value petrochemicals from crude oil, supporting the company's efforts to address global climate change by enabling experimentation in chemicals, fuels and carbon dioxide (CO_2) utilization technologies.

Conventional research timelines are being reduced by half at the new HTR-Lab — the first catalysis research laboratory of its kind in the Middle East — where unprecedented cutting-edge discoveries of advanced chemical technologies are being enabled with increasing frequency.

This innovative, custom-built research "laboratory of the future" will boost our research and development capabilities, and help bring our catalytic technologies more rapidly to market.

Behind the rapid results from the HTR-Lab are robust and flexible catalyst evaluation pieces of equipment of varying capacities, which are seamlessly integrated and simultaneously being used by scientists to quickly produce breakthrough research outcomes with a substantively wider range of findings.

The primary function of the HTR-Lab is to target the company's high priority sustainability themes, spanning "crude to chemicals," "oil to hydrogen," and "passenger transport," as well as other areas relevant to the

The parallelized robotic metal loading unit is operated by HTR-Lab engineer Noor Sulais for exploring the design space of metal loading on different supports. *Top Right:* HTR-Lab engineer Mohammad Alkhunaizi connects one of the 16 reactors in the high-throughput platform for screening different catalysts and analyzing their performance for promising candidates for technology development. *Right:* HTR-Lab engineer Ahmad Jazzar prepares the robotic zeolite synthesis unit for running an automated procedure for producing multiple supports under different conditions with a high degree of precision dosing and reproducibility.

expansion of the company's chemicals business.

Chief technology officer Ahmad O. Al-Khowaiter explained that the exceptional results are being facilitated by the capability of the HTR-Lab's customized equipment to process multiple catalysts at one time, providing for a massive increase in research throughput.

"Once the idea is tested, specialized analysis software is used to rapidly study the massive amount of data from the tested dozens of catalysts to uncover efficiencies," said Al-Khowaiter. "The lab accelerates the discovery of technologies, reduces timelines for commercialization, and dramatically reduces cost and risk."

Technology Council **visit**

The HTR-Lab was inaugurated in late July by the Saudi Aramco Technology Council, led by Saudi Aramco's president and CEO, Amin Nasser.

The newly formed research laboratory was the first of its kind in the region and on par with the best in the world, Nasser noted.

"The inauguration of the High-Throughput Research Laboratory marks a key milestone in the company becoming a world-renowned center for downstream and sustainability research and development," said Nasser.

Above: Student intern Hashim Khunaizi (left) and HTR-Lab engineer Mohammed Merri operate the robotic zeolite synthesis unit. *Top and Bottom Right:* Some of the equipment used at the HTR-Lab includes a robotic catalyst synthesis unit, and a catalyst metal impregnation system, which significantly reduce catalyst synthesis and screening times — accelerating research and discovery.

"Improving chemical technologies drives efficiencies of scale and resource optimization," he said. "It also creates a capability to increase conversion and maximize chemicals yield for new and existing processes, thereby providing added value to a barrel of oil."

During the inauguration, the Technology Council had an opportunity to see in action how the newly installed robotic synthesis tools and sophisticated simultaneous reactor systems accelerate catalyst discovery and associated process development efforts.

Significant findings

With its tailor-made integrated workflows, the HTR-Lab is already significantly expediting the "time to market" for a range of technologies.

Among the discoveries is a significant improvement in the process to convert a low-value butenes raffinates stream to propylene at improved yield and profitability, and a process to convert heavy reformate aromatics to valuable xylenes.

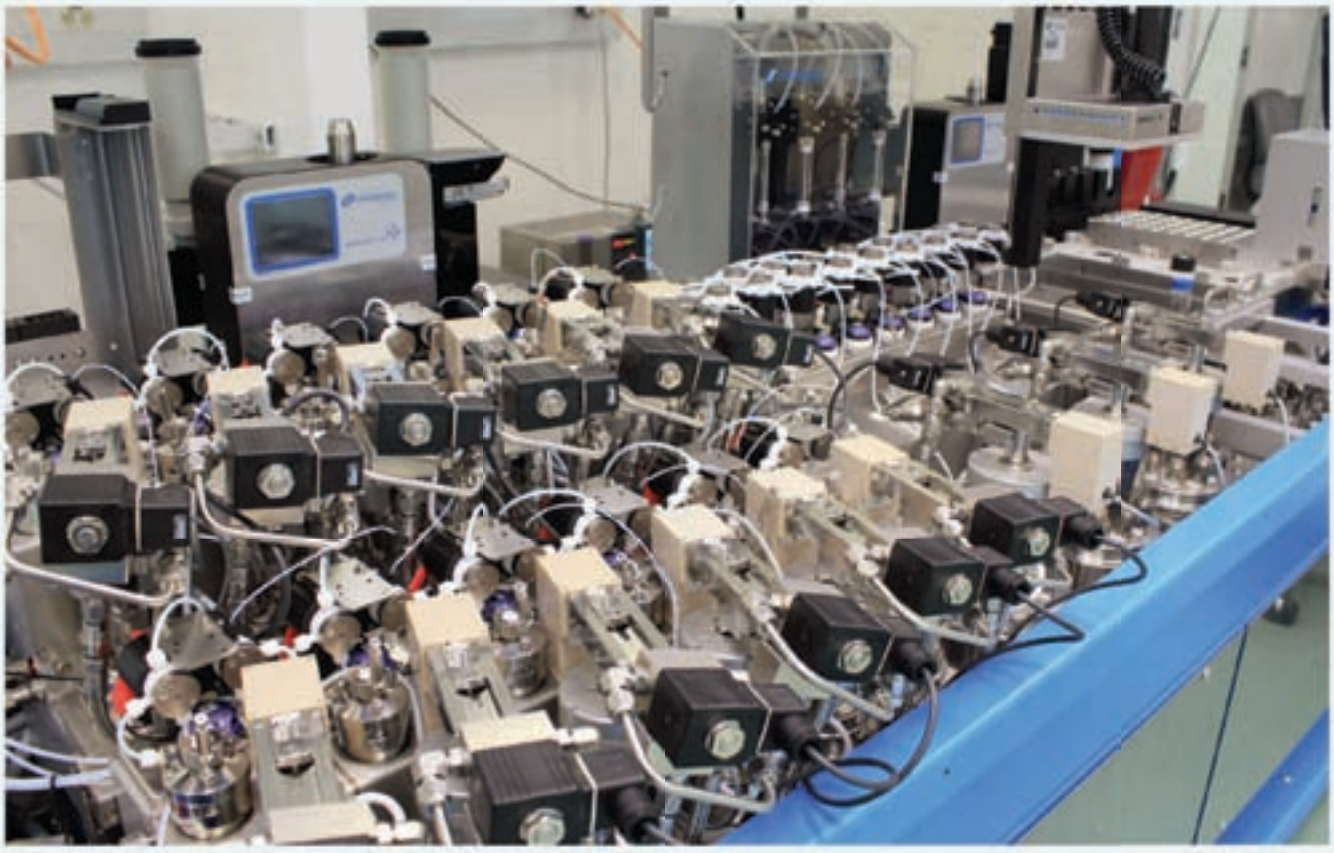
Importantly, the work produced here supports the company's efforts to address global climate change by enabling experimentation in chemicals, fuels, and CO_2 utilization technologies.

Our own downstream business

The HTR-Lab is one component of Saudi Aramco's significant preparation for the production of high-value petrochemicals from crude oil.

The outcome of the HTR-Lab research will be rolled out and applied at new and existing Saudi Aramco petrochemical plants and refineries, and has the potential to be licensed globally to interested downstream parties.

Researching the most effective conversion of crude oil and other low-value petrochemical streams is an integral part of the company's larger vision to be a world leading integrated energy and chemicals company, and the HTR-Lab is an important enabler of this strategic intent.



OCTANE ON DEMAND RAPTOR

BOOSTS THE PERFORMANCE AND EFFICIENCY OF ARAMCO'S TRANSPORT TECHNOLOGIES PORTFOLIO

BY KAI MORGANTI AND HEATHER L. O'CONNOR

Aramco has recently fitted its Octane on Demand (OoD) technology to the Ford Raptor, re-engineering Ford's iconic vehicle to be even faster, while boosting engine performance and efficiency.

The 2018 Raptor, overhauled by Aramco engineers, has two fuel tanks; one with high-octane fuel for hard acceleration, and a second with a conventional gasoline for normal driving. The modified engine automatically switches between the fuels depending on the driver's needs.

Aramco's OoD technology allows for significantly more advanced spark timing at higher load operating conditions, resulting in more efficient combustion, higher torque, and higher power output.

Although this application of OoD technology was geared toward raising performance, the system can also be adapted to provide significantly increased fuel economy and reduced greenhouse gas emissions.

An international team of scientists and engineers at Saudi Aramco's global research centers in Detroit, Paris, Dhahran, and Beijing are working on a number of technologies targeting improved fuel economy, lower carbon dioxide (CO_2) footprints, and lower pollutant emissions.

"What we are doing at the Detroit Research Center complements the work occurring in our other Saudi Aramco research centers around the world," said David Cleary, the Detroit Research Center's leader.

"The upgraded Ford Raptor is a great example of our research, development, and integration work focused on a lower emission future for transport. It is one of many technologies we are developing with the goal to greatly reduce CO_2 and criteria pollutant emissions."

OCTANE ON DEMAND

In a different application focused on lowering CO_2 emissions, a midsized Peugeot 308 vehicle was equipped with OoD technology by engineers in Aramco's Paris Research Center. Aramco scientists estimate the life cycle CO_2 footprint of the demonstration vehicle is up to 13% lower than a production model.

Although the Peugeot 308 and Raptor demonstration

Ahmad O. Al-Khowaiter, chief technology officer at Saudi Aramco, speaking with U.S. business news channel CNBC at the 2018 North American International Auto Show in Detroit.

vehicles are both equipped with two fuel tanks, which require fueling with two different fuels, Aramco engineers have also been inventing processes for onboard octane separation.

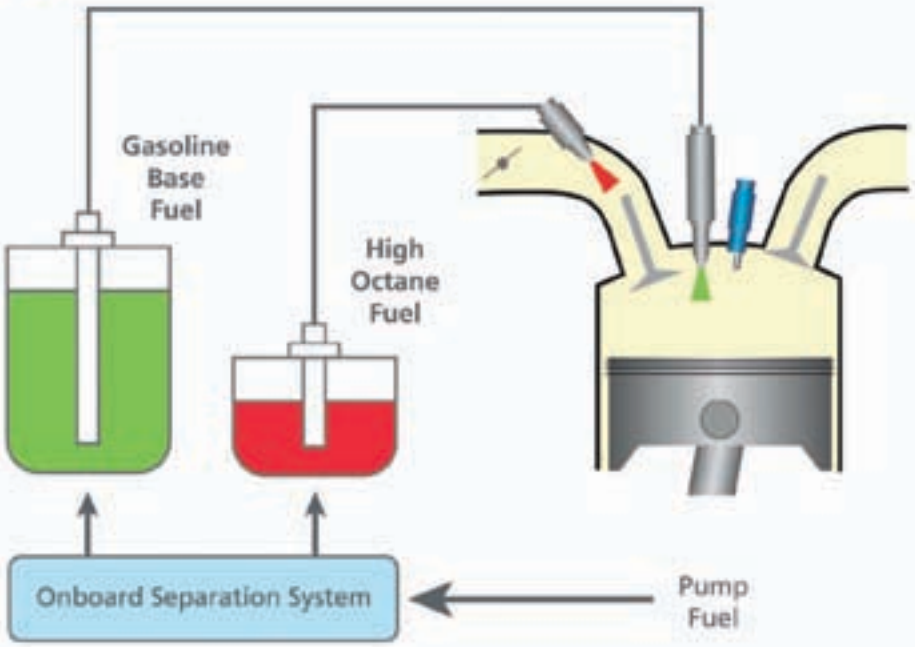
"This technology is capable of producing the two fuels onboard the vehicle, from pump fuel purchased at a regular gas station," said Amer A. Amer, transport chief technologist in the Saudi Aramco Research & Development Center.

"Several variants of this technology have already been evaluated in our global research centers. These provide an interesting technology scope for combining performance and efficiency."

ARAMCO'S AUTOMOTIVE TECHNOLOGY PORTFOLIO

OoD is only one of a number of research projects under way that have the power to substantially improve the efficiency, CO_2 footprint, and emis-

The Octane on Demand Raptor demonstration vehicle is equipped with two tanks that require fueling with two different fuels. The global team has also been inventing processes for onboard octane separation, which is capable of producing the two fuels onboard the vehicle from pump fuel purchased at a regular gas station.



sions of the internal combustion engine.

Aramco's flagship engine technology — gasoline compression ignition (GCI) — offers the performance and efficiency of a diesel engine, but with considerably lower emissions. By further modifying the technology through fuel improvements, Aramco scientists are bringing about substantially reduced emissions, and even greater fuel economy.

The GCI technology could be applied to passenger vehicles as well as heavy-duty commercial fleets, providing competitive transport solutions with lower greenhouse gas and criteria pollutant emissions.

Aramco's GCI program was one of the highlights of the 2018 North American International Auto Show in Detroit, and drew the attention of both industry and the general public. GCI technology was also exhibited at the SAE International Powertrain, Fuels and Lubricants meeting this past September, in Heidelberg, Germany, and at the Future Investment Initiative this past October, in Riyadh, Saudi Arabia. GCI has been the focus of a number of media stories by CNBC and *www.trucks.com*, a top rated site.

GCI is also being paired with the Achates Power Opposed-Piston (O-P) engine — a novel design that uses two pistons per cylinder to create a higher expansion ratio and lower heat losses from the combustion process. The

MORE THAN
20
RESEARCH PAPERS

focusing on Octane on Demand have been presented by Saudi Aramco scientists at international events. Several patents have also been filed.

A gasoline compression ignition engine designed and under development by Aramco scientists.

Aramco's global research centers focus on demonstrating sustainable transport technologies. The state-of-the-art centers are located in close proximity to leading automotive companies and key transport stakeholders.

"CONTINUING TO IMPROVE THE EFFICIENCY OF TODAY'S ENGINES IS ONE OF THE MOST COST-EFFECTIVE PATHWAYS TO ACHIEVE MEANINGFUL REDUCTIONS IN GREENHOUSE GAS EMISSIONS."

– AHMAD O. AL-KHOWAITER, CHIEF TECHNOLOGY OFFICER AT SAUDI ARAMCO

The gasoline compression ignition technology is also being paired with the Achates Power Opposed-Piston (O-P) engine, a novel design that uses two pistons per cylinder. The O-P configuration boosts fuel economy by up to 50% compared to existing gasoline engines, without sacrificing power, drivability, or performance.

O-P configuration boosts fuel economy by up to 50% compared to existing gasoline engines, without sacrificing power, drivability, or performance.

Achates Power is one of the first technology companies to receive venture capital funding from Oil and Gas Climate Initiative (OGCI) Climate Investments, the billion dollar investment arm of the OGCI.

Mobile carbon capture is another example of an innovative technology, which can lower the CO_2 footprint of the transport sector. Refined over nine years by Saudi Aramco scientists in Dhahran, the latest variant of the technology can capture up to 25% of the CO_2 emitted from the exhaust. The CO_2 is stored onboard the vehicle, and can be used in a variety of industrial and commercial applications once offloaded.

Aramco engineers have successfully integrated mobile carbon capture technology into a midsize Toyota Camry passenger vehicle, and recently, a Class 8 heavy-duty truck. By combining mobile carbon capture with GCI and other efficiency improving technologies, Aramco is striving to achieve a 50% reduction in the CO_2 footprint of heavy-duty vehicles used to transport freight. The technology will debut in 2019.

"This work shows all that is possible through technology as we plan for automobiles of the future," said Bernie Porter, Vehicle Integration Group leader of the Aramco Research Center-Detroit.

In addition to in-house technology development, Aramco is actively partnering with leading global automakers as highlighted in August 2018, when Saudi Aramco and Mazda announced they are collaborating on a joint research project, together with Japan's National Institute of Advanced Industrial Science and Technology in Tokyo.

Using its refining expertise, Saudi Aramco will formulate a variety of low

In a different application focused on lowering carbon dioxide (CO_2) emissions, a midsized Peugeot 308 vehicle was equipped with Octane on Demand technology by engineers in Aramco's Paris Research Center. Aramco scientists estimate the life cycle CO_2 footprint of the demonstration vehicle is up to 13% lower than a production model.

carbon fuels, while Mazda will develop an advanced prototype engine based on its successful SKYACTIV® platform. This combination is expected to deliver a sizable reduction in the CO_2 footprint of internal combustion engines.

"Internal combustion engines will continue to play a major role in transportation for the foreseeable future," said Ahmad O. Al-Khowaiter, chief technology officer at Saudi Aramco.

"Continuing to improve the efficiency of today's engines is one of the most cost-effective pathways to achieve meaningful reductions in greenhouse gas emissions. We believe technologies such as Octane on Demand, GCI, and mobile carbon capture offer considerable scope for addressing the climate challenge," said Al-Khowaiter.

ENVIRONMENTAL STEWARDSHIP

Saudi Aramco's research in the field of engine and fuel efficiency is part of its commitment to environmental stewardship. The company's global research centers serve as a platform to showcase sustainable transport technologies, and enable Saudi Aramco's researchers to engage with European, U.S., and Chinese automakers and technology providers.

The centers include the Research & Development Center in Dhahran, the Aramco Research Center-Detroit, together with the Aramco Fuel Research Center-Paris, and the Beijing Research Center.

The global research centers also work closely with the Clean Combustion Research Center at King Abdullah University of Science and Technology (KAUST) through the FUELCOM collaboration.

EXPANDING SAUDI ARABIA'S

GAS PORTFOLIO

THROUGH

Innovation and Technology Advancement

The Gas Reservoir Management Department (GRMD) team in front of a wellhead at the Upstream Professional Development Center, where GRMD plays a major role in providing courses and training.

BY ADNAN A. AL-KANAAN, ZILLUR RAHIM, AND MICHAEL D. HAAS

"Perhaps oil is the first thing associated with Saudi Arabia by the outside world, but to us, gas is equally essential to our continued economic growth," stated Ali I. Al-Naimi (then Minister of Petroleum and Mineral Resources, Saudi Arabia), while in Yanbu', Saudi Arabia in October 1997.

These few words were uttered at the very onset of the Saudi Arabian gas development program and not much of the gas resource was known and available at that time. But after 21 years, we can see how close this statement has come to be reality. Indeed, Saudi economic growth, and the building of new industries, the continuous supply of energy, and the creation of job opportunities for hundreds and thousands of the local population have been made possible with the advent, progress, and success of gas development and production.

Going back in history, the discovery gas well in Dammam was spudded toward the end of 1956, and the first gas production from the Khuff-A reservoir started in early 1962. That was the first stepping stone in the expedition of natural gas exploration in the Kingdom, ushering in a new era of development, although the main thrust for gas expansion did not come about until the end of the 1990s.

Saudi Arabia's gas resources are a major focus of the Kingdom in meeting the future energy demand, which includes supplying household electricity, heating and cooling, water desalination plants, and downstream chemical and major industries. Natural gas is available in huge quantities in Saudi Arabia and is found as nonassociated gas — different than associated gas, which is in the solution with the oil in the reservoir, and is separated at the surface.

Natural gas reserve exploitation is undergoing a major

Members from the Gas Reservoir Management Department look on as Adnan A. Al-Kanaan, manager, assesses the formation quality from cores cut from different wells and reservoir sections. The cores are used to understand reservoirs, match and calibrate logs and engineering models, and optimize acid and fluids for stimulation treatments.

transformation, as the strongest source of all energy supplies in the Kingdom, to ensure a plentiful sustained supply; which brings with it an increase in manpower, funding, new technology application, exploration, and development. The use of natural gas for energy generation saves the more valuable remaining crude oil for export purposes, thereby generating revenue for the Kingdom.

The history of Saudi Arabia's gas program has been rich in achievements and growth over the last 40 years. In 1975, the Kingdom initiated the Master Gas System (MGS) that became operational by 1977 with the commissioning of the Berri, Shedgum, and 'Uthmaniyah gas plants to process only the associated gas that is recovered with oil production.

TYPES OF PETROLEUM GAS

Associated petroleum gas, or associated gas, is a form of natural gas that is found with deposits of petroleum, either dissolved in the oil or as a free "gas cap" above the oil in the reservoir. Nonassociated gas is a natural gas found in a natural gas reservoir that does not contain crude oil. Such a reservoir can contain some amount of liquid condensate that is produced during the production of natural gas.

In 1984, nonassociated gas from the 'Uthmaniyah and Shedgum Khuff reservoirs was introduced into the MGS. In 2001 and 2003, two new grass-root gas plants in the Hawiyah and Haradh areas, respectively, were put fully onstream to process only nonassociated gas. This was followed by the Hawiyah gas plant expansion, along with the Hawiyah natural gas liquid recovery plant. Furthermore, the Khursaniyah gas plant (KGP) went onstream in 2010 to process only associated gas, and later in 2011, the KGP facilities were expanded to process nonassociated gas from the Karan reservoir's Khuff gas — Saudi Aramco's first offshore nonassociated gas development.

The future of the gas program is bright, with the addition of several new gas plants along with new field developments and the construction of offshore platforms,

facilities, and subsea pipelines to transport gas several hundred kilometers for gas processing. The addition of new discoveries, drilling, and production will quickly raise the raw gas feed for the MGS to a stunning 20 billion scfd.

The Saudi Arabian gas fields expand over the Kingdom from far south in the Rub' al-Khali (The Empty Quarter), west to the Red Sea, north to Midyan, and east where the majority of the gas can be found in and around the super-giant Ghawar field area, as well as offshore in the Arabian Gulf.

The gas can be found at all depths, from as shallow as thousands of feet to over 15,000 feet, and is stored in different types of reservoirs, including sandstone, dolomite, and carbonate facies. Every reservoir is different and requires tremendous innovation and technology to unlock the reserve potential and to ensure the Kingdom maximizes the recovery of one of its most prized resources.

THE EARLY DAYS

Saudi Aramco has been exploring for oil and gas since the early 1930s, and until recently, it was always difficult to predict whether an exploration well was going to find oil, gas, or be a dry hole. Saudi Arabia has been blessed with an abundance of both types of hydrocarbons, and starting in the 1970s, Saudi Arabia realized the importance of its natural gas resources.

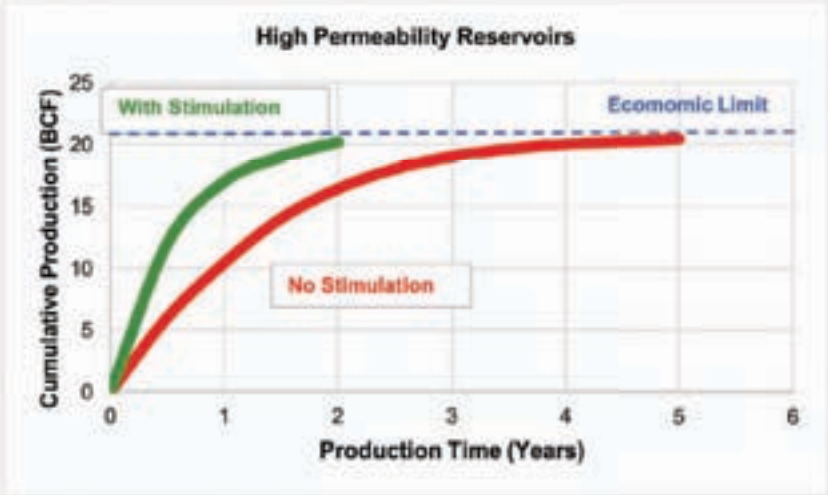
For years, many countries flared their associated natural gas to access the oil reserves. Natural gas did not have much value and was not considered to have an international market. Over the years, it has become evident that natural gas is a clean, less costly, environmentally safe, and strong energy resource that must be preserved, exploited, and properly utilized for industrialized and developing nations.

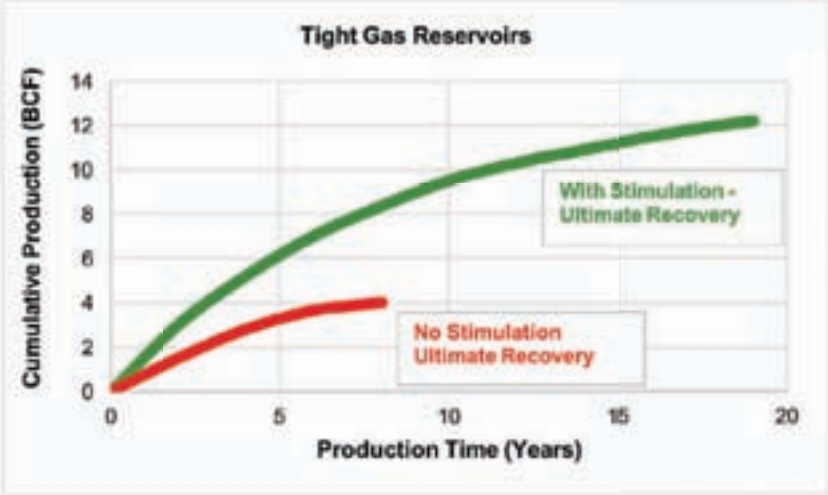
Due to the abundance of natural gas, more and more uses — in addition to power generation and industrial usage — are being identified. That includes liquefied natural gas, which can be stored at very low temperatures as a liquid in tankers and shipped around the world from gas-rich countries to countries needing natural gas supplies. In addition, natural gas is being utilized for use in transportation. Compressed natural gas or liquefied petroleum gas is being used to fuel many types of transportation, including cars, trucks, buses, tractors, and other motorized vehicles specially designed to run on natural gas.

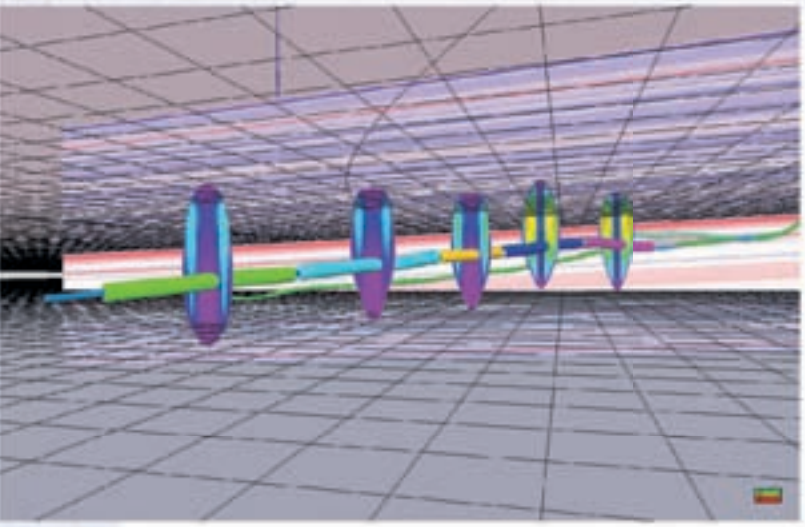
Saudi Aramco's natural gas team has grown tremendously since the 1990s, when only a handful of engineers and technicians reported as a unit to the bigger oil group division, and department levels that were responsible for developing and producing Saudi Arabia's huge oil reserves. As the work gradually grew with the drilling of wells and finding new gas reserves, the gas unit quickly transformed into a division, and subsequently, into a full-fledged department in 2012, known as the Gas Reservoir Management Department (GRMD). Today, with a team of 120 engineers and technologists, GRMD manages close to a 1,000 nonassociated gas producing wells, 100 fields, 40 different reservoirs, 10 billion scfd of production, and hundreds of trillions of cubic feet of natural gas reserves.

Saudi Arabia's gas reservoirs have a broad spectrum of characteristics. There are the easily producible excellent quality reservoirs with porous rocks for fluid flow, and the deeper and tighter porous challenging reservoirs that take

High permeability reservoirs can be produced down to an economic limit within a reasonable time without stimulation, although stimulation will accelerate reserves recovery (top), but tight gas reservoirs can only produce economically with multistage hydraulic fracturing; the ultimate recovery from tight gas is always much lower than that from conventional gas reservoirs (bottom).







Transverse fractures independently generated from a horizontal lateral gas well showing increased reservoir contact, enhancing gas production.

huge capital investment, novel production mechanisms, and ingenuity to access the reserves. There are also formation intervals that are fragile, and unconsolidated deposits containing massive amounts of gas requiring careful drilling.

The highly consolidated and very tight deposits, on the other hand, must undergo massive hydraulic fracturing to unlock the gas. The variation in reservoir bottom-hole temperatures, from 250 °F to over 300 °F, formation pressures from a few thousand to over 10,000 pounds per square inch, and condensate content from very rich with hundreds of barrels of condensate per million scf to dry gas with no associated condensate, all pose many challenges and require unique approaches in each area, reservoir, or sector for efficient exploitation.

Regardless of reservoir characteristics, the GRMD strategy is to focus on efficiency, maximize recovery, and maintain high safety standards requiring the continuous development of novel ideas and concepts, improvement of existing technologies, and appropriate use and implementation of new techniques, processes, and strategies. GRMD works hand-in-hand with other departments associated with geoscience, drilling, production, operations, and research, to reach the overall success in the exploitation of natural gas.

WORKING WITH THE INTERNATIONAL COMMUNITY

GRMD has established itself in the global petroleum engineering sector as a world-class operator and manager using innovative ideas and novel technologies for improved hydrocarbon recovery.

At the same time, the department has heavily focused on coordinating with international organizations and societies to share its experience through active participation in forums, workshops, conferences, and technical events. In the past five years, GRMD has published more than 150 technical papers with the Society of Petroleum Engineers (SPE).

A considerable number of new technologies were developed and applied during the past decade that led to a cost-effective, efficient, and successful expansion of the gas program. The following few technologies and strategic steps made a huge impact, enabling the gas program to increase reserves, production, and sustainability.

HYDRAULIC FRACTURING

The objective is to accelerate gas production and reserve recovery in moderate flow capacity reservoirs and commercialize and increase the estimated ultimate recovery in reservoirs that have low flow capacity. These tight reservoirs exhibit permeability values of less than 0.1 millidarcy and sometimes even in the nano-darcy range, making them virtually impossible to flow at a reasonable rate with simple conventional drilling, perforation mechanisms, and stimulation treatments. Massive hydraulic fracturing considerably increases the reservoir to well contact area, thereby allowing the hydrocarbon to flow at rates that are much higher and more sustainable, bringing down the payout time and increasing the rate of return.

"The gas program is the backbone of the Kingdom's energy supply and with massive expansion projects applying new technology, the production will quadruple in the next five years — since the inception of the MGS. Gas is plentiful, environmentally friendly, with low production costs and high energy efficiency, making it the most attractive resource for the Kingdom."

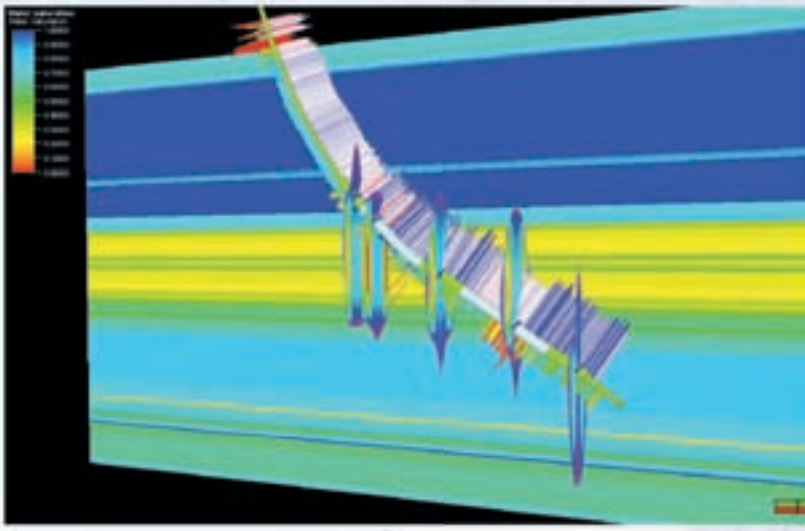
— Adnan A. Al-Kanaan, manager, GRMD

One aspect of fracturing is the use of carbon dioxide (CO_2) assisted energized fluid or foam. As the reservoir's pressure goes down with long-term production, it becomes challenging to produce back the fracturing fluids and initiate gas production without the use of external energy. Use of CO_2 in its liquid form can drastically reduce the use of freshwater, and when pumped as a fracturing fluid, provides the additional pumping pressure that is required to fracture the reservoir and transport the proppant.

At reservoir conditions, CO_2 always behaves like a supercritical fluid, leaving the reservoir in a gaseous state during flow back, thereby providing energy, and significantly reducing damage compared to when conventional fracturing fluids are applied.

To minimize cost, stimulation engineers are currently considering the use of local products. GRMD is conducting tests on Saudi sand obtained from some specific areas that are found to be of good quality, shape, and size to potentially replace the more costly proppant in channel fracturing treatments. Another evolving technology in hydraulic fracturing is the use of seawater as a base fracturing fluid. While the laboratories are constantly working on new chemicals that will enable seawater to be compatible with the reservoir fluids and the additives that are used to provide fracturing fluid, including the viscosity and cross-linking capability that it needs, this technology, when widely used, will revolutionize the drilling industry.

The use of hydraulic fracturing along with other novel technologies have changed the gas production outlook. Tight gas wells that would not otherwise produce at acceptable rates can now produce at higher sustained rates by drilling them horizontally and applying multistage fracturing. There has been significant improvements in the ultimate reserves recovery, and the addition of new reserves. As unconventional gas from tight and ultra-tight reservoirs and shales is being discovered, more and more complex multistage fracturing will be needed to exploit those reserves.



Slanted lateral and transverse hydraulic fractures with real time logging data illustrating reservoir properties along the well trajectory.

UNDERBALANCED COILED TUBING DRILLING

Underbalanced coiled tubing drilling (UBCTD) is another technology breakthrough that is being used in the gas program to enhance production and increase gas recovery. This technology enables an assessment of reservoir performance by monitoring gas flow as the reservoir is drilled in real time, enabling the engineer to geosteer through the reservoir to achieve higher reservoir contact and production. Wells are drilled underbalanced, meaning the reservoir pressure is higher than the pressure exerted

A carbon dioxide energized fracture treatment field operation where the pump lines are insulated to preserve the injected fluid temperature.

A wellhead in the Karan field. The valves and flow line control gas flow from the reservoir to the surface and into the trunk line that carries natural gas to the gas plant for processing into the Master Gas System and distribution to the customers.

from drilling fluids, therefore, the well keeps producing to the surface during drilling, and hydrocarbon is captured directly into the gas production system for sales.

Besides monitoring gas performance while drilling, UBCTD also reduces any damage that is caused by conventional drilling — where the mud weight exceeds reservoir pressure and mud filtrate enters the reservoir, causing clays and other minerals to swell that can reduce reservoir permeability. UBCTD provides great flexibility, allowing for the drilling of multiple laterals or horizontal sections of different lengths and at different depths out of a single well, which significantly enhances productivity.

OFFSHORE DRILLING AND COMPLETIONS

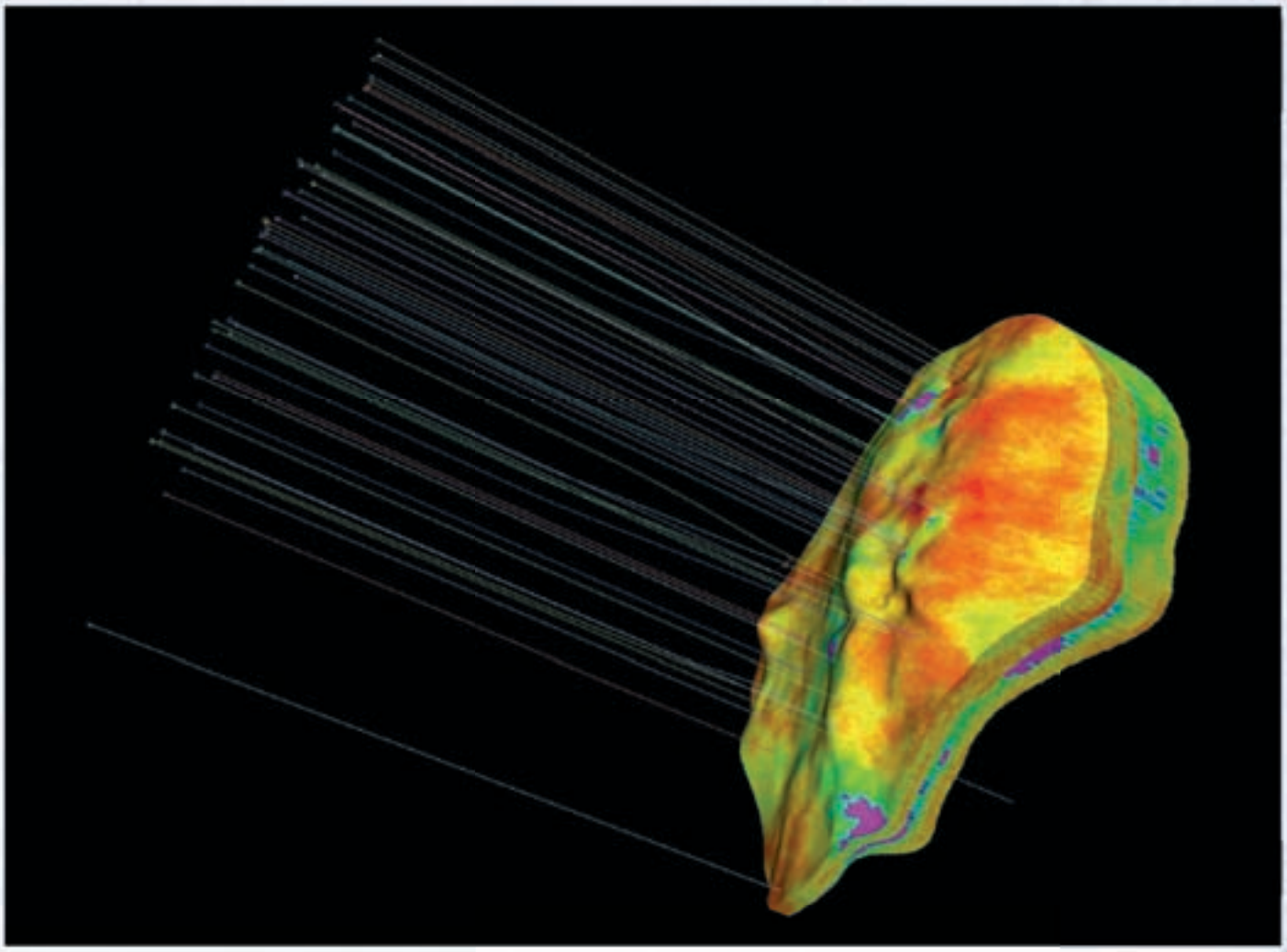
Full-field development plans for the offshore completions include large tubulars and very high working pressure applied for the gas reservoirs requiring large "Gorilla Class" jack-up drilling rigs for the first time ever in the gas program.

These high rate wells resulted in significant development cost savings and provided critical production flexibility.

The design maximizes gas production from each well and reduces the overall development costs by minimizing the number of wells and surface facilities required without impacting production. The wells are capable of producing much higher production than typical onshore wells and sometimes more than the daily production rate of some gas fields outside the Middle East.

DELINEATION AND DEEPENING STRATEGY

GRMD management has championed the approach of tapping new conventional gas resources in and around existing fields with delineation (exploratory) wells, resulting in the discovery of new reservoirs and adding to reserves by extending previous field limits.



A 14,000 foot deep sandstone structure illustrating reservoir properties, sweet spots, and layer attributes; horizontal and slanted laterals are landed on target reservoirs and geosteered to stay in zone, then completed and hydraulically fractured to contact adjacent layers that increases the flow area, expedites recovery, and adds to recoverable reserves (image courtesy of Osman Hamid).

In addition, deepening selected wells has proven to be a very cost-effective method to access previously untapped deeper formations. The use of both strategies has helped double the nonassociated gas reserves in the past 15 years.

GAS PROGRAM FUTURE

Saudi Aramco has made the decision to invest in both conventional and unconventional methods to increase the Kingdom's energy capacity. The gas program will require significant capital expenditures — especially for offshore, deep-water, and remote areas that will require a talented and experienced workforce to ensure projects are economical and completed within scope, and with on time delivery.

Saudi Aramco is proud of both of its onshore and offshore field developments that have always focused on safety, efficiency, the use of new technology, and state-of-the-art operations, along with staying within budget. The increase of talent and technology has ensured the Kingdom with a long-term gas source that will be used to meet the country's future energy requirements and provide opportunities and employment to future generations.

The application of innovative ideas is an essential enabler to meeting the Kingdom's future energy needs, and new concepts, ideas, and plans are being assessed and deployed across the whole spectrum of upstream operations. Proven technologies, along with new ones, are routinely being trial tested and implemented to enhance production rates and maximize reserve recovery. All of the concerned petroleum engineering and geoscience disciplines are working as an integrated team to ensure that the entire process chain from exploration, drilling, delineation, development planning, facility construction, installation, commissioning, startup, and production is done efficiently and cost effectively.

Implementing novel technology, new initiatives, a focused vision, and concerted efforts have substantially accelerated the Kingdom's gas development program. With the great history and the successes achieved throughout the development and expansion of the program, Saudi Aramco is confident about its ability to support the Kingdom's energy sectors and strengthen its economic growth for many more years to come.

abbrev.

Saudi Aramco news in brief

Amin Nasser, president and CEO of Saudi Aramco, and Patrick Pouyanné, chairman and CEO of Total, watch as a joint development agreement for the front-end engineering and design of a giant petrochemical complex in Jubail is signed by Abdulaziz M. Al-Judaimi, senior vice president of Downstream for Saudi Aramco, and Bernard Pinatel, president of Refining and Chemicals for Total.

Saudi Aramco and Total launch engineering studies to build a giant petrochemical complex in Jubail

DHAHRAN, SAUDI ARABIA — A joint development agreement between Saudi Aramco and Total was recently signed for the front-end engineering and design of a giant petrochemical complex in Jubail, on Saudi Arabia's eastern coast.

Announced in April 2018, the world-class complex will be located next to, and integrated with, the Saudi Aramco Total Refining and Petrochemical Co. (SATORP) — a state-of-the-art refinery operated by Saudi Aramco (62.5%) and Total (37.5%) — to fully exploit operational synergies.

It will comprise a mixed-feed cracker (50% ethane and refinery off-gases) — the first in the Arabian Gulf region to be integrated with a refinery — with a capacity of 1.5 million tons per year of ethylene and related high-value petrochemical units. The project, which will add a new slate of products produced in the Kingdom, represents an investment of approximately $5 billion dollars and is scheduled for startup in 2024.

Aramco Asia-Japan, Miraikan sign agreement to promote science and technology

TOKYO, JAPAN — Aramco Asia-Japan (AAJ) recently signed an agreement with The National Museum of Emerging Science and Innovation to contribute to the efforts of disseminating knowledge while enhancing the public interest and understanding of science and technology among local residents.

Locally known as Miraikan, which broadly means "future museum" in Japanese, it is the latest partner of AAJ and Saudi Aramco's corporate social responsibility endeavor for 2018 under the pillar of promoting a knowledge society.

Located in the metropolitan area of Tokyo, the museum attracts more than one million visitors from all over the world every year. The experience-based exhibitions not only showcase cutting-edge science and technology, but also

Omar Al Amudi, AAJ representative director (fifth from left), poses with AAJ representatives, Mamoru Mohri, chief executive director of Miraikan (fourth from left) and Miraikan delegates in front of the symbolic globe-like display "Geo-Cosmos."

help the audiences understand how science and technology can influence the future.

The unique setup of Miraikan is its design to prompt visitors to stop, ponder, and discuss the future of science and technology. Miraikan's first-of-its-kind, globe-like display "Geo-Cosmos" that is made with organic electroluminescent panels displaying virtual real-time events of global weather patterns, ocean temperatures, as well as other geographic, scientific, and socioeconomic topics.

Aramco Asia, CUPB ink deal to further strategic collaboration

BEIJING, CHINA — In the presence of Saudi Aramco senior vice president of Upstream Mohammed Y. Al Qahtani, Aramco Asia president Anwar Al Hejazi recently signed a Memorandum of Understanding (MoU) with China University of Petroleum (Beijing) (CUPB) to enhance their partnership and closer collaboration.

The MoU is intended to explore added value opportunities for joint research in the field of research and technology, education, social outreach, and community service betterment for mutual benefit. The MoU marks the elevation of the Aramco CUPB cooperation from an informal partnership to a strategic level.

Through the MoU, the two sides will establish a collaboration framework that would facilitate academic exchanges, bring in novel technologies to handle upstream challenges, and encourage community engagement to maximize the benefit in a professional manner.

Witnessed by Saudi Aramco senior vice president of Upstream Mohammed Y. Al Qahtani, Aramco Asia president Anwar Al Hejazi signed a MoU with professor Li Gensheng, vice president of China University of Petroleum in Beijing, China.

Fully behind OGCI: Saudi Aramco reinforces commitment to reduce greenhouse gas emissions

NEW YORK, USA — Saudi Aramco, a worldwide leading integrated energy and chemicals company, and a founding member of the Oil and Gas Climate Initiative (OGCI), recently joined several major oil and gas companies and key energy and climate leaders for the fourth annual meeting of OGCI in New York City.

At the meeting, CEOs of OGCI's 10 existing member companies and the three newly joined members discussed the industry's approaches to decrease greenhouse gas (GHG) emissions with key stakeholders.

The OGCI also unveiled plans to reduce the collective average methane intensity of members' core upstream oil and gas operations to below 0.25% by 2025, with a goal of reaching 0.2%, corresponding to a reduction by one-third.

Amin Nasser joins fellow OGCI member CEOs at the organization's annual meeting held in New York City.

The first delivery of crude oil cargo arrives at Pengerang Deepwater Terminal 2 in Malaysia, marking the transition into the commissioning phase for startup at the mega-refinery project.

According to a recent study published in the journal *Science*, which analyzed emissions from nearly 9,000 actively producing oil fields in 90 countries, Saudi Arabia's crude oil production has one of the lowest carbon emissions per barrel. The low carbon intensity advantage of Saudi Arabian crude oil is a result of multiple factors, including the company's continuous implementation of best-in-class reservoir management practices, flare minimization, GHG management, and methane leak detection, and repair.

Malaysia mega-refinery project receives first crude oil cargo

PENGERANG, JOHOR, MALAYSIA — Pengerang Refining and Petrochemical (PRefChem) achieved a significant milestone in the construction of its refinery at the Pengerang Integrated Complex (PIC) with the arrival of the first crude oil cargo at Pengerang Deepwater Terminal 2, marking its transition into the commissioning phase for startup.

With a refining capacity of 300,000 barrels of crude oil per day, the refinery — upon completion — will produce a range of refined petroleum products (including gasoline and diesel) that meet Euro 5 fuel specifications. Additionally, the refinery will provide feedstock for the integrated petrochemicals complex within the PIC, which has the capacity to produce 3.3 million tons per annum.

The cargo of 2 million barrels of crude oil supplied by Petroliam Nasional Berhad (Petronas) and Saudi Aramco will be used for commissioning and testing activities, which are scheduled to commence in October. Currently, the construction of the refinery is nearing completion.

ASC headquarters inaugurated in Houston

HOUSTON, TEXAS, USA — The Aramco Services Company (ASC) board has officially inaugurated ASC's new headquarters in North America.

Located in downtown Houston, the building's top six floors house ASC functions, including Procurement and Logistics, Public Affairs, Upstream, Technical Services, Finance, Law, and Industrial Relations.

The environment incorporates a "new era" of design that reflects today's best practices with open spaces for style and functionality.

While the move was brought about by the flood waters of 2017's Hurricane Harvey — one of the costliest natural disasters in U.S. history — a year later ASC's resilient team finds itself in a bright, airy, and inviting environment designed for collaboration. This includes natural illumination, recessed LED ceiling lights, and sound absorption; as well as "adjustable" work spaces, including ergonomic chairs, and adjustable height desks.

The new offices bring a bright, new look to the Aramco Services Company in Houston. Here, employees take advantage of a large open space to review images for an upcoming edition of *AramcoWorld*.

Aramco Asia participants, including Fahad Al Othman, Aramco Asia acting president, Waleed Al Helal, Public Affairs director, and Tareq Al Sabti, technical services director, and selected staff members from both Beijing and Xiamen, as well as CMCN general director Liu Yi, pose for a group photo at the CMCN and Aramco Asia Eco-Restoration Base on Haimen Island, in Southeast China's Fujian Province.

Aramco Asia supports mangrove conservation in China's Fujian Province

BEIJING, CHINA — Aramco Asia has provided much-needed support to the China Mangrove Conservation Network (CMCN) after entering into an agreement in April this year, within the framework of Saudi Aramco's 2018 donation program.

The green initiative's objectives are to facilitate and support the conservation and protection of mangrove swamps on Haimen Island, in Southeast China's Fujian Province.

This program is one of many social corporate responsibility initiatives that Aramco Asia is carrying out to implement Saudi Aramco's out-of-Kingdom donation strategy that promotes the corporate social responsibility pillars of knowledge society and environment in areas of operations.

Under the agreement, Aramco Asia took the specific area of the island as an adopted conservation land to conduct mangrove planting and post-planting management work such as coastline cleanup and invasive species removal.

Saudi Aramco collaboration seeks to develop most advanced engine and fuel combination

DHAHRAN, SAUDI ARABIA — Saudi Aramco Technologies Company (a Saudi Aramco company), Mazda, and the National Institute of Advanced Industrial Science and Technology recently announced a cooperative research program to develop advanced engine and fuel combinations, with the potential for meaningful improvements in engine efficiency and carbon dioxide (CO_2) reductions assessed on a well-to-wheel basis.

In this collaboration, Saudi Aramco will contribute through its knowledge and research to support gasoline compression ignition (GCI) technology as a viable development route to achieving high fuel efficiency with low emissions; and new fuel formulations to further complement this engine concept. The GCI concept, which is Saudi Aramco's flagship project within this research program, will enable a 25% to 30% reduction in CO_2 compared to conventional gasoline spark ignition engines.

Mazda's engine technologies and Saudi Aramco's GCI fuel technologies complement each other. The GCI fuel has a lower carbon content and higher heating value than commercial diesel and gasoline fuels, and the lean burn engine emits lower CO_2 than conventional gasoline engines.

Saudi Aramco will provide low carbon content new fuels, and Mazda will contribute a high-efficiency prototype engine based on their SKYACTIV technologies.

The joint work is expected to be completed in fiscal year 2020, with ongoing contributions by researchers from all three parties.

Saudi Aramco Technologies Company, in collaboration with Mazda and the National Institute of Advanced Industrial Science and Technology, announced a cooperative research program to develop advanced engine and fuel combinations to improve engine efficiency and reduce carbon dioxide emissions.

Saudi Aramco
dimensions INTERNATIONAL
Corporate Communication
Support Department
C-11B, Room AN-1080
North Admin Building #175
Dhahran 31311, Saudi Arabia

worldview

Kongobu-ji, Japan

Yoko Ishii captured this image of the rock garden in Kongobu-ji, "Temple of the Diamond Mountain Peak," at the end of October.

Surrounded by mountains, the temple is located in Koyasan, Wakayama prefecture, in the southcentral part of Japan, which is famous as a UNESCO World Heritage site.

The temple was originally constructed in 1593, although the site is part of an active monastic center founded over 12 centuries ago.

The temple's traditional rock garden is Japan's largest, at 2,340 square meters, containing 140 granite stones arranged to appear like a pair of dragons emerging from the clouds.

She used her smartphone, a Galaxy S8, to capture this image. Ishii lives and works in Tokyo as a Public Relations specialist for the Management & Strategic Studies Support Department. She has been with Aramco Asia-Japan since 2014.