

*EPRASHEED*  
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2011 – Issue 23

# Saudi Arabia oil & gas

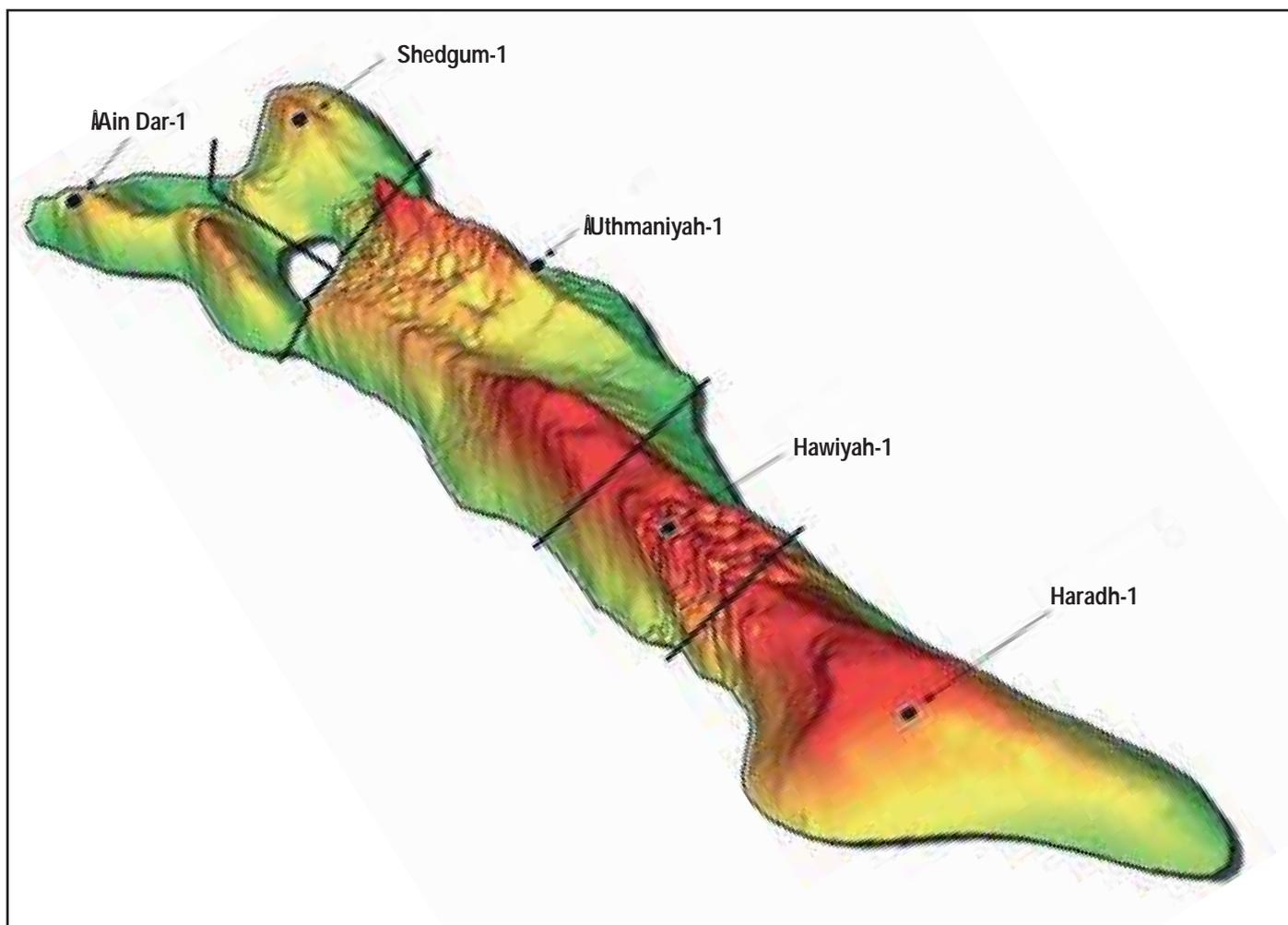
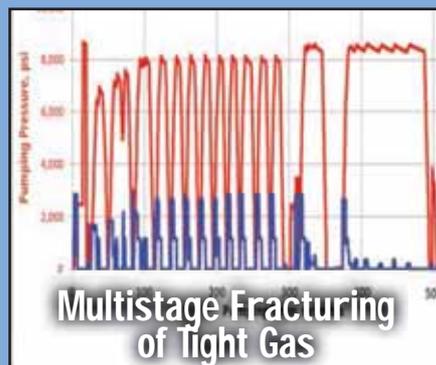
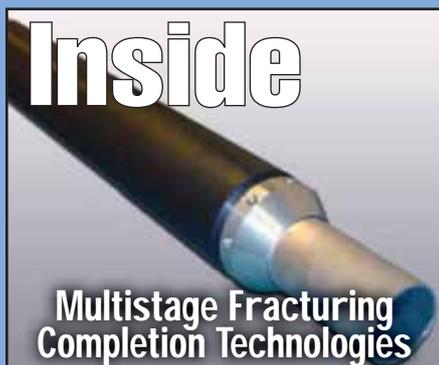
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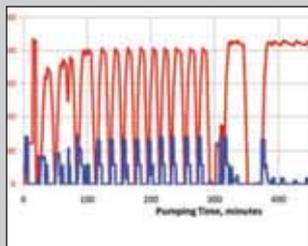
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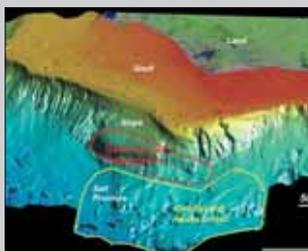
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**The submission deadline is November 30, 2011, and the authors will be notified of proposal acceptance by December 31, 2011.**

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# Fulfilling a Higher Purpose: Four Tenets For a New “Golden Age” of Petroleum

Speech by Khalid A. Al-Falih, President and CEO, Saudi Aramco, at the World Petroleum Congress..



DOHA, QATAR, 6 Dec 2011

“Your Highnesses, Excellencies, ladies and gentlemen: good morning. It is a pleasure to join you today – and I would like to thank Randy for both his kind invitation and his thorough introduction. Once every three years our industry comes together for one of its most important gatherings, the World Petroleum Congress, and it is a privilege for me to address this international audience here in Doha, one of the great energy capitals of the world.

I am particularly glad to speak to you now, when we are on the cusp of what I believe will be a new renaissance for petroleum. This belief, as I recently outlined, emanates from four new sweeping realities that are reshaping the world of energy, especially petroleum.

First, an increasing abundance of oil and gas supplies

serving to deflate “peak oil” and energy security concerns;

Second, the faltering pace of various alternative energy sources, including renewables and nuclear;

Third, new economic realities, leaving neither the resources nor the resolve to make massive investments in idealistic but unrealistic energy programs;

And fourth, a shift in environmental priorities, including the fact that climate change has been superseded on the global agenda by the need for economic recovery, job creation, and fiscal discipline.

As a result, we now have a confluence of factors which I hope will position the petroleum industry for a new era of success. Rather than the supply scarcity which many predicted, we have adequate oil and gas supplies, due

“To develop adequate and reliable energy resources, we must weather the inevitable short-term cross-winds and the ups and downs of the market while holding fast to our strategic assessments and core convictions.”

in large part to the contributions of unconventional resources. That also means the world now has even more time for the gradual but meaningful development of renewables, and for them to overcome technical, economic, environmental and consumer acceptance obstacles by competing on a level playing field.

Ladies and gentlemen, these sweeping realities and the new era they herald are important not just for our industry, but for the entire global economy and societies the world over. That’s because petroleum powers all kinds of economic activity, from transportation and services to chemicals, agriculture and manufacturing; it enables economic and social development for communities; and it fuels the more affluent lifestyles which the world’s ever-increasing population will continue to demand. In fact, it’s fair to say that without petroleum, nothing ticks!

But when I speak about a “renaissance” for our industry, I’m not talking about another decade of boom where we spend more and make more. Rather, I am referring

to an era in which we fulfill our commitments to humanity by helping to elevate and sustain the quality of life across the globe, including meeting our obligations to the natural environment. To me, that is the higher purpose we serve through the energy we provide.

And let me caution that while many of the conditions for a new “golden age” are in place, there is nothing inevitable about the long term business success of our companies unless we ensure the greater prosperity for the stakeholders we serve. Although our industry has accomplished much, and while we can take pride in our achievements, we will have to work hard to get things right. So today, I would like to describe a set of four key tenets that can guide us on our way to a renaissance for oil and gas, while helping to fulfill the higher purpose of our industry.

The first of those tenets is what I refer to as our “staying power”: the adoption of a long-term approach to business, grounded by both realism and resilience. In other words, it is what an athlete might term “stamina.”

“Although refining margins have been under pressure, we believe that in time these refineries will be both competitive and profitable, as well as essential to meet the market’s rising need for high-quality fuels and petrochemical products.”

To develop adequate and reliable energy resources, we must weather the inevitable short-term cross-winds and the ups and downs of the market while holding fast to our strategic assessments and core convictions. Such stamina is essential if we are to meet the expectations of our customers for increasing petroleum supplies, even as the industry as a whole moves to more difficult and more expensive frontiers. I’ll be the first to acknowledge that adhering to that long-term view isn’t easy when the financial markets demand short-term results—and yet I believe it is critical if we are to bring this new golden age to fruition. Let me elaborate.

As you know, it takes a long time to develop petroleum projects in increasingly harsh, complex and demanding environments. The typical upstream project cycle in our industry, from leasing to exploration and then to production, is in the range of 10 to 15 years. Combine this long cycle time with the traditional volatility of

the oil market, consider the increasing scope and scale of many projects, and add in how many other factors can change over a decade and a half, and it is clear our business is not for the faint of heart. And while stamina and resilience may not matter to the sprinter, they are absolutely essential to the marathon runner.

To drive home this point, allow me to cite one example from among Saudi Aramco’s own portfolio of megaprojects.

Our Manifa project, at 900,000 barrels per day of capacity, is one of the largest heavy crude oil increments ever undertaken. Furthermore, the field’s geography – in shallow waters in the fragile ecology of the Arabian Gulf – requires unique, environmentally-friendly access solutions involving a novel causeway design linking drilling islands to shore. When we made the investment decision on Manifa in 2007, oil prices were

“... it is my strong conviction that the potential of technology is limited solely by the confines of our own imagination, and our willingness to commit resources to research and technology development.”

above 70 dollars per barrel and demand prospects were looking strong. But right after fixed-price contracts were awarded, the global economic crisis turned everything upside down.

Crude prices slumped to below 35 dollars, demand projections fell, and yet project costs did not proportionally decrease, clouding the outlook for the investment. At that point we were sitting on some four million barrels per day of spare capacity – even without Manifa – and many suggested we terminate our contracts and build later, once demand rebounded. But most of our contractors were already suffering due to the recession, and had we cancelled the program they would have had to lay off a substantial number of personnel. Aside from undermining the bonds of partnership we enjoy with our contractors, the loss of capacity and capability among some of our most valued service providers would clearly have negative ramifications for our future projects.

So instead of simply scratching Manifa – which might have made sense when viewed only in the short-term – we undertook a thorough joint review of the program with our contractors. That resulted in an intelligent and economic redesign of the project and its schedule, such as continuing work on surface facilities but stretching out the drilling campaign. We thus extended selected segments of the program by two years and saved more than two billion dollars in the process. It was difficult, but we stayed with Manifa despite the economic winds blowing around us, and the project is on schedule for a 2013 start-up.

Our downstream investment program, involving a number of world-scale refining and petrochemical investments in the Kingdom and abroad with a total cost of around 90 billion dollars, is no different. Although refining margins have been under pressure, we believe that in time these refineries will be both competitive and profitable, as well as essential to meet the market’s

“... forward-looking petroleum companies should provide meaningful training to their local employees, transfer technology, share expertise and best practices, and undertake research and development locally.”

rising need for high-quality fuels and petrochemical products.

Our hosts here in Qatar are also familiar with gyrating markets – this time with integrated natural gas investments. To its credit, Qatar has stayed the course with its development plans in spite of depressed prices and a changed outlook. This decision to press ahead reflects Qatar’s long-term assessment of healthy demand for clean natural gas – and today LNG prices are recovering due to surging demand for energy in developing Asia. Qatar is now poised to reap the benefits from its exports – underscoring the virtues of stamina.

My second tenet centers on technology.

As we all know, the industry has come a long way from its earliest days. Upstream, the advent of seismic technology – especially 3-D seismic – has transformed exploration. In development the industry moved from shallow onshore wells to offshore, then deep offshore and now the Arctic. Likewise, we’ve progressed from

vertical shafts to horizontal and multilateral drilling, and on again to intelligent well completions. Chemicals based on petroleum have helped to make our lives more comfortable, more convenient, and healthier and safer than ever before. In the area of environmental protection, emissions of conventional pollutants from automobiles have been reduced by more than 95 percent since 1970. Ladies and gentlemen, as impressive as all of this may sound, I believe we’ve still only scratched the surface.

In fact, it is my strong conviction that the potential of technology is limited solely by the confines of our own imagination, and our willingness to commit resources to research and technology development. Much of the new upstream and downstream processing technologies will come from within the industry. But in terms of end-use solutions such as improving the efficiency of petroleum, there are major untapped opportunities on both the “software” and “hardware,” or equipment, sides of the equation. For example, in transportation both oil companies and manufacturers of road vehi-

“ Saudi Aramco’s belief in technological advancement is reflected in our recently articulated strategic intent for technology, which calls for the company to transform into one of the world’s leading energy technology companies during the coming decade. ”

cles, aircraft, ships and locomotives could and indeed should collaborate. I invite these various hardware manufacturers to come work with us on enhancing the performance of petroleum in their products, in ways that would be both economically and environmentally beneficial.

In my view, we also need to go beyond incremental improvements and look for big, game-changing ideas with the potential to revolutionize our business. More than a century ago, great inventions such as the diesel engine and the application of seismic technology in petroleum exploration were made. The onus is now on us to create our own disruptive technologies. This can be done by going back to basic research – including work in fundamental sciences like physics, chemistry and biology – as well as applied R&D to make dramatic advances that will enable us to really push the envelope of

petroleum technology and unlock its future potential. But we need to face the reality that our industry lags behind when it comes to R&D spending, and we need to do a lot more in this critical area.

Saudi Aramco’s belief in technological advancement is reflected in our recently articulated strategic intent for technology, which calls for the company to transform into one of the world’s leading energy technology companies during the coming decade. We will back this intent with an expanded commitment of world-class R&D resources, both human and financial. The technology domains on which we will focus encompass the entire value chain of petroleum, with special emphasis on groundbreaking research. We are working on such futuristic initiatives as our proprietary Res-Bot technology, which involves intelligent nano-sensors providing direct and real-time data on reservoir prop-

“...as always, values and ethics must be the foundation of our industry’s approach to people, so that our standards of integrity, reliability and discipline are preserved, while overlaying them with an organizational culture that enables top performance and encourages innovative and entrepreneurial thinking.”

erties; highly advanced and efficient reservoir simulation of massive systems; the use of super-critical water for desulfurization of oil; the management of carbon from mobile sources; and game-changing research into transportation fuels for the future. Here again, staying power and stamina are critical, and they serve as the foundation of all our R&D endeavors.

My friends, the third tenet for an optimal future for petroleum is people. As you know, the oil business is facing a major generational shift – what has been termed the “Great Crew Change” – as many of the most experienced engineers, technicians and specialized personnel reach retirement and a new crop of young professionals joins our ranks. There is both challenge and

opportunity in this generational shift: the challenge of transferring hard-won expertise to a new generation, and the opportunity of capitalizing on the different and exciting skill sets, expectations, and worldview of this rising generation of young men and women.

And as always, values and ethics must be the foundation of our industry’s approach to people, so that our standards of integrity, reliability and discipline are preserved, while overlaying them with an organizational culture that enables top performance and encourages innovative and entrepreneurial thinking. That means moving away from the old command-and-control model typically found in the oil patch, and embracing quick decision-making and operational agility; greater

empowerment coupled with increased accountability; and cross-disciplinary teams which transcend traditional organizational lines.

At our company, we are putting in place systems and structures which allow us to tap the energy and ideas of young professionals while also communicating the fundamental principles of our organizational culture – a process I have described as getting young people ready for the company, while getting the company ready for this young generation. To that end, we recently established a Young Leaders Advisory Board – or “Y-LAB” for short – to advise senior leadership on the views that younger employees have of our transformation journey, and to sample their ideas and insights.

My fourth tenet today is responsibility, by which I mean starting with our widely accepted precept of protecting the natural environment but then extending the responsibility framework to include our societal obligations, the combination I have usually referred to as true sustainability.

The oil industry as a whole has committed itself to a responsible approach to business, which begins with producing and consuming petroleum in a sustainable manner consistent with our societal license to operate. Because oil and gas will continue to play a dominant role on the world’s energy scene for generations to come, it is imperative that we work even harder to minimize the environmental footprint of petroleum—especially its carbon emissions.

I’m glad that the industry has given special attention to the environmental aspects of petroleum production and its end-use. But the responsibility concept I’m addressing is much broader, and I am somewhat disappointed that the “annual sustainability reports” issued by some leading global corporations are largely limited to their environmental activities. In my view, our industry’s approach to responsibility should include deeper and broader engagement in the societies and economies we serve – and that applies equally to national oil companies and multinationals alike.

On the societal front, our strategic engagement must include helping local economies grow and diversify, and thus create well-paying jobs, by adding value to the commodities we produce through the leverage of competitive advantages like ready access to abundant resources, a young labor force, ample infrastructure, rising domestic demand, and favorable financial conditions. Our societal agenda should also include the

promotion and procurement of local goods and services whenever possible. In addition, forward-looking petroleum companies should provide meaningful training to their local employees, transfer technology, share expertise and best practices, and undertake research and development locally.

At the same time, petroleum producers need to extend support to local educational institutions to raise educational standards, particularly in technical fields. Having young people well-versed in the so-called “STEM” disciplines – science, technology, engineering and mathematics – will be critical both for our own industry’s human resource pipeline in the years and decades ahead and for the lasting development of many host nations. Over time, such programs can greatly enhance the innovation and entrepreneurial ecosystems in developing economies, helping them to be more competitive in the global arena and diversify away from an overdependence on commodities.

When viewed in this larger context, it becomes clear that the tenet of responsibility is not a matter of nice-to-have, nice-to-do charitable activities, but rather of initiatives which provide real returns for the enterprise: they are driven not just by benevolence, but by good business sense. Nor should these programs be seen as a distraction from the commercial dimensions of our businesses or from operational excellence. Rather, “responsibility” entails a concurrent focus on efficient and cost-effective petroleum activities, targeted strategic investment in local economies and communities, and environmental stewardship.

Ladies and gentlemen, these four tenets – stamina, technology, people and responsibility – represent enormous and complex challenges for our industry, and in fact I believe they are too big for us to tackle on our own. If our industry continues to labor just in its own field, working in isolation from other relevant actors and players, then valuable lessons, best practices, innovative technologies and exciting synergies will be wasted.

What we need instead is what I would term “cross-boundary collaboration,” by which I mean pooling resources, sharing ideas, and teaming with companies, institutions and agencies outside the oil and gas business. Such collaboration is not totally new: we analyze rocks using computer tomography developed by health care companies, prospect with satellite imaging pioneered by the defense and aerospace industries, and harness massive computational power built by the IT

sector. But how many of those tools and technologies were developed purposely in direct response to our own demand?

Furthermore, there is a whole universe of possibilities when it comes to the other tenets I have outlined: a long-term approach to business, developing people, and meeting our commitments to society and the environment. So our collaborative agenda should extend beyond technical issues and encompass so-called “soft” issues such as education and knowledge, social and broad economic development, and of course care for the natural world. That means expanding cooperation beyond business and industry, and working with government agencies and regulatory authorities, academia, and of course non-governmental organizations.

Frankly speaking, we have much to learn but also much to share with other sectors, and I believe that given the nuances of the human experience and the complexity of our modern societies and economies, solutions to pressing issues are best developed by utilizing multiple perspectives and bodies of knowledge. Because in the end, the most daunting challenges we face are not merely problems for our industry, but rather challenges for humanity as a whole.

Ladies and gentlemen, to summarize, I believe all of the elements necessary for a new golden age of petroleum are present – and despite the many challenges

ahead, it’s an exciting and even exhilarating time to be in the oil business. But to make the most of these conditions, we need to demonstrate stamina over the long haul; make strategic investments in research and technology; create an environment which enables our people to excel; and work responsibly to support society and protect the planet. We must do this while committing ourselves to a level of cooperation and collaboration that goes beyond the confines of our industry, and creates meaningful solutions and dynamic synergies.

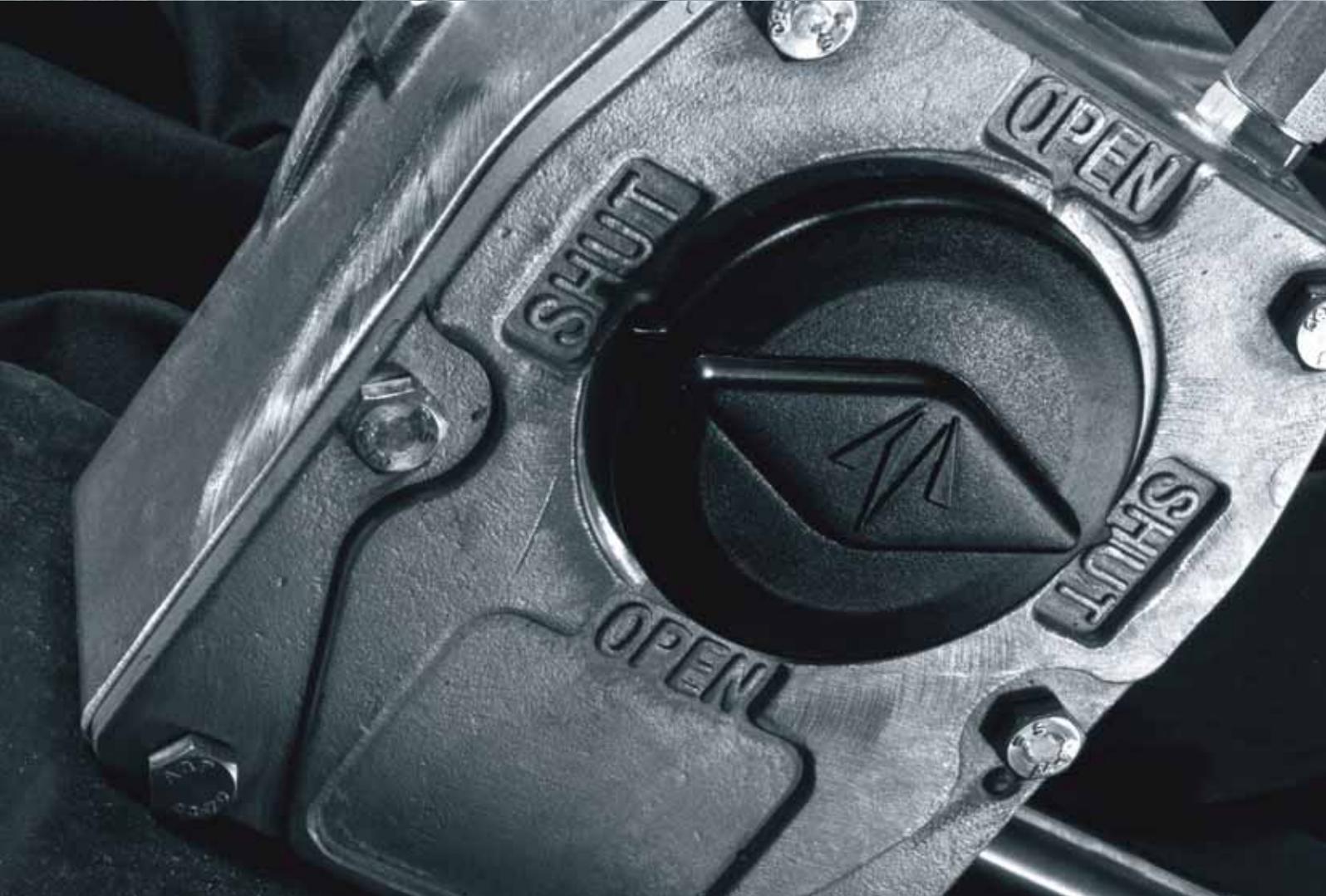
Then and only then will we reverse the widespread but misguided view of oil companies as profit-hungry, environmentally irresponsible and dismissive of society’s concerns. Instead, people will come to realize that our industry is at the forefront of securing greater prosperity for humankind, and that petroleum is an indispensable element in helping people realize their aspirations for a brighter future.

My friends, the degree to which we succeed in meeting those challenges will not only shape our industry’s fortunes, but will help to determine the condition of our fellow human beings for many decades to come. To me, that is our higher purpose as energy providers: enabling prosperity while powering possibilities.

Thank you, ladies and gentlemen, for your attention today.” 🕯



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# Resetting the Energy Conversation: the Need for Realism

By Khalid A. Al-Falih, President and CEO, Saudi Aramco.



RIYAHAD, SAUDI ARABIA,  
21 November 2011

“Your Excellencies, distinguished guests, ladies and gentlemen: good morning. It is a great pleasure to speak to you today, and a tremendous privilege to participate in this inaugural conference at the King Abdullah Petroleum Studies and Research Center. This is an institution of great promise and importance both to the Kingdom and the wider world, and I wish the Center, its staff and its partner institutions every success in their future endeavors. I would also like to note with appreciation the unwavering support and personal interest of the Custodian of the Two Holy Mosques, King Abdullah ibn Abdulaziz Al Sa’ud, for the Center that bears his name.

Ladies and gentlemen, this Energy Dialogue comes at an opportune moment: a moment when the global conversation about energy in general, and petroleum in particular, needs to be reset in light of several far-reaching new realities. I strongly believe that if we are to blaze a path to an optimum energy future, our collective analysis must be more rigorous and our discussion more pragmatic—but also more inclusive and progressive than in the past.

We all know that the world of energy is in a state of constant flux, given that gyrating markets, groundbreaking technologies, and fresh and exciting commer-

cial opportunities are central features of our business environment. But while change is nothing new for our industry, recently there have been four major developments—or what I call sweeping new realities—which in my view call for a reexamination of energy priorities, and a more realistic approach to the energy challenges and opportunities we face. Those four developments will be the focus of my remarks today.

The first of these new realities is the increasing abundance of oil and gas supplies, largely due to significant technological advances which are unlocking additional resources. A few years ago, much of the global energy debate was based on the premise of acute resource scarcity and its economic and political ramifications. Policy and investment choices have therefore largely been framed against a backdrop of constrained oil and gas resources and a need to transition with deliberate speed to one or more alternatives.

Today, talk of oil and gas scarcity has disappeared from both the energy press and the general media, to be replaced by news of increasingly plentiful supplies. In addition to abundant conventional petroleum reserves, vast resources of unconventional hydrocarbons have now been targeted for development around the world, and can be produced feasibly and economically.

Only five years ago, for example, observers spoke confidently of the need to build dozens of new LNG import terminals in the United States and of the overdepend-

Well-established conventional suppliers will continue to account for most production, but there is also a great deal of excitement around untapped conventional resources in frontier areas like deep offshore and the Arctic.

ence of European consumers on Russian gas. Now, by contrast, the challenge is finding an “outlet” for the new production of shale gas, and downward pressure on natural gas prices. The positive impact of increased shale gas supplies on American petrochemicals manufacturing is already apparent, and given the vast shale gas resources and ramped-up production in the US, there are even plans to convert existing LNG import terminals into export facilities. To get some sense of the scale of these changes, consider that the estimates of unconventional gas in place around the world are in the range of 35 thousand trillion cubic feet, compared to currently proven conventional gas reserves of 64 hundred TCF.

Abundance isn't limited to gas reserves, but is also the new headline when it comes to oil. Rather than supply scarcity, oil supplies remain at comfortable levels, even given rising demand from fast-growing nations like China and India. Well-established conventional suppliers will continue to account for most produc-

tion, but there is also a great deal of excitement around untapped conventional resources in frontier areas like deep offshore and the Arctic. Last year, even as the world consumed nearly 30 billion barrels of oil, not only was the industry able to replace this production but global petroleum reserves actually increased by nearly seven billion barrels, as companies increasingly turned toward higher risk areas.

In addition, there is a new emphasis in the industry on unconventional liquids, and shale gas technologies are also being applied to shale oil. The massive heavy oil potential in both North and South America is drawing greater attention, and the future development of kerogen-based oil shales remains an enormous target. Some are even talking about an era of “energy independence” for the Americas, based on the immense conventional and unconventional hydrocarbon resources located there. While that might be stretching the point, it is clear that the abundance of resources and the more “balanced” geographical distribution of

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The flip side of that coin is the second new reality underscoring the need for greater pragmatism in our energy discussions: the faltering pace of renewables and other alternatives.

Just a few years ago, the assertion was that the costs of renewables would decline rapidly as their technical performance improved, making them economic without the need for subsidies. As it turns out, progress has been slow, in part because of continued technical difficulties, and in part because of the much more favorable

economics of proven energy sources which compete directly with many modern renewables. When the economics of hydrocarbon sources shift, this impacts the fortunes of alternatives, so as prices for natural gas in the US halved with the advent of shale gas supplies, the comparative economics of alternative renewables weakened significantly.

This could easily have been foreseen, and in fact at Saudi Aramco we voiced concern a few years ago over the formation of “green bubbles.” At the time we noted that overly optimistic targets and accelerated development plans for renewables would end up hurting those very industries if they were unable to deliver. And as we know, once investors and the public lose confidence in a sector, it is very difficult to attract additional

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capital and regain popular support. We have recently witnessed the bankruptcies of some notable companies in the renewable energy sector around the world, and unfortunately there may be further failures to come.

As I said, this current contraction should not come as any great shock. We all recall government policies which helped direct private sector investments toward a “hydrogen economy” which has not panned out. Then we witnessed what I call the “biofuels bonanza,” which siphoned off taxpayer monies into subsidies for an unsustainable energy source, while also impacting food prices. Then it was thought that cellulosic biofuels – which could be produced without diverting food crops from the family table to the fuel tank – would

quickly become economically competitive with established sources. Today though, forecasts of biofuels production are much less bullish, and even the more realistic production targets are being pushed farther into the future.

There have also been changes in the situation of nuclear energy, which we believe can play an important role in meeting the world’s rapidly rising electric power demand. Unfortunately, its prospects have taken a serious hit due to the Fukushima incident, associated with the tragic earthquake and tsunami in Japan. As a result, a number of existing plants around the world are being wound down and some planned construction has been halted, which will negatively impact the volume of installed nuclear capacity in the short run. However, it

“Today, climate change has been eclipsed on the global agenda by the priorities of economic growth, job creation and fiscal discipline, particularly in the developed countries that were the strongest advocates of aggressive action to reduce greenhouse gas emissions just a few years ago.”

is our earnest hope that the impact of Fukushima will not be long lasting.

In short, given the technical, economic, environmental and consumer acceptance barriers which must still be overcome, the significant adoption of various alternative fuels and new technologies at a global scale still seems some way off. Furthermore, government attempts to “pick winners” among alternatives – even before the contenders are in the starting gate – have proven ineffectual, and in my opinion counterproductive. What is certain is that there is a great deal of uncertainty which surrounds the future of various renewable sources and alternative technologies – particularly in light of the new abundance of oil and gas resources.

That is not to say that we should turn our backs on renewables – rather, the opposite is true. In fact, we’re investing in them at Saudi Aramco, with a particular emphasis on solar. We believe that alternatives can and will make a greater contribution to global energy supplies than they do at present, and we welcome that growth. But the expansion of renewables and alternative energy technologies should be rational and gradual, and tied to their economic, environmental and technical performance.

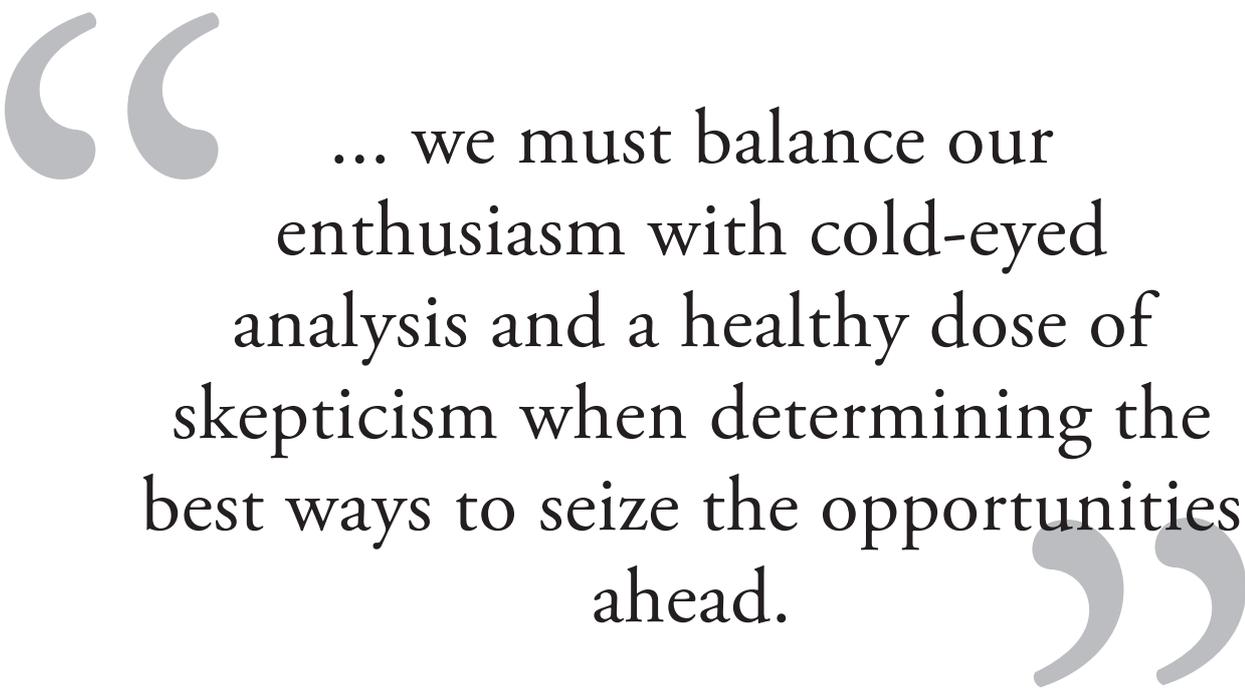
That is one reason I place such emphasis on the exciting developments in conventional and unconventional oil and gas, and the fact that these sources will play a much bigger role in meeting global demand for a much longer time than many once believed. In my opinion,

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this new reality is just what we need for the realistic development and deployment of renewables. Because of these additional oil and gas resources, the world now has the time it needs to develop alternatives in a pragmatic and sustainable fashion, rather than rushing headlong toward an unproven and more expensive energy mix – and that is a cause for optimism.

Let me turn now to the third reality which must be factored into a new, more pragmatic energy discussion: the global economic turbulence of the last few years is persisting, indicating structural issues and fundamental changes in the character of the world economy and how it functions, as opposed to this being a short-term phenomenon.

Considering the pressing need to rebalance the global economy, to jump-start the economies of most advanced nations, and to create new employment opportunities in both the developed and developing world, there is frankly no appetite for massive investments in expensive, ill-thought-out energy policies and pet projects. We see weak economic performance and poor jobs numbers in the US, the mounting sovereign debt in a number of Eurozone economies, continued worries about the exposure of major banks around the world to this sovereign debt, and the specter of a double-dip global recession. All that makes spending on aggressive energy programs unlikely – which in turn invalidates the basic assumptions of many energy transformation scenarios.



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Therefore, I argue that our energy discussion needs to take greater account of economic realities, and place much greater emphasis on the affordability of energy. That prerequisite should always have been factored into the global energy equation, and I think it's a measure of just how unrealistic many of our energy conversations have become that people were banking on governments spending trillions of dollars over time in support of renewables, biofuels, and other unproven alternative energy technologies through subsidies, direct support, and the imposition of taxes and tariffs on conventional energy.

The economic headwinds of recent years have underscored the fact that neither the public sector nor businesses and consumers have the resources or resolve to pay for idealistic but unrealistic energy or environmental policies, particularly when the projected returns are so questionable and so dependent on unsustainable

governmental programs or subsidies. In other words, theory at the academic or policy level is one thing and implementation on the ground is quite another.

One problem with more exotic and more expensive energy solutions is the resulting rise in energy prices, which makes it more costly to perform such mundane activities as heating homes or moving people and goods, and acts as a brake on economic growth. And if energy policies become increasingly impractical while taxes of various types also rise in order to shore up budgets, offset deficits and pay for these excesses, the entire approach would run counter to the goal of creating much-needed jobs, given that economies would become less competitive and price themselves out of the market.

But it is also important to note that even as developed economies mull plans to switch from petroleum-based

fuels to electric vehicles and set aggressive green-energy targets, about 1.4 billion people – roughly one in five individuals on the planet – still have no access to electricity. About twice that number rely on primitive biomass such as wood or agricultural and animal waste for cooking and heating. So aside from the impracticality of massive state spending on overly ambitious energy programs, any discussion of affordability must also recognize that energy poverty would inevitably be exacerbated by a short, sharp and impulsive rush away from proven sources and toward much more expensive alternatives.

This leads to my fourth point, which relates to environmental policy.

The new emphasis on economic recovery and growth is also changing the nature of the environmental debate around energy. Today, climate change has been eclipsed on the global agenda by the priorities of economic growth, job creation and fiscal discipline, particularly in the developed countries that were the strongest advocates of aggressive action to reduce greenhouse gas emissions just a few years ago. For developing countries striving to lift millions of their citizens out of poverty, strangling economic growth under the guise of environmental protection was never affordable or viable in the first place.

So in contrast to the emotion surrounding the Copenhagen meeting of the United Nations Framework Convention on Climate Change back in 2009, there is relatively little public attention being given to the UNFCCC gathering to be convened in Durban next week. Where energy and the environment do intersect, recently the focus has been on localized impacts like offshore spills in the Gulf of Mexico, the South Pacific or Bohai Bay; the path of pipelines in the American Midwest; or the effects of hydraulic fracturing on groundwater. Global warming, by contrast, has moved some way down the global policy agenda.

My friends, the confluence of these four new realities – increasing supplies of oil and gas, the failure of alternatives to gain traction, the inability of economies to foot the bill for expensive energy agendas, and shifting environmental priorities – have turned the terms of the global energy dialogue upside down. Therefore, we

must recast our discussion in light of actual conditions rather than wishful thinking.

We need a more practical and flexible approach that is better able to imagine and deal with future uncertainties, and I believe we need to expand the conversation to parts of the global community which have thus far been underrepresented. Voices from the developing world need to be heard alongside those of the advanced economies, we need to hear from producers and consumers alike, and there should be a more balanced participation in the discussion from all regions of the globe. We also need to maintain an optimistic spirit about our energy future, because I feel strongly that the greatest opportunities for our industry still lie ahead of us. Yet we must balance our enthusiasm with cold-eyed analysis and a healthy dose of skepticism when determining the best ways to seize the opportunities ahead.

So I am very excited about the King Abdullah Petroleum Studies and Research Center, and the role it will play not only in helping to clarify domestic and international energy issues, but also in developing a strong policy framework in which to tackle them. In addition to its own independent studies, the Center also provides an ideal venue for wide-ranging discussions of petroleum-related topics, and creates a new forum for global energy stakeholders to exchange views.

That's important, because until now most energy-oriented think tanks engaged in petroleum-related issues were found in industrialized, consumer countries. This institution, by contrast, is located in a producing country, a nation which has consistently and continuously played a central role in providing much needed stability to the global energy market and which has taken a leading role in promoting consumer-producer dialogue. It is also a country that is still developing, but has experienced phenomenal economic growth and prosperity over the last half-century. The Center adds a new and distinct but I believe welcome voice in the global conversation about energy and sustainability, and we have high expectations of the Center, its staff and its scholars.

My friends, regardless of the ways in which energy policy options have been debated and determined in

the past, what is most important at this point is where we go from here in these economically austere times. Therefore, I would like to close my remarks by inviting all stakeholders – and when it comes to energy, everyone is an interested party – to refocus on specific policy changes to help create a more pragmatic and affordable energy future. I'll be very candid here.

- First, adopt more sensible, market-driven energy policies, rather than selectively subsidizing alternatives or applying unrealistic regulatory and fiscal constraints on proven energy sources. These more balanced policies should leverage the comparative advantages and complementary nature of various energy sources around the world.

- Second, given that hydrocarbons will be with us for the long run and are so critical to the world's economic future, I call for much greater collaboration among various entities in joint R&D programs aimed at improving their environmental as well as economic performance, whether in transportation, petrochemicals or the creation of advanced futuristic materials. This includes carbon capture from mobile sources, including its management through various means. I strongly believe that significant additional resources need to be devoted to these R&D programs.

- Third, concentrate worldwide on the lowest hanging fruit of efficiency improvement. As an example, simply increasing mileage efficiency of vehicles from 30 to 60 miles per gallon can cut emissions in 2050 by a billion tons of carbon dioxide per year, based on typical assumptions applied to a global fleet of two billion vehicles. Emissions from buildings can also be slashed by half, and there are many other opportunities available to lower our carbon intensity.

- Fourth, considering the increased supplies of natural gas, its lower carbon content and emissions as compared to coal, and the greater efficiencies of natural gas plants, move increasingly to gas-based electricity generation. As a result, in fifty years we could be emitting one billion tons of carbon per year using natural gas,

instead of two billion tons annually from coal-based power plants.

- Fifth, apply carbon capture and sequestration to large power and industrial plants, while research is undertaken into new commercial uses of carbon. Coal-burning power plants produce about a quarter of the world's carbon emissions, and CCS could be applied to perhaps a thousand large coal power plants in the next 50 years.

- Sixth and finally, pursue a rational environmental agenda using an objective analysis of costs and benefits, including the need to balance the twin imperatives of economic and social development on the one hand, and environmental stewardship on the other. And as I mentioned earlier, it is vital that environmental programs concentrate on environmental objectives, rather than advancing other agendas under the pretext of protecting our natural world.

Ladies and gentlemen, as I have outlined this morning, recent transformations have significantly altered the energy landscape, particularly when it comes to petroleum. Mistaken assumptions that once dominated the debate have been exposed as unrealistic and impractical – and that provides us with a valuable opportunity to recast our collective conversation about energy and to conduct the discussion on a much more realistic basis.

For me, a more pragmatic and more productive conversation about energy must recognize the four new realities I have described today, and focus on the six key policy action items I just laid out. I hope I have provided you with sufficient food for thought, and look forward to participating in such a dialogue with you and with others. I also look forward with great anticipation to the constructive role that the King Abdullah Petroleum Studies and Research Center will play in those exchanges.

Ladies and gentlemen, I appreciate your attention this morning, and I thank the Center for giving me the opportunity to share my views with such a distinguished group. Thank you." 🕯

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# Success Criteria for Multistage Fracturing of Tight Gas in Saudi Arabia

By Dr. Zillur Rahim, Adnan A. Al-Kanaan, Bryan Johnston, Stuart Wilson, Dr. Hamoud A. Al-Anazi and Daniel Kalinin.

## Abstract

The purpose of open hole multistage fracturing (MSF) is to improve hydrocarbon production and recovery in moderate to tight reservoirs. To date, 17 open hole MSF systems have been installed in deep gas carbonate and sandstone wells in Saudi Arabia. Of these, 16 installations have been stimulated (acid or proppant fractured) and flowed back<sup>1</sup>. Overall, the production results from the use of open hole multistage systems deployed in the Southern Area gas fields have been very positive with some variation – most of the wells responded positively and are excellent producers (>20 million standard cubic feet per day (MMscfd)); some showed average results of 8-12 MMscfd; and a few, completed in a tight reservoir, produced at relatively low rates, <3 MMscfd, and did not carry enough wellhead pressure to be connected to the production grid. This article explores the factors that impact the success of open hole multistage completion systems. Some important factors include the type of open hole multistage system used, formation properties, completion liner size, packer type, number and size of stimulation stages, treatment type, well azimuth and fluids pumped. Conclusions are drawn based on careful data analysis to confirm the best practice for successful open hole multistage deployment and conducting effective fracture treatment.

This article uses extensive field data and correlates factors to show the applicability of open hole MSF technology. Analysis will cover pre- and post-stimulation data showing the results from the treatments. This analysis will show the factors that contribute to the successful deployment of the completion system, the achievement of higher production rates, and the choice of the right candidates to obtain positive results from the treatment. This article will also show that while the various well and reservoir characteristics have a significant influence on overall well productivity, the completion type is critical and plays a central role in the success of the stimulation treatment and final production levels.

Open hole multistage systems have been deployed extensively in North America, but they are relatively new in the Middle East. This is because the conventional horizontal wells are usually high producers and only require small stimulation treatment to clean up the near wellbore area from drilling induced damage. With the growing exploration of tight gas and unconventional resources, the need for MSF is increasing. The tight gas zones in Saudi Arabia are typically deeper and more complex, with higher temperatures and pressures, than most tight gas zones in North America, and therefore require much more accuracy and precision in open

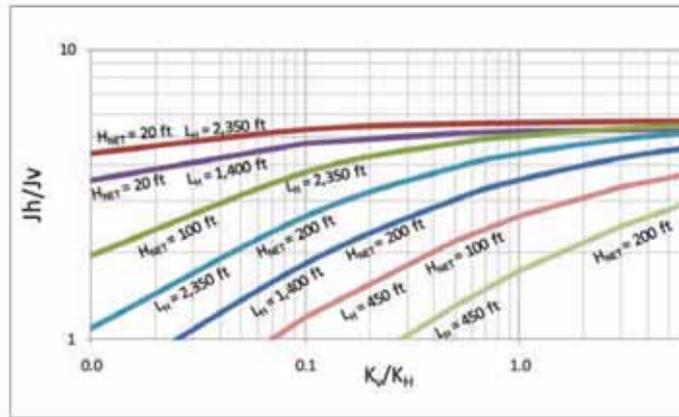


Fig. 1. The productivity increase of horizontal wells over vertical wells for different anisotropy, horizontal lengths and net pay thickness.

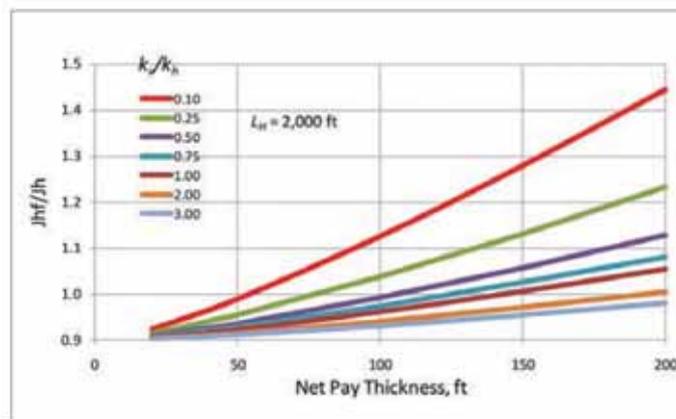


Fig. 2. The productivity increase of a horizontal fractured well over open hole horizontal wells as a function of net pay thickness ( $X = 100$  ft,  $NFR = 4$ ).

hole multistage technology applications. This article discusses the factors that contribute to higher production levels for these types of completion systems.

### Introduction

Drilling of conventional vertical wells limits the amount of exposure between the wellbore and the producing intervals, and this in turn limits production capability. Even when a vertical well is hydraulically fractured, it does not necessarily boost production to the level required to sustain a long-term flow rate due to the tighter nature of the rock. Advancements in direction-

al drilling with slanted or near-horizontal wells hold great promise to increase production by dramatically increasing the contact area with the producing interval. Subsequently, it became apparent that this longer wellbore contact alone was not always sufficient to provide the production increases expected, and therefore stimulation treatment is required to realize production targets and beyond.

A comprehensive parametric study recently conducted in the Gas Reservoir Management Division of Saudi Aramco documented some critical results, showing of

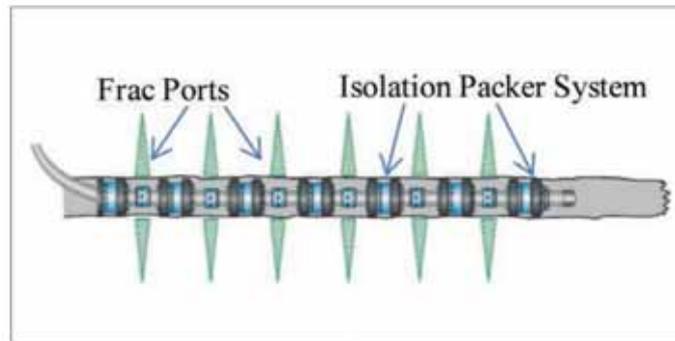


Fig. 3. Open hole multistage assembly showing packers and fracturing ports.

Well Name	Reservoir	Open Hole Size	Tubing Dia.	Dev. from $\sigma_{max}$	Balanced Unbalanced	Open Hole Anchor	Hydraulic Port	No. of Stages	Initial Job Design	Stage 1 Job Type	Stage 2 Job Type	Stage 3 Job Type	Stage 4 Job Type	Flowback between Stages	Stabilized Gas Production MMscfd
Well #1	Carbonate	8 $\frac{1}{2}$ "	5 $\frac{1}{2}$ "	6°	Balanced	Yes	Dual	3	Acid Frac	Acid Frac	Acid Frac	Acid Frac	N/A	No	30
Well #2	Carbonate	8 $\frac{1}{2}$ "	5 $\frac{1}{2}$ "	2°	Balanced	Yes	Dual	3	Acid Frac	Acid Frac	Acid Frac	Acid Frac	N/A	No	30
Well #3	Carbonate	8 $\frac{1}{2}$ "	5 $\frac{1}{2}$ "	15°	Unbalanced	Yes	Dual	3	Acid Frac	Acid Frac	Acid Frac	Acid Frac	N/A	No	20
Well #4	Carbonate	8 $\frac{1}{2}$ "	5 $\frac{1}{2}$ "	16°	Unbalanced	Yes	Dual	3	Acid Frac	Acid Frac	Acid Frac	Acid Frac	N/A	No	30
Well #5	Carbonate	8 $\frac{1}{2}$ "	5 $\frac{1}{2}$ "	22°	Unbalanced	Yes	Dual	4	Acid Frac	Acid Frac	Acid Frac	Acid Frac	Acid Frac	No	20
Well #6	Carbonate	8 $\frac{1}{2}$ "	5 $\frac{1}{2}$ "	10°	Unbalanced	Yes	Dual	3	Acid Frac	Acid Frac	Acid Matrix	Acid Matrix	N/A	Yes	15
Well #7	Sandstone	5 $\frac{1}{2}$ "	4 $\frac{1}{2}$ "	7°	Unbalanced	No	Single	2	Prop Frac	Prop Frac	Prop Frac	N/A	N/A	Yes	2
Well #8	Sandstone	5 $\frac{1}{2}$ "	4 $\frac{1}{2}$ "	90°	Unbalanced	Yes	Dual	4	Prop Frac	Prop Frac	Prop Frac	Prop Frac	Prop Frac	No	12
Well #9	Carbonate	5 $\frac{1}{2}$ "	4 $\frac{1}{2}$ "	65°	Unbalanced	No	Single	3	Acid Frac	Acid Matrix	Acid Matrix	N/A	N/A	Yes	12
Well #10	Carbonate	8 $\frac{1}{2}$ "	5 $\frac{1}{2}$ "	5°	Unbalanced	No	Single	3	Acid Frac	Acid Matrix	Acid Matrix	N/A	N/A	N/A	8
Well #11	Carbonate	5 $\frac{1}{2}$ "	5 $\frac{1}{2}$ "	24°	Unbalanced	Yes	Dual	3	Acid Frac	Acid Frac	Acid Matrix	Acid Matrix	N/A	Yes	15
Well #12	Carbonate	5 $\frac{1}{2}$ "	5 $\frac{1}{2}$ "	30°	Balanced	Yes	Dual	2	Acid Frac	Acid Matrix	N/A	N/A	N/A	Yes	10
Well #13	Sandstone	5 $\frac{1}{2}$ "	5 $\frac{1}{2}$ "	29°	Balanced	No	Single	4	Prop Frac	Prop Frac	N/A	N/A	N/A	N/A	2
Well #14	Carbonate	5 $\frac{1}{2}$ "	5 $\frac{1}{2}$ "	10°	Balanced	No	Single	3	Acid Frac	Acid Frac	Acid Matrix	Acid Matrix	N/A	No	10
Well #15	Carbonate	5 $\frac{1}{2}$ "	5 $\frac{1}{2}$ "	7°	Balanced	No	Single	3	Acid Frac	Acid Frac	Acid Matrix	Acid Matrix	N/A	No	2
Well #16	Carbonate	5 $\frac{1}{2}$ "	5 $\frac{1}{2}$ "	7°	Balanced	No	Single	2	Acid Frac	Acid Frac	Acid Matrix	N/A	N/A	Yes	N/A
Well #17	Carbonate	5 $\frac{1}{2}$ "	5 $\frac{1}{2}$ "	80°	Balanced	No	Single	3	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 1. Open hole multistage installations in Saudi Arabian gas reservoirs<sup>1</sup>

productivity increases based on well configuration and reservoir properties<sup>2</sup>. The productivity index ratio between horizontal and vertical wells, Fig. 1, and between fractured and open hole horizontal wells, Fig. 2, illustrates the expected improvement to be obtained from higher reservoir contact and hydraulic fracturing.

Treatment of horizontal wellbores by either matrix stimulation or hydraulic fracturing is required to remove damage caused during drilling and to penetrate deeper into the reservoir to increase the contact area. Pumping stimulation treatments into long horizontal intervals has not been as effective as expected. The treat-

	Net Pay (ft)	Well Radius (ft)	Well Length (ft)	Frac Half Length (ft)	Number of Fracs	Reservoir Contact (sq. ft)	Folds Increase in Contact Area
Vertical	100	0.24	100			154	1
Vertical Frac	100	0.24	100	200	1	80,000	520
Horizontal	100	0.24	2,000			3,076	20
Horizontal Frac (Longitudinal)	100	0.24	2,000	300	3	363,076	2,361
Horizontal Frac (Transverse)	100	0.24	2,000	200	8	643,076	4,181

Table 2. Reservoir contact achieved from different well types

ments typically end up going into the most permeable formation. If the most permeable zone is not gas producing, the treatment has little or no effect on production. Acid “washing” by jetting the formation has not resulted in long-term production improvement either. It became apparent that horizontal wellbores had to be segmented so that treatments could be applied to each segment and hydraulic fracturing, rather than near well stimulation, could be implemented. Many segmenting methods were attempted, including cementing a liner; perforating, treating and plugging the zone; and then moving up hole to stimulate subsequent intervals (“plug and perf” method). Most of the early isolation methods attempted were found to be either ineffective and risky, or prohibitively expensive and time consuming.

The open hole multistage system with mechanical packers was developed in 2001. Between 2001 and 2006, open hole multistage became the completion of choice for low permeability horizontal wells in North America. It is estimated that to date more than 8,000 open hole multistage fracturing (MSF) jobs have been performed worldwide. Several competitive products have been developed by various service companies.

Saudi Aramco, in an initiative to produce gas from its unconventional and tighter formations, has installed 17 open hole multistage systems since 2007 in carbonate and sandstone gas-producing formations<sup>1</sup>. The type of open hole multistage used depends on environment, reservoir quality and rate expectation<sup>3-6</sup>.

The open hole multistage system is deployed in an open hole environment<sup>3</sup>. As depicted in Fig. 3, the completion is designed such that it covers the entire open hole section; packers are placed to isolate individual intervals, fracturing ports are placed in between the packers, and the system is set with hydraulic forces, becoming robust and permanent.

With an open hole multistage system, fracturing is initiated from the toe of the lateral toward the heel, each time isolating the previously treated interval using a ball-drop mechanism. Usually a total flow back and cleanup is carried out after the stimulation of all stages.

The open hole multistage systems are deployed, and packers and ports are set, according to the reservoir development indicated by open hole log interpreta-

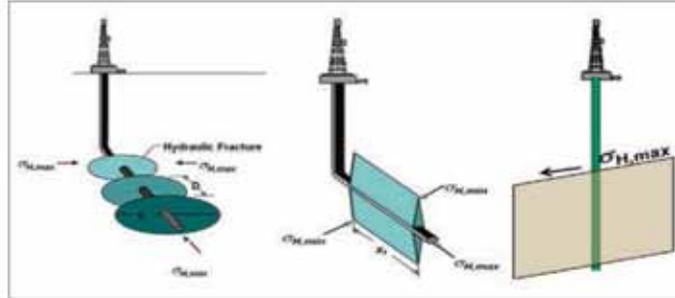


Fig. 4. Different wellbore configurations and fracture geometry showing reservoir wellbore connectivity.

tion. The objective from the reservoir standpoint is to segment the horizontal wellbores into several compartments and to conduct hydraulic fracturing treatments in each compartment. With the deployment of the 17 installations and the results obtained after the fracturing treatments, it has been possible to sort through and analyze the formation, reservoir, completion and production test data, and look for trends and correlations among the variables.

The open hole multistage systems deployed were provided by major service companies. Overall, the results have been good, but some specific conclusions can be drawn concerning the functional variations among the different completion installations. These evaluations have been based on the mechanics of the completion systems, operational aspects of deployment and results obtained after the treatment. This article will identify the variables, discuss the way these variables can impact production results and comment on best practices to improve success. Table 1 provides a summary of results to date from the installations placed in carbonates and sandstones in Saudi Arabia's gas fields.

The following is a comprehensive identification and discussion of the factors that influence the production performance of wells completed with the open hole multistage systems.

### Well Azimuth

It is preferred from the fracturing point of view (and therefore productivity) to drill the horizontal wellbore toward  $\sigma_{\min}$  so that transverse (or orthogonal) fractures are created by the hydraulic fracturing treatments<sup>1, 2</sup>. Figure 4 depicts longitudinal and transverse fracture geometries, showing the difference between the two configurations, and compares them with a single fracture created from a vertical well. In the case of transverse fractures, several fractures can be placed one beside the other, as they will basically remain independent of each other. In comparison, the number of longitudinal fractures created in a single lateral is limited, as the induced fracture from one interval risks growing and overlapping the zone next to it, particularly if the two adjacent intervals are not isolated with a tight barrier.

As seen in Table 2, the reservoir contact areas increase with the number of fractures, and horizontal wells surpass vertical wells. This provides an initial incentive to drill horizontal wells toward  $\sigma_{\min}$  and place as many fractures as needed and desired for long-term sustained productivity. Of course, a net present value calculation must be done to assess the economic aspect of the development project so as to select the optimal number of hydraulic fractures.

Wells drilled in the direction of maximum in-situ stress,

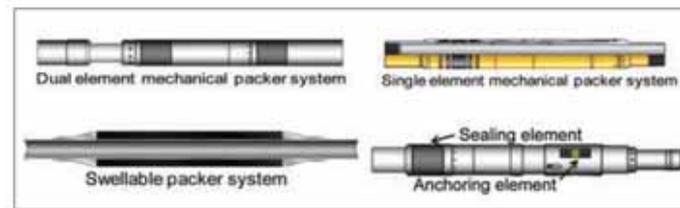


Fig. 5. Different packer types for open hole multistage assemblies.

$\sigma_{\max}$ , might require lower mud density to maintain a stable wellbore. These wells are less likely to intersect open natural fractures, if they exist. The hydraulic fractures created in such well types will be longitudinal. On the other hand, if wellbores are aligned toward  $\sigma_{\min}$ , higher mud weight may be required for wellbore stability while drilling. This configuration will allow the well to intersect more open natural fractures, but can generate high mud losses. Hydraulic fractures created in such a wellbore will be transverse.

Although the drilling process is challenging, the improved long-term sustained productivity achieved by open hole multistage completion and effective MSF treatment justifies drilling wells toward  $\sigma_{\min}$ .

### Formation Type

The following three different types of formation in Saudi Arabia are candidates for MSF treatments.

#### Moderate and High Permeability Carbonates

Wells completed with the open hole multistage system in some fractured reservoirs have shown positive results. Initial production has been higher than in wells completed traditionally, with either open hole or perforated liner systems. Post-fracture production decline has also generally been much slower and gentler.

#### Low Permeability Carbonates

Wells completed in such reservoirs have been somewhat challenging, as they require higher treating pressures to

initiate and propagate fractures. Nearly all wells drilled in such formations were drilled along or somewhat close to the natural fracture plane,  $\sigma_{\max}$ . Two wells were drilled perpendicular to the natural fracture plane (Well #10 and Well #17). Well #10 was inconclusive because of the mechanical failure of the hardware. In Well #17, the open hole multistage became differentially stuck and had to be set approximately 300 ft higher than planned. This resulted in undesirable fracture port locations and packer positions. Further intervention is required on this well to mitigate the problem.

#### Sandstone

Three wells have been completed with open hole multistage systems in relatively tight formations. Well #8 was drilled along the natural fracture plane, and Well #9 was drilled perpendicular to the natural fracture plane. Well #13 was drilled near vertical, at only 30° inclination. Production results from Well #8 and Well #13 were less than expected; however, an excellent production rate was achieved from Well #9. Each of the four stages on this well showed unique fracture signatures, confirming independent creation of fractures, while the other two wells did not have such a signature.

While fracturing the first stage, if a good fracture signature is seen from the pressure response but while treating the subsequent zone, and no unique pressure signature is identified, then the probability of the initial treatment breaking and propagating into the next zone becomes high. This indicates that the open hole pack-

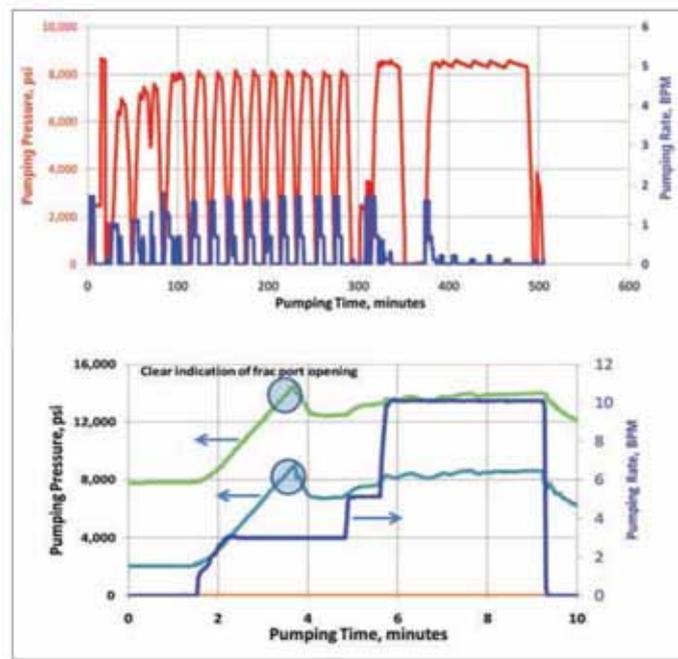


Fig. 6. The pressure response from two wells showing the fracturing port status after pressurizing the open hole multistage system

ers meant to isolate the neighboring intervals could not contain the pressure and were bypassed. In an unbalanced system, this can happen due to the piston effect exerted on the system during the treatment of the first stage.

### Types of Open Hole Multistage

Three primary types of open hole multistage systems are currently being installed in Saudi Arabia's gas wells, Fig. 5. The differences among the assemblies are important and need to be thoroughly understood to make the optimal selection choice and to conduct fracturing that will give the desired gas rates.

#### Packer Type and Deployment of the Assembly

One essential part of the open hole multistage assembly is the packer system. Two major types of packers are used; one type is the hydraulically operated mechanical packer, while the other type is the swellable elastomer packer (SEP) enabled by the presence of hy-

drocarbons. Once the open hole multistage system is deployed at its designed depth, the first type of packer is set with hydraulic pressure, while the second type requires some lag time and the presence of hydrocarbons before it is totally set in the reservoir. Of the mechanical packer systems, one offers two separate sealing elements (dual packer system), adjacent to each other and separated by 3 ft, while the other one only has a single element. The system with two sealing elements is obviously more robust; it provides more protection against high treating pressure and restrains fracture growth to the neighboring interval.

The SEP is activated when it comes into contact with hydrocarbons. Changing wellbore salinity, temperature, viscosity, acid or gas can affect seal performance and the wait time for the packer to expand, swell, and isolate the intended intervals<sup>7</sup>. The temperature drop that the SEP will experience has a significant impact on the performance of the packer system<sup>7</sup>. The anchoring

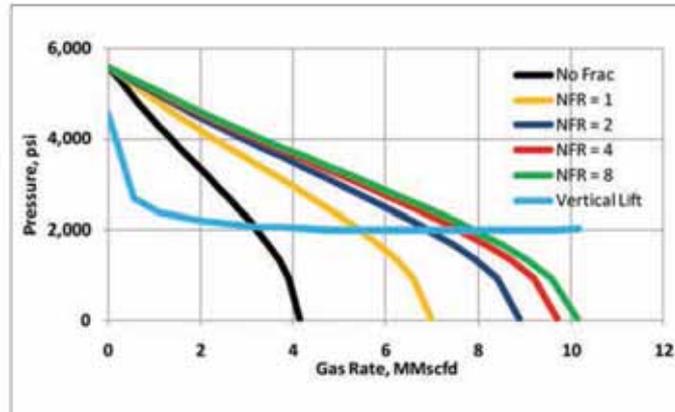


Fig. 7. The inflow performance shows an improved rate with induced fractures.

force of the SEPs must be larger than the forces acting on the SEP during a stimulation treatment. The differential pressures that the packers can withstand also vary, but in general the mechanical packers are much stronger and offer higher resistance.

The mechanical packers are short in length, which adds to flexibility in deployment, and they can be easily run in moderate dogleg severity wells (up to 30°/100 ft). The outside diameters are not greater than those of standard completion equipment, which is also a positive side of the system. In contrast, the SEP is much longer and has an outside diameter larger than that of standard completion equipment. This combination makes the SEP system more difficult to deploy.

### Anchor System

Incorporation of an open hole anchor mechanism into the open hole multistage assembly is essential for stability and packer integrity, Fig. 5. The open hole anchor is placed at the bottom of the assembly and is set at the same time as the open hole packers. Significant forces

are placed on the open hole multistage assembly during fracturing operations, depending on in-situ stress and geomechanical properties, and also as temperature decreases when cooler fluids are pumped. The effect of temperature change alone, as cooler fluids are pumped from the surface and contact the open hole multistage assembly at the formation, can cause high tensile loads due to shrinkage of the liner. If the open hole multistage assembly moves after the packers are set, the packer elements will encounter traction or elongation, damage will occur, and packer sealing capability will be severely compromised. The piston type movement that often occurs during fracturing operations can be resisted by the anchor mechanism. For this reason it is highly recommended that an anchor mechanism be part of the completion system.

### First Stage Balanced vs. Unbalanced

There are two possible configurations for the lowermost fracturing port. This port can be placed above the lowermost packer or it can be placed below this packer. If the first stage fracturing port is above the lowermost

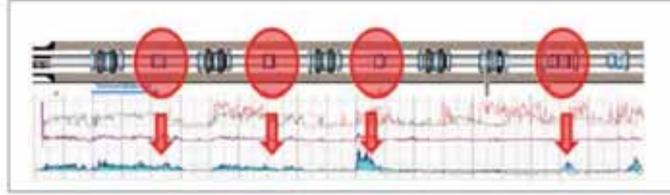


Fig. 8. Example of an open hole multistage assembly in sandstone.

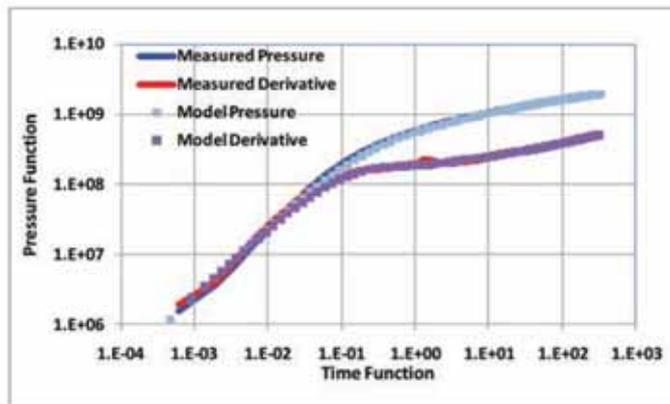


Fig. 9. Pressure test of Well SD-1.

packer, the configuration is called “balanced.” As fracturing pressure is pumped through this fracturing port, equal hydraulic forces are applied to the packers above and below. These equal forces cancel each other out, and there is no net force trying to move the open hole multistage system.

If the first stage fracturing port is below the lowermost packer, the configuration is called “unbalanced.” This is because when stimulation fluids are pumped through this fracturing port, hydraulic forces are applied only to the packer above. This force will try to “piston” the open hole multistage system upwards. If this piston force is greater than the anchoring force, the open hole multistage system will be shifted, and the packer seals

will be compromised. Based on an analysis and field results of the open hole multistage system, it has been determined that all open hole multistage systems installed in all formation types should be balanced.

#### Sleeve Dimension

All service companies use ball activated fracturing sleeves to open access to different stages. The different increment diameters of the ball sizes consist of 1/2”, 1/4” and 1/8” increments. With smaller increments, the overall ball seat size can be maintained higher, thereby providing better access and communication after the treatment when balls are flowed back. The open hole MSF sleeves in some cases can be reclosed only after the ball seats have been milled out. The option of re-

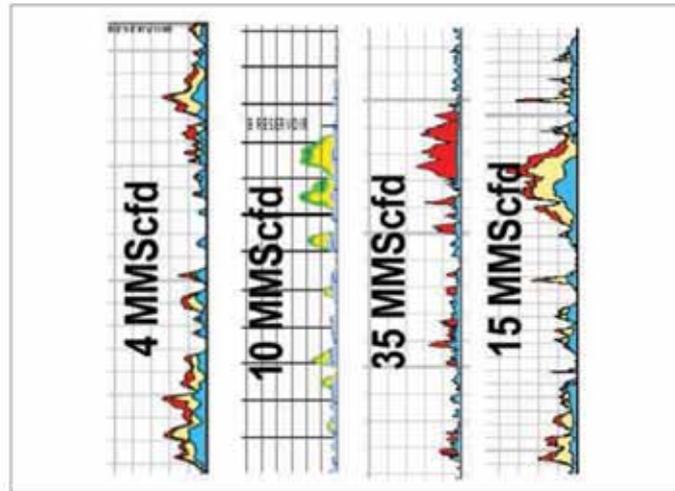


Fig. 10. Example of a heterogeneous carbonate reservoir.

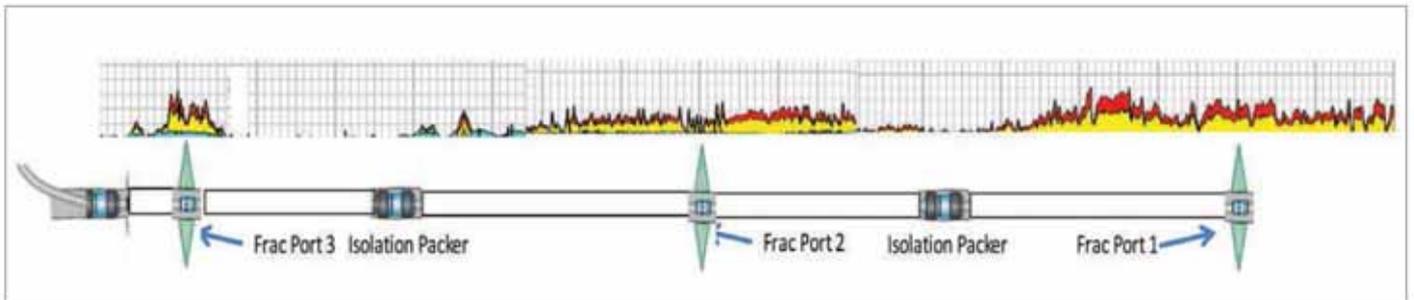


Fig. 11. Example of an open hole multistage assembly in a carbonate reservoir.

closing the fracturing sleeves with the ball seats in place is a better and preferred option, as the risk of intervention in such a case is avoided.

### Pressure Rating

So far, all of the open hole multistage systems run in Saudi Aramco's deep gas wells have been rated to a maximum of 10,000 psi of pressure. For most carbonate reservoirs, this rating is sufficient, as breakdown and stimulation pressures typically reach a maximum of only 8,500 psi, which is within the "comfort" zone for this equipment. For some lower permeability carbonate wells, however, pressures near 10,000 psi are required to break down these zones.

Few wells have been completed with the open hole multistage systems in sandstone reservoirs, though one well in particular has tested at a high gas rate. The sandstone wells require proppant fracturing. Although the stimulation and treatment pressures observed on these initial wells were within the 10,000 psi ratings for this equipment, the bottom-hole pressure (BHP) in tighter formations is anticipated to be in a higher range. With proppant fracturing, there is always a risk of screen-out while pumping high viscosity fracturing fluids at very high rates and pressures. If a premature screen-out occurs, the BHP can exceed the maximum equipment rating due to a sudden loss of friction pressure while surface and hydrostatic pressures are at their

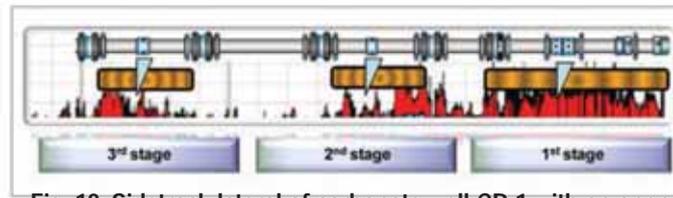


Fig. 12. Sidetrack lateral of carbonate well CR-1 with an open hole multistage assembly. 19 1,000 1

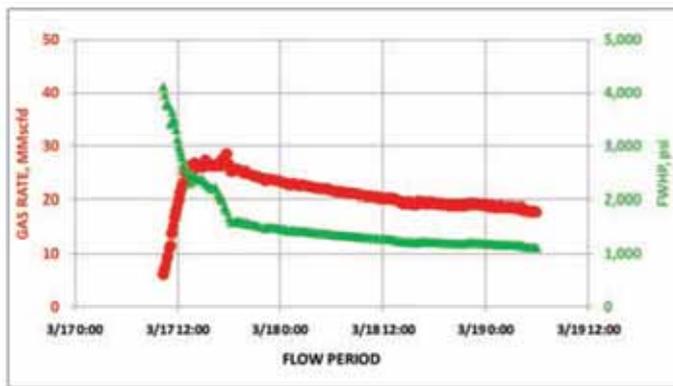


Fig. 13. Gas rate after the Stage 1 fracture treatment.

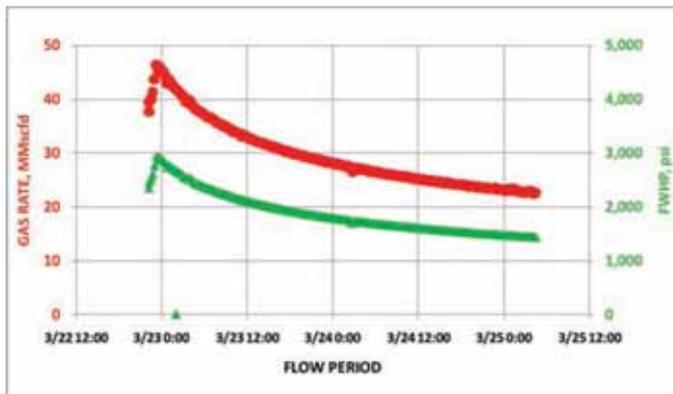


Fig. 14. Combined gas rate after the Stage 2 matrix acid.

maximum. Saudi Aramco is currently exploring the use of 15,000 psi equipment to get the pressures required for breakdown and stimulation without being limited by a lower maximum pressure.

**Ease of Opening of Hydraulic Fracturing Port**

The first port is opened hydraulically by pressurizing the open hole multistage system. It is very important that the opening of this port be smooth and trouble

free. As part of normal practice, a well, after being completed with the open hole multistage system, is left for a certain period of time before fracture treatment. Depending on the situation and schedule, the fracture ports may be exposed to the completion fluids for a very long time. The ports must be tested to determine their ability to withstand the completion fluids, temperature and bottom-hole environment. A rigorous quality control process must be carried out to ensure

“ The ports must be tested to determine their ability to withstand the completion fluids, temperature and bottom-hole environment.”

the smooth actuation and positive functioning of the system.

A dual sleeve hydraulic fracturing device is preferable. Since the opening of this device is essential to the operation of the open hole multistage system, a second independent sleeve is incorporated into the design. There have been no incidents where a dual sleeve hydraulic fracturing device has failed to open.

The two pressure responses, Fig. 6, indicating if a port has opened or not can be measured by analyzing the pressure decline after pumping. The pressure response (decline) must be separated from the decline that occurs as the system is bled off. The plot on the top shows that the pressure in the wellbore is maintained as injection is conducted. Even when the injection rate is dropped to zero (the last stage, starting at ~380 minutes), the pressure (red color line) continues to stay the same. This clearly shows that the fracture port has not been opened. This is different from the example shown in the bottom where, with an injection rate (blue curve) of 3 barrels per minute (bpm) around 3.5 minutes into pumping, the pressure suddenly drops, indicating the opening of the fracturing port.

### Open Hole Size

Deep gas open hole multistage systems have been deployed in two different hole and completion sizes: a 57/8" open hole with a 41/2" liner, and a 83/8" open hole with a 51/2" liner.

The installations in the 83/8" open hole were generally much higher producing wells – most likely resulting from the greater initial contact area with the wellbore. But this greater productivity can also be related to better reservoir quality. Not enough information is currently available to arrive at a firm conclusion. For horizontal wells with open hole multistage completions and MSF treatment, the size of the open hole should not be a factor as open hole contact area is negligible compared to the fracture area.

### Number of Stages/Size of Stages

Depending upon reservoir properties, contact length and well configuration, an increased number of stages will add to production as shown earlier in Table 2. The economics, however, have to be worked out because every additional treatment will have an incremental cost. Figure 7 shows the inflow performance relationship curve for an example case, where a 2,000

“... this indicates that a greater number of shorter intervals and more concentrated stages will increase the contact area across the entire open hole section.”

ft lateral wellbore has been placed horizontally in an interval of 10 md-ft. For a flowing wellhead pressure (FWHP) of 1,500 psi, the plot clearly shows the benefit of additional fractures (NFR stands for “number of induced fractures”). A 50% to 60% improved productivity can be attained if the number of induced fractures is increased from one to eight.

The number of stages in Saudi Aramco’s gas wells has typically ranged from two to four. This is because most of the wells are aligned with the  $\sigma_{\max}$ , thereby restricting the number of independent fractures that can be realistically induced. Production was greater where the wellbores were separated into an increased number of shorter intervals. In general, this indicates that a greater number of shorter intervals and more concentrated stages will increase the contact area across the entire open hole section.

Stage lengths have varied from 200 ft to 1,000 ft. In one installation (not yet stimulated), packers were

placed immediately below and above the production intervals determined from the open hole logs. Non-productive sections, as indicated by the open hole logs, were “blanked” off so that stimulation treatments were not pumped in non-reservoir intervals. The other purpose for these additional packers is to create space between fracture treatments in case longitudinal fractures are propagated.

### Flowback Between Stages

Typically, MSF operations focus a great deal on the efficiency of the pumping treatment. All stages are stimulated sequentially, and at the end of the fracturing operations, all zones are flowed back simultaneously, commingling the flow from all compartments. This is how the first MSF operations were completed in Saudi Arabia, and on all successfully deployed operations, the treatments showed very good production performance; however, with the goal of evaluating the performance of the individual segments, it was decided to attempt flow back of each stage immediately following the

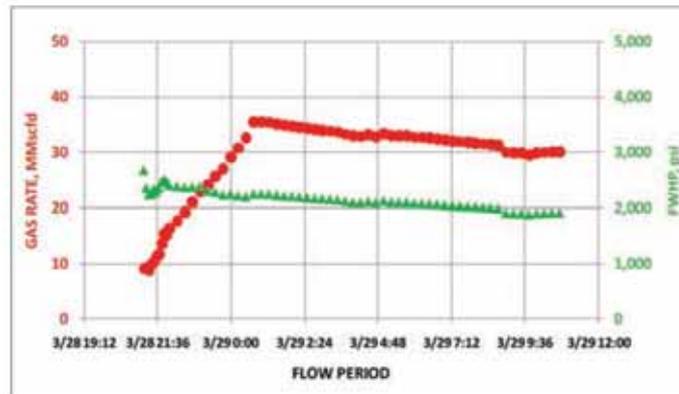


Fig. 15. Combined gas rate after the Stage 3 matrix acid.

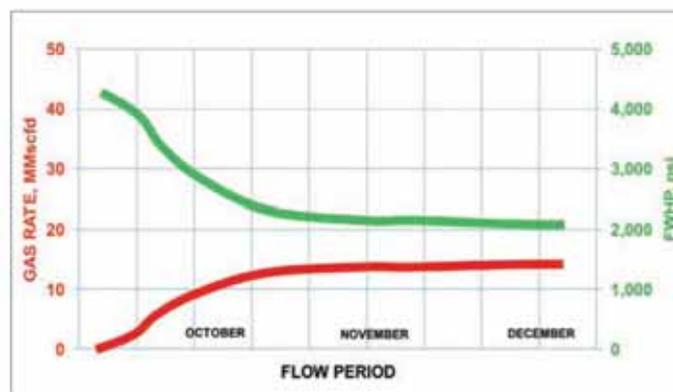


Fig. 16. Long-term production profile shows a stabilized rate

Gas Rate, MMscfd	FWHP, psi	Stages
19	1,000	1
22	1,300	1+2
30	1,900	1+2+3
30	1,900	All/Stabilized

Table 3. Stages 1, 2 and 3 cumulative performances

fracturing treatment. The previously fractured (lower) stages would remain open, and as upper stages were fractured, the flow would be cumulative. The first flow back would clearly show the first stage treatment performance, and subsequent incremental production could then be ascertained. For example, if after the post first stage, production was measured to be 5 million standard cubic feet per day (MMscfd), and

then the combined production of flow back from the first and second stage was measured at 12 MMscfd, the assumption was that the second stage contributed 7 MMscfd to the overall production.

This idea works well in theory, but in practice the results were not always conclusive. Stage 1 flow back from Well #6 was very good, and the measured rate

“Most of the tight Khuff reservoirs are now completed horizontally with open hole multistage, and multiple fractures are induced for improved recovery.”

was 15 MMscfd. Following the opening of the Stage 2 port, the injection pressure was much lower than expected. It was concluded that the fluid being pumped into Stage 2 was most likely reentering the initial fracture created from Stage 1. This led to the on-site decision to discontinue the fracturing for Stage 2 and instead pump a matrix acid treatment using diverters into the newly opened stage. After flow back of Stage 2, some incremental production was observed, with an approximately 18 MMscfd total combined flow rate, and therefore a Stage 2 contribution of 3 MMscfd was estimated. This was much lower than what was expected from this zone. After some discussion and analysis of the post-job data, there was a consensus of opinion that after flowing back the initial stage, the reservoir went from a highly positive charged zone where a large amount of fluid had been pumped, pressurizing the formation, to a negatively charged zone that had become drawn down and under pressured. As a consequence, the in-situ stresses decreased in this interval. Therefore, when the Stage 2 port was opened, the fluid followed the path of least resistance, the majority of the treatment was pumped into the lesser charged initial

fracture of Stage 1. The fiber diversion system used in the matrix treatment for Stage 2 helped to divert some of this flow away from the Stage 1 fracture; however, it would not initiate new fractured sections, and therefore the production target could not be achieved.

### Reservoir Quality

Two main treatment types are currently being conducted in tight gas reservoirs – proppant fracturing in sandstones and acid fracturing in carbonates. Due to the highly vertical heterogeneous nature of the formation and its relatively low permeability, the development plan required: (1) drilling of horizontal wells, and (2) conduct of an MSF operation.

### Example Well SD-1

An example well (SD-1) drilled in the direction  $\sigma_{\min}$  is illustrated in Fig. 8. The azimuth of the well was optimal, as the vertical fractures generated by hydraulic forces would be transverse. The well encountered about 1,400 ft of net pay thickness with moderate porosity. The open hole log confirmed that the reservoir is tight and highly heterogeneous; a permeability-thickness

product kh for the well of about 10 md-ft was initially calculated, which falls within the tight sand category. Based on the open hole log, four stage fracturing was designed, and the open hole multistage system was deployed with fracturing ports placed next to the somewhat better developed porosity sections, as indicated in the figure. The treatment went well and about 650,000 lbs of proppant was successfully pumped in four stages. The well was cleaned up, and an initial rate of about 18 MMscfd was achieved at 2,000 psi FWHP. The post-treatment deliverability test indicated, for  $kh=10$  md-ft, a combined fracture length of about 700 ft and fracture conductivity of 700 md-ft, indicating a successfully designed and implemented fracture treatment, Fig. 9.

Figure 10 demonstrates the heterogeneity in the Khuff carbonate reservoir. Within a small spacing, well properties can vary significantly, as shown by the production response from the four wells presented in this figure. As such, drilling horizontal wells to intersect more reservoir area and further improving contact through MSF are important to tap the full potential of a well. Most of the tight Khuff reservoirs are now completed horizontally with open hole multistage, and multiple fractures are induced for improved recovery. An example of a multistage completion in a carbonate reservoir, Fig. 11 shows the placement of three fracturing ports in the developed reservoir sections. The open hole isolation packers are located in the non-reservoir sections, where good hole conditions have been identified.

### Treatments Pumped in Saudi Arabian Gas Reservoirs

Typical acid fracturing treatments in carbonate formations involve pumping the treatment fluids in several phases. The initial treatment begins with a pad stage to extend the hydraulic fracture length. Then acid is pumped, using 28% hydrochloric acid to etch the fracture surface, create wormholes and hold the fracture open.

In the cases previously mentioned, where the fracture treatment was pumped into a new stage and communication between this and the previous stage was observed, the subsequent stage was designed as a matrix acid treatment. In this new design, to avoid pumping too much fluid into the previous interval, a diversion

fluid system was used so as to increase the chances of treating the new interval. When the fiber-laden viscoelastic system acid reaches a formation, it viscosifies and temporarily restricts the flow into the treated interval. Acid can then be diverted into the new section. Polymer based pad and buffer stages can typically be omitted in this remedial treatment design.

### Example Well CR-1

A sidetrack of Well CR-1 achieved a net pay of 1,600 ft, Fig. 12, and open hole multistage equipment was successfully installed for treating the entire interval in three stages. The well was cleaned up after stimulating each stage to estimate the potential of the stimulated interval. Figures 13 to 15 and Table 3 present the production from Stage 1 (acid fractured), Stage 1 and Stage 2 combined (Stage 2 matrix acid), and all stages combined (Stage 3 matrix acid). A stabilized flow of 20 MMscfd was achieved, shown in the long-term production profile of the well, Fig. 16, indicating a very successful MSF treatment. In proppant fracturing treatments for sandstone formations, the initial approach was to begin fairly conservatively in terms of the proppant size, loading, and total proppant mass to reduce the probability of screen-out. A tapered design was pumped, where finer 30/50 mesh proppant is used for the initial stages, followed by coarser 20/40 mesh proppant as a tail-in to help add fracture width and conductivity in the near wellbore area.

### Conclusions and Recommendations

1. Wells completed with an appropriate open hole multistage system and properly stimulated are better producers than offset wells that are completed with conventional systems.
2. Optimal results are achieved when wells are drilled in the direction of  $\sigma_{\min}$  (perpendicular to the natural fracture plane,  $\sigma_{\max}$ ), completed with an open hole multistage assembly and subsequently stimulated with MSF. These wells provide the best improved gas rate and recovery.
3. Wells that are drilled in the direction of  $\sigma_{\max}$  (parallel to the natural fracture plane), completed with an open hole multistage system and stimulated with MSF still provide superior production and gentler rate decline compared to open hole completions.

SEPs are usually not recommended for stimulation treatments, as high differential pressure and a change in temperature may affect the sealing performance of the system.

4. Wells completed with dual element packers have superior integrity to withstand fracturing pressure.

5. Proper care should be taken to place and set the packer assembly in a good gauged hole interval.

6. SEPs are usually not recommended for stimulation treatments, as high differential pressure and a change in temperature may affect the sealing performance of the system.

7. An open hole anchor mechanism is essential to prevent movement of the open hole multistage system during fracturing treatments.

8. The balanced open hole multistage system provides more stability by counteracting piston effects during fracturing and is highly recommended.

9. Smaller increments between fracturing port ball seat sizes (recommended size: 1/4" or less) enable a larger internal diameter to be maintained in the com-

pletion, thereby allowing for coiled tubing access if required.

10. Open hole multistage systems with dual hydraulic sleeves open reliably even after prolonged exposure to completion fluids at reservoir temperature.

11. An increased number of fracture stages provides optimum production. Net present value calculations should be done to determine the optimal number of fractures.

12. The use of additional packers spaced at a minimum of three joints (120 ft) apart in carbonates is beneficial to minimize the potential for longitudinal fracture breakthrough and to blank off nonproductive intervals.

13. For long horizontal intervals, there is a need for segmenting and completing the well with the open hole multistage assembly to ensure effective stimulation treatment in all portions of the reservoir. There is

an even greater need for open hole multistage and MSF in tighter, heterogeneous formations.

## Nomenclature

$J_h$	Horizontal well productivity index
$J_v$	Vertical well productivity index
$J_{hf}$	Fractured horizontal well productivity index
$k_v$	Vertical permeability
$k_h$	Horizontal permeability
$kh$	Permeability thickness product, md
NFR	Number of transverse fractures
$X_f$	Fracture half-length
$\sigma_{max}$	Maximum in-situ stress
$\sigma_{min}$	Minimum in-situ stress

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## Biographies



Dr. Zillur Rahim is a Petroleum Engineering Consultant with Saudi Aramco's Gas Reservoir Management Division. His expertise includes well stimulation design, analysis and optimization, pressure transient test analysis, gas field development, planning and reservoir management. Prior to joining Saudi Aramco, Rahim worked as a Senior Reservoir Engineer with Holditch & Associates, Inc., and later with Schlumberger Reservoir Technologies in College Station, TX. He has taught petroleum engineering industry courses and has developed analytical and numerical models to history match and forecast production and well testing data, and to simulate 3D hydraulic fracture propagation, proppant transport, and acid reaction and penetration. Rahim has authored 50 Society of Petroleum Engineers (SPE) papers and numerous in-house technical documents. He is a member of SPE and a technical editor for the Journal of Petroleum Science and Engineering (JPSE). Rahim is a registered Professional Engineer in the State of Texas and a mentor for Saudi Aramco's Technologist Development Program (TDP). He is an instructor for the Reservoir Stimulation and Hydraulic Fracturing course for the Upstream Professional Development Center (UPDC) of Saudi Aramco. Rahim received his B.S. degree from the Institut Algerien du Petrole, Boumerdes, Algeria, and his M.S. and Ph.D. degrees from Texas A&M University, College Station, TX, all in Petroleum Engineering.



Adnan A. Al-Kanaan is the General Supervisor for the Gas Reservoir Management Division, where he heads a team of more than 30 petroleum engineering professionals working to meet the Kingdom's increasing gas demand for its internal consumption. He started his career at the Saudi Shell Petrochemical Company as a Senior Process Engineer. Adnan then joined Saudi

Aramco in 1997 and was an integral part of the technical team responsible for the on-time initiation of the two major Hawiyah and Haradh Gas Plants that currently process billion cubic feet (BCF) of gas per day. He also manages Karan and Wasit, the two giant offshore gas increment projects, with expected total production capacity of 5.5 BCF of gas per day. Adnan has 13 years of diversified experience in reservoir management, field development, reserves assessment, gas production engineering and mentoring young professionals. His areas of interest include reservoir engineering, well test analysis, reservoir characterization and reservoir development planning. Adnan received his B.S. degree in Chemical Engineering from King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia. He is a member of the Society of Petroleum Engineers (SPE).



Bryan Johnston is the Business Development Coordinator for Packers Plus serving the Middle East Gulf countries. He has worked in the oil services industry for 20 years in operational, technical and marketing positions and is experienced in cementing, stimulation and downhole tools. Bryan worked for Dowell Schlumberger as a Field Engineer, then as a Operations Supervisor and District Manager. He worked with McAllister Petroleum Services, the manufacturer of inflatable packer products, as Marketing Manager. When that company was acquired by Weatherford Bryan worked in sales and business development positions within Weatherford before joining Packers Plus in 2006. He received his technical diploma from the British Columbia Institute of Technology, Burnaby, British Columbia, Canada, and an MBA degree from the University of British Columbia, Vancouver, British Columbia, Canada. Bryan is a coauthor on several papers on multistage stimulation in the Gulf Region and he is a member of the Society of Petroleum Engineers (SPE).



Stuart Wilson is a Stage FRAC Manager for Schlumberger Well Services in 'Udhailiyah, Saudi Arabia, responsible for the marketing and technical development of the company's multistage fracturing completion business

throughout Saudi Arabia and the Middle East region. After earning his B.Eng. degree in Mechanical Engineering from the University of Hertfordshire, Hertfordshire, England, and his M.Eng. degree in Business and Operations Management from the Norwegian Institute of Technology, Trondheim, Norway in 1997, Stuart joined Schlumberger as a Field Engineer in Stavanger. He worked 5 years in various technical and operational positions in Norway and Denmark. From 2002 until 2005, Stuart served as the worldwide product champion for the Schlumberger coiled tubing (CT) inflatable packer business. In late 2005, he became the GeoMarket Technical Engineer in Moscow, covering CT operations in the Russia area. In 2006 until late 2007, Stuart worked as the CT Operations Manager for the Far East-Russia GeoMarket region in the Sakhalin area, working on several projects, including Lunskeye. From 2008 until taking his current post in 2009, he served as the multistage fracturing completion product champion based in Dubai, U.A.E., covering the Middle East and Far East regions. Stuart is the author of several papers on multistage fracturing, inflatable packers, and CT offshore technology. In 2003, he was named a World Oil New Horizons award finalist. Stuart is a member of the Society of Petroleum Engineers (SPE).



Dr. Hamoud A. Al-Anazi is a Supervisor in the Gas Reservoir Management Division in the Southern Area Reservoir Management Department. His areas of interests include studies on formation damage, fluid flow in

porous media and gas condensate reservoirs. Hamoud has published more than 38 papers in local/interna-

tional conferences and refereed journals. He is an active member of the Society of Petroleum Engineers (SPE) where he serves on several committees for SPE technical conferences. In 1994, Hamoud received his B.S. degree in Chemical Engineering from King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia, and in 1999 and 2003, respectively, he received his M.S. and Ph.D. degrees in Petroleum Engineering, both from the University of Texas at Austin, Austin, TX.



Daniel Kalinin is the Schlumberger Reservoir Stimulation Domain Manager based in al-Khobar, Saudi Arabia. He is responsible for the integration of Schlumberger expertise in reservoir evaluation and characteriza-

tion into fracturing and stimulation in Saudi Arabia, Bahrain and Kuwait. Before coming to Saudi Arabia in 2009, Daniel was involved in G&G support of the Chicontepec integrated well construction project in Mexico, carbonate stimulation in Kazakhstan, and development of a stimulation activity in Turkmenistan and Uzbekistan. He took part in the start of the fracturing boom in Russia in the late 1990s. Before joining Schlumberger in 1999, he worked for a joint venture of Canadian Fracmaster in Western Siberia, working his way up from field testing to Engineering Superintendent. Daniel received his B.S. degree in Structural Geology from Novosibirsk State University, Novosibirsk, Russia, in 1993, and another degree in Economics from Tomsk State University of Architecture and Construction, Tomsk, Russia. He also attended various post-grad programs at the University of Tulsa, Tulsa, OK, and the Imperial College, London, U.K.

# Evaluation of Multistage Fracturing Completion Technologies as Deployed in the Southern Area Gas Fields of Saudi Arabia

By Mohammed A. Al-Ghazal, Abdulaziz M. Al-Sagr and Saad M. Al-Driweesh.

Due to the increasing demand for oil and gas resources to support worldwide development plans, our industry is always actively engaged in exploring new frontiers in drilling and production, including tight multilayered reservoirs. It is becoming evident more than ever that producing the most oil and gas out of the drilled reservoirs is a must. Accordingly, completion techniques have emerged as a crucial well construction parameter and a key to successfully producing wells.

Several completion techniques have been exhaustively tested in Saudi Aramco to determine the most

successful completion mode for each reservoir. Of those various techniques, open hole multistage fracturing (MSF) has demonstrated superior performance in minimizing skin damage and maximizing reservoir contact through efficient propagation of fracture networks within the rock matrix.

Overall, the production results from wells completed using open hole MSF systems – as deployed in the Southern Area gas fields – have been very positive. Of the 15 wells where this new technology was utilized, the majority of the wells have met or exceeded the pre-stimulation expectations for gas production. Various

Completion Equipment Supplier	Supplier A									Supplier B				Supplier C	
Well Name	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7	Well 8	Well 9	Well 10	Well 11	Well 12	Well 13	Well 14	Well 15
Completion Date	Jun 2007	Nov 2007	July 2009	Sep 2009	Nov 2009	Dec 2009	Feb 2010	Apr 2010	Jun 2010	Dec 2009	Mar 2010	May 2010	Sep 2010	Oct 2010	Apr 2010
Target Production	30 MM	15 MM	10 MM	15 MM	18 MM	10 MM	10 MM	10 MM	10 MM	15 MM	15 MM	Unable to	10 MM	8 MM	10 MM
Stabilized Gas Production	63 MM	66.1 MM	21.5 MM	54.4 MM	35.2 MM	18.7 MM	17.6 MM	20.25 MM	12 MM*	1.6 MM	2.2 MM	open	11.8 MM	3.6 MM	2.6 MM
Difference	33 MM	51.1 MM	11.5 MM	39.4 MM	17.2 MM	8.7 MM	7.6 MM	10.25 MM	2 MM	-13.4 MM	-12.8 MM	Sleeve	1.8 MM	-4.4 MM	-7.4 MM
Pressure sufficient for hook-up to the production line	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No	No

Table 1. A comparison of all 15 operations completed to date between the three MSF completion technology suppliers

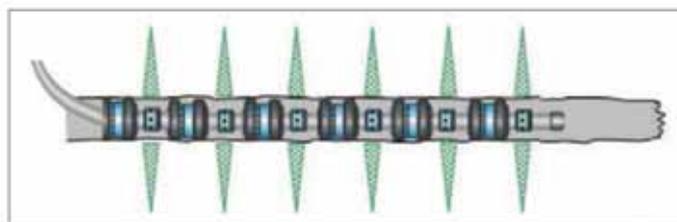


Fig. 1. An unbalanced system with the hydraulic frac port (Stage 1) at the bottom of the lower completion

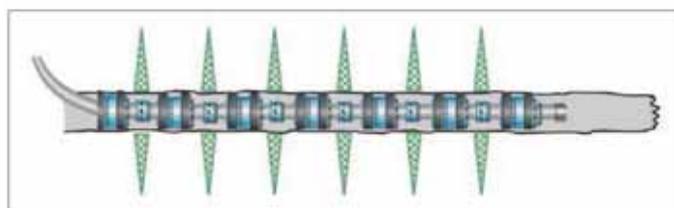


Fig. 2. A balanced system with the hydraulic frac port (Stage 1) between two packers.

multistage open hole completion systems were run over these 15 wells and the production results were varied. This article highlights these systems and discusses their impact on the fracturing operation and the final stabilized well production.

This article presents some case studies of MSF operations and investigates their operational impact on productivity enhancement. Following the lessons learned and best practices derived from these experiences, the findings from this article with correct implementation, should increase the probability of conducting a successful MSF job and achieving improved productivity.

While well trajectory and reservoir characteristics are important determinants of well productivity, completion design also plays a significant role in long-term stabilized production and reservoir draining efficiency. Hydraulic fracturing is required for increased oil and gas recovery. Effective wellbore compartmentalization by means of open hole packers – especially in low and nonuniform permeability reservoirs – is key to success-

ful multistage fracturing (MSF) operations. It is therefore important to describe and compare the modes of operation of and the effects of the various downhole conditions on the main open hole packer designs available to our industry today.

Since the beginning of 2007, a total of 15 wells in Saudi Aramco's Southern Area gas fields have been completed with open hole MSF systems. Target formations have spanned Khuff B and C carbonates and pre-Khuff (Unayzah) clastics. Drilling has included both 8<sup>3</sup>/<sub>8</sub>" and 5<sup>7</sup>/<sub>8</sub>" hole sizes and up to four stages per well. Table 1 provides a comparison for all 15 operations completed to date between the three completion technology suppliers.

Out of the 15 wells:

- Ten wells (67%) have exceeded the gas rate target production.
- Eight wells (53%) have exceeded the target rates with enough flowing wellhead pressure (FWHP) to connect directly to the trunk line.



Fig. 3. Inflatable packer element.

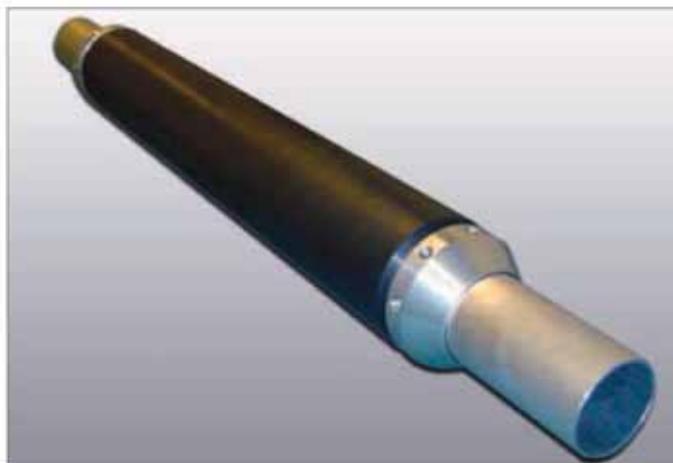


Fig. 4. Swellable packer element.

- Two wells (13%) have exceeded the target gas rates, but could not be connected to a trunk line due to insufficient FWHP.
- Five wells (47%) did not meet the expected post-stimulation target gas rates.

Along with these statistics, it should also be noted that out of the 10 wells that exceeded the target production rate, nine wells (90%) were completed using Supplier A and one well (10%) was completed using Supplier B. Out of the eight wells that could be hooked up to the production pipeline, all of them (100%) were completed using Supplier A.

An unbalanced MSF completion design means that the lowest stage in the completion is open at the bottom to allow fracturing out of the toe section of the system, Fig. 1. In contrast a balanced system is where the Stage 1 stimulation zone is between two packers, Fig. 2.

#### **Comparison of the Open Hole Packers**

*Inflatable Packers.* Sometimes referred to as external casing packers (ECPs), these are normally constructed of base pipe similar to the completion casing/liner/tubing, Fig. 3. The construction allows the packer element to be mechanically fixed to the outer diameter (OD) of the base pipe at both ends, leaving an annulus between the OD and element's internal diameter (ID). The base



Fig. 5. Mechanical dual seal packer.



Fig. 6. Mechanical single seal packer.

pipe would normally have a valve system that opens at a predetermined pressure to allow tubing fluid to fill that annulus and “inflate” the element. The valve system would then trip closed at another predetermined “higher” pressure to lock the fluid inside the element and retain the post-inflation element dimensions, sealing the packer against the wellbore. Inherent design limitations (very low differential pressure capabilities) of these packers have discounted their use in MSF applications.

*Swellable Packers.* Sometimes referred to as swellable element packers (SEPs) and/or reactive element packers (REPs), Fig. 4, these are constructed of a base pipe similar to the completion liner/tubing, then specific rubber is molded, thermally cured and glued to the base pipe. Sometimes backup rings are integrated into the design to keep the rubber element in place. Swellable packers are usually 10 ft to 30 ft long and constructed

with 80 to 90 durometer hardness rubber.

Significant upfront design and planning is required so that the proper packer is selected for each operation (job specific design). Three factors dictate the down-hole performance of swellable packers:

- Bottom-hole temperature (Most determinant factor, as temperature variations could be crucial).
- Wellbore fluids (completion, stimulation and production).
- Ratio of base pipe OD to wellbore ID.

Significant pre-job data should be collected for each well hole section of the well. Once the necessary information is gathered, planners can estimate the packer dimensions (base pipe OD and element thickness) as well as the swell period required to achieve the desired pressure rating. As soon as the element comes in

Well Number	Results for Hydraulic Frac Port Opening	Mud Used	Tree Saver Used	CT Used
Well #1	Immediately opened as planned	Formate	No	No
Well #2	Immediately opened as planned	Formate	No	No
Well #3	Immediately opened as planned	Formate	No	No
Well #4	Immediately opened as planned	Formate	No	No
Well #5	Immediately opened as planned	Formate	No	No
Well #6	Opened after 1 day pressure cycling due to barite mud	Barite	No	Yes
Well #7	Immediately opened as planned	Formate	No	No
Well #8	Immediately opened as planned	Formate	No <td No	
Well #9	Immediately opened as planned	Formate	No	No
Well #10	Opened after 2 days pressure cycling	Formate	Yes	Yes
Well #11	Opened after 3 days pressure cycling	Formate	Yes	Yes
Well #12	Unable to open after 3 days pressure cycling	Formate	Yes	Yes
Well #13	Opened during drilling phase of the operation	Formate	Yes	No
Well #14	Opened during drilling phase of the operation	Formate	Yes	No
Well #15	Unable to open - Abrasi jetting required	Formate	Yes	Yes

Table 2. Summary showing the history of the hydraulic frac port openings on all MSF operations

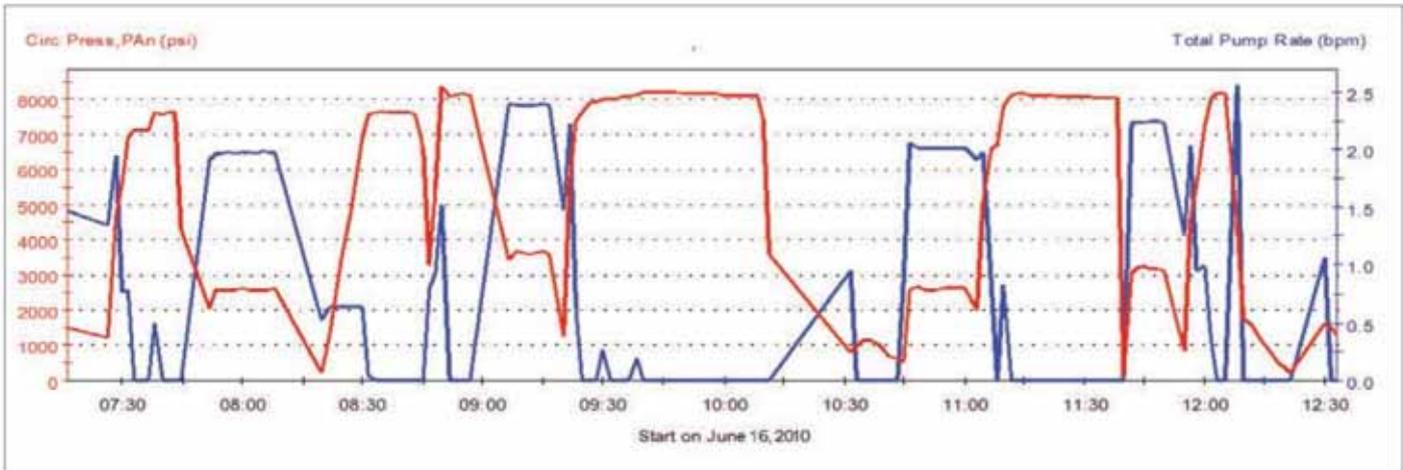


Fig. 7. Well #10 cycling with CT attempted six times to open the first port. The maximum wellhead pressure reached was approximately 7,474 psi.

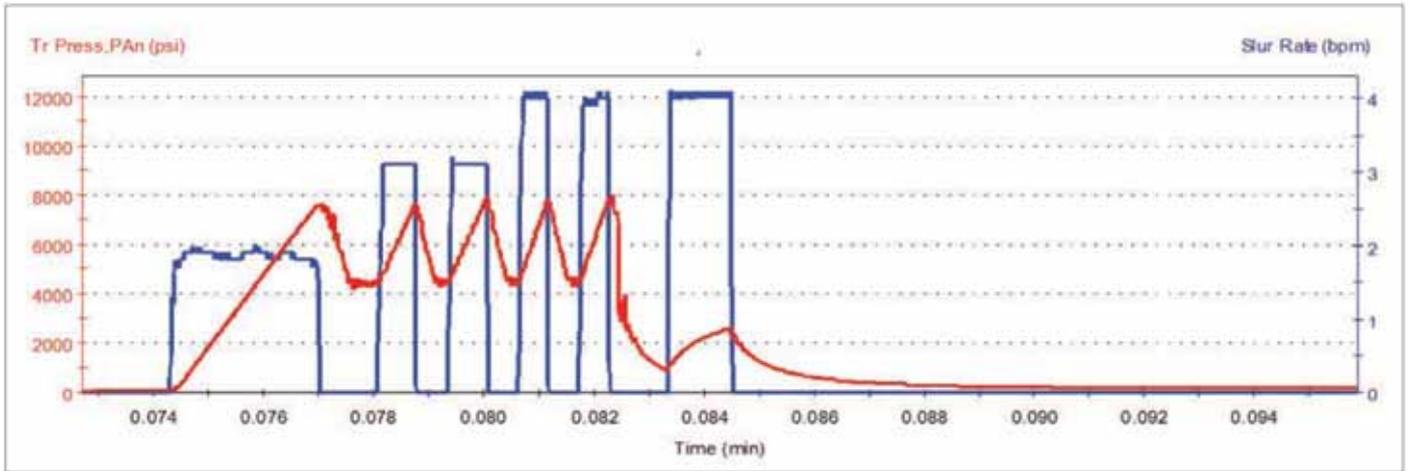


Fig. 8. Well #11 frac pumps attempted five times to open the port by bullheading. On the fifth attempt, the port was opened at 8,000 psi and 4 bpm.

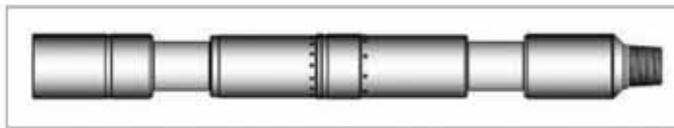


Fig. 9. Dual acting external frac port (with two independent sleeves and separate sets of shear screws).

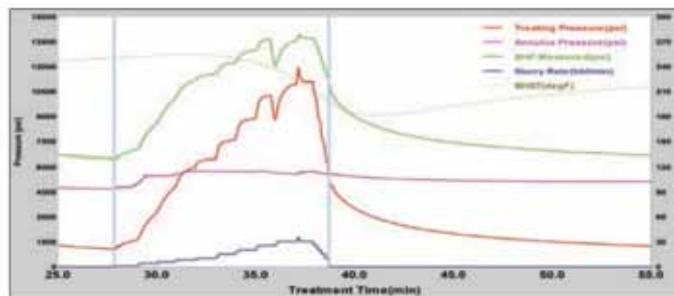


Fig. 10. The pressure drop seen on Well #10 during an injection test with water.

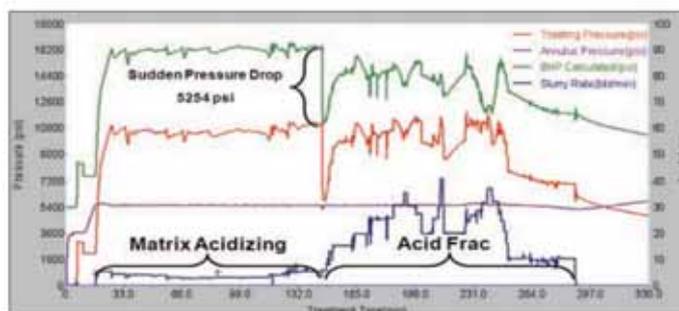


Fig. 11. The pressure drop seen on Well #6 during the main treatment.

“Mud rheology, particularly with respect to oil content, as well as stuck pipe and/or other delays due to problems while running in the hole could potentially skew the design calculations and cause the element to start swelling prematurely.”

contact with its corresponding fluid (water or hydrocarbon), it begins to swell. Therefore, to discourage premature swelling, retardant chemicals are normally mixed in the rubber recipe or otherwise applied to the element OD. Because the swell process is a function of time, temperature and fluid, these crucial factors must be carefully observed during job design and execution. Mud rheology, particularly with respect to oil content, as well as stuck pipe and/or other delays due to problems while running in the hole could potentially skew the design calculations and cause the element to start swelling prematurely. The time to swell ranges from hours to weeks, dependent on well conditions and element design.

Obviously, there are differences in the features and

specs of swellable packers from various providers; however, the above represents the common aspects of all designs.

*Mechanical Packers.* Hydraulically set mechanical open hole packers use rubber pack off elements that are compressed when set to form a seal between the completion and the open hole. A successful packer design used in many Saudi Aramco Southern Area gas field completions is the open hole MSF packer, which features two separate rubber elements, Fig. 5, unlike other designs that possess a single element, Fig. 6.

These separate elements are compressed by means of two opposing pistons in the center of the packer to create two independent sealing points against the wellbore

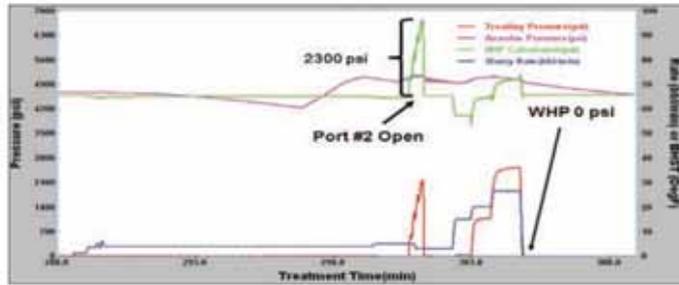


Fig. 12. Communication between stages 1 and 2 for Well #10.

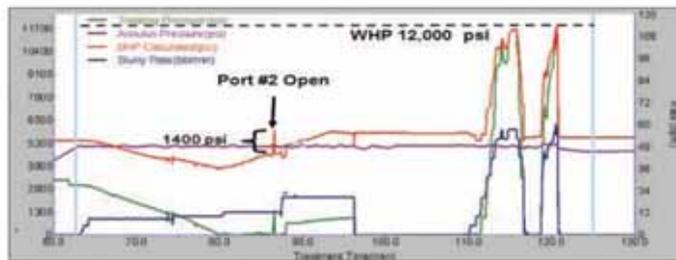


Fig. 13. Communication between stages 1 and 2 for Well #6.



Fig. 14. Open hole anchoring packer (complete with anchoring slips and single seal), as run on Well #6.



Fig. 15. Open hole dual sealing packer (less anchoring capabilities).



Fig. 16. Diagram showing the calculated forces acting on the lower open hole packer during the first stage treatment in an unbalanced system with no open hole anchor packer.

Well Name	Open Hole Size (in)	Completion Size OD (in)	Completion Size ID (in)	Open Hole Annulus Area (sq in)	Bottom-Hole Pressure (psi)	Reservoir Pressure (psi)	Differential Pressure (psi)	Force Created on Lowest Packer (lbsf)	Shrinkage due to Temperature Difference (lbsf)	Resulting Upward Force Created (lbsf)	Friction Forces based T&D Analysis (lbsf)	Completion Length (ft)	Resulting Liner Movement (ft) Up Hole from TD
WELL #6	8-3/8"	5.5"	4.7	37.74	16,200	6,600	9,600	362,304	50,000	412,304	80,000	3,760	8 ft
WELL #11	5-7/8"	4.5"	3.813	17.49	13,500	5,200	8,300	145,164	50,000	195,164	60,000	5,284	12 ft

Table 3. Liner upward movement resulting from applied forces on the lower packer when treating Stage 1 in an unbalanced system.

Advantages	Disadvantages
Fracturing of the toe section of the well is possible.	The system is not balanced in the first stage.
If deployment issues are encountered, e.g., differential or mechanical sticking, where the completion needs to be set, the toe section can still be reached.	There is an immediate upward force placed on the bottom of the lowest packer, directly above the hydraulic frac port.
For sandstone formations, the open hole anchoring is potentially improved with better contact to the rock face, and there is no risk of the acid eroding away the rock around the anchor slips.	For carbonate operations, there is a potential for the acid treatment to erode the rock around the open hole anchor packer, increasing the risk of movement of the slips.
	For sandstone operations, there is a chance that the fracturing breakdown pressure will be very high, pushing the 10 K psi differential pressure limitations of the packer. At these high pressures, a balanced system would be preferred.
	If the open hole anchor packer fails, there will be a movement up hole and a high potential to damage the open hole packer seals.
	If no open hole anchor packer exists in the completion, the upward movement is certain to damage the open hole packer seals.

Table 4. First stage unbalanced systems.

Advantages	Disadvantages
The system is balanced in the first stage.	Full fracturing of the toe section of the well is not possible without perforating the lower joint.
In case of an emergency, the toe of the well can be perforated and then fractured, if a single joint is placed between the toe circulation sub and the open hole anchor packer.	If deployment issues are encountered, e.g., differential or mechanical sticking, where the completion needs to be set, the toe section can still be reached.
There is an immediate upward force placed on the bottom of the lowest packer, directly above the hydraulic frac port.	If no open hole anchor packer exists in the completion, there is still a tendency for the completion to move downwards. This movement increases the risk of damage to the open hole packer seals.
For carbonate operations, the potential for the acid treatment to erode the rock around the open hole anchor packer is greatly reduced, since it is protected from above by the open hole sealing packers.	

Table 5. First stage balanced systems.

Hydraulically set mechanical open hole packers use rubber pack off elements that are compressed when set to form a seal between the completion and the open hole.

ID. In setting this packer, the tubing is pressured up. This pressure acts directly on the cross-sectional area of the setting pistons, causing them to move apart (in opposite directions) to set both elements.

The setting mechanism of this packer is characterized by a dynamic setting mode, which uses the frac surface pumping pressure to continuously adjust the pack off force on each element to maintain the seal. When the packer is subject to pressures higher than its initial setting pressure, the ratchet will move further and pack off the element anew – this action not only copes with borehole changes, but also increases the differential pressure rating, due to the additional pack off force delivered to the element with an increased hydrostatic pressure. This allows the two elements to cope with even the most catastrophic problems any packer can suffer in a MSF operation:

- Shrinkage due to cooling, resulting in a decreased sealing pressure.

- Post-setting borehole washout due to turbulence or acid effect.

The mechanical dual sealing element packer is just above 5 ft long, which makes it readily adaptable to high doglegs and build rates.

Other mechanical open hole packers feature only one pack off element with a static setting mechanism. Therefore, the ability of those tools to respond to post-setting dynamic borehole conditions during the fracturing operation is compromised. These packers also tend to lose their initial optimum sealing pressure due to shrinkage of the rubber element once the cooler fracturing operation treatment is pumped down the hole.

#### Comparison of the External Pressure Sleeve/Port Tools

Table 2 shows the history of the hydraulic frac port openings as per the suppliers. The P-sleeve from Supplier B had problems with opening on the first three



“There is a potential drawback to running an unbalanced system as it is reliant on the open hole anchor packer, to avoid upward movement of the system.”

port. The improvement and development of a dual actuating sleeve to address these opening issues have made it a much more reliable and robust solution. The hydraulic frac port is a key component in the completion system, and thereby, by having a dual actuating system, reduces the overall risk to the operation.

The dual acting hydraulic frac port features two independently acting sleeves, i.e., the two sleeves are shear-pinned separately, so that if one sleeve fails to actuate, the second sleeve will function as a contingency, Fig. 9. When used previously, the dual external hydraulic frac port showed very positive results.

On all Supplier A jobs, the dual external port opened immediately as planned, except on Well #6 where barite mud was used for the first time. It was decided never to use barite mud again, due to the potential problems with mud particulates plugging the wellbore pores and preventing injectivity into the reservoir rock; however, the dual external sleeve still opened after a short period of pressure cycling.

#### **Comparison of the Lower Completion Open Hole Anchoring Tools**

In both Well #6 and Well #10, large pressure drops were seen when pumping into Stage 1. In Well #10 this phenomenon was seen during the first injection step rate test (SRT), from 10,100 psi to 8,400 psi, Fig. 10. In Well #6, a similar drop in surface pressure was observed following spotting acid/mutual acid during the main treatment; there was a drop of 5,254 psi surface pressure, from 16,054 to 10,800 psi, Fig. 11. When pumping commenced in Stage 2 for both wells, it was very clear that there was communication between zones and that the packers were likely to be no longer holding pressure. As shown in Figs. 12 and 13, there was an immediate pressure decline to 0 psi surface pressure when pumping was stopped.

For the two initial gas well completion operations in 2007 (Well #1 and Well #2), the MSF systems were all in a balanced configuration. Due to deployment issues related to mechanical and/or differential sticking – where the completion was unable to reach the

“Testing performed in open hole conditions showed it is possible to drag the packer up hole with certain overpull, depending on various downhole conditions.”

target depth – it was decided that an unbalanced system would be preferred in subsequent wells. The theory was that if the lower multistage completion was unable to reach target depth, then the toe section of the well would still be able to be treated in some form. Therefore, all of the eight systems run in the next 12 months were unbalanced systems.

There is a potential drawback to running an unbalanced system as it is reliant on the open hole anchor packer, to avoid upward movement of the system, Fig. 14. The lower completion is clearly anchored at the top by a liner hanger, which acts as a fixed point at the top, but without anchoring at the bottom of the system, it is free to move upwards. For the completion run on Well #10, no open hole anchor packers were utilized.

The important consideration here is that the open hole sealing packers offer near negligible anchoring capability, Fig. 15. Testing performed in open hole conditions showed it is possible to drag the packer up hole with certain overpull, depending on various downhole con-

ditions. Given the open hole diameter and the high pressures involved during the stimulation treatments, the upward forces created – which act on the lowermost packer – are very high (up to 400,000 lbs upward force on the lower packer). The concern with an unbalanced system, as used with Well #6, is that the open hole anchor packer is immediately exposed to the acid treatment. With acid erosion of the formation around the slips of the anchor packer comes the possibility that the anchor can lose its grip on the open hole rock face and begin to slide up hole. When that anchoring ability is lost, the completion undergoes a rapid upward pistoning effect, and all of the lower completion moves a significant distance up hole. This well-proven phenomenon is simply related to the forces resulting from the high pressure, Fig. 16.

For example, with an unbalanced system inside a  $8\frac{3}{8}$ " hole, the piston area trying to push the packers up the hole is  $37.742$ ", resulting in an upward force of 377,400 lbs with 10,000 psi differential pressure applied. In this case, the tubing shrinkage increases the

force by approximately another 50,000 lbs. Therefore, the total upwards force is ~420,000 lbs.

For a balanced system inside a  $8\frac{3}{8}$ " hole, the piston area trying to push the packers apart is 55.092", so with 10,000 psi applied, there is over 550,000 lbs of force trying to part the tubing. This force is counteracted somewhat by tubing shrinkage due to temperature drop, dropping the force down to ~500,000 lbs.

In a  $5\frac{7}{8}$ " hole, the numbers are 27.112" for a balanced system and 17.492" for an unbalanced system, equaling 270,000 lbs (220,000 lbs with shrinkage) and 175,000 lbs (225,000 lbs with shrinkage).

Therefore, as shown in Table 3, the upward movement of the lowest open hole packers could be as much as 12 ft. When the pressure is released, the completion will slide back towards its original position. With every pressure cycle, the upward force on this lowest zone will be created again, resulting in compression of the liner. The implication is that with a set packer sliding along the open hole rock face several times during the pressure cycles, it is very likely that the packer seals will be damaged, thereby reducing the packer's sealing ability and resulting in clear communication between zones. Communication would initially be between Zones 1 and 2, but it would subsequently involve the rest of the zones, as movement of the entire completion would likely damage all of the open hole packer seals.

For all formation types, a balanced system would be the preferred method of running the MSF completion. This is simply because when the first stage is in a balanced condition, the forces created during the fracturing treatment are equally applied, in opposing directions, to each packer. For carbonate formations, the need for a balanced system is greatly increased; with an unbalanced system, there is a high potential risk of the acid treatment eroding away the formation around the slips of the open hole anchor packer, while with a balanced system, the open hole anchor packer is protected by the upper open hole sealing packer.

In both unbalanced and balanced systems, an open hole anchor packer is needed to avoid any excessive movement of the liner and the open hole packer dur-

ing the fracturing treatments.

In sandstone formations, because of the reduced potential for erosion of the rock around the slips (since the treatment will be a proppant frac), the open hole anchor packer should remain well set throughout the fracturing process. Both unbalanced and balanced systems therefore are possible options. Given the bottom-hole pressures created by the increased hydrostatic fluid column and the likely high breakdown fracturing pressures, the system will certainly be put to its limits, and again extra assurance would be gained on the first stage by running a balanced system. Tables 4 and 5 list the advantages and disadvantages of the balanced and unbalanced systems.

Due to improved operating running procedures and the centralization of the liner, all of the recent systems have reached target depth without issue<sup>1</sup>.

The recommendation for forthcoming wells is to standardize the use of balanced systems, as shown in Fig. 17. The idea behind the design is to run a balanced system with the open hole anchor packer – run at the bottom of the multistage completion – positioned at a single joint above the toe circulation subassembly (including float collars and guide shoe). Above the open hole anchor packer will be a dual element open hole mechanical packer. Above that packer will be the first stage frac port (a dual external opening hydraulic frac port). The system is designed so that the open hole anchor packer will not see any of the acid treatment fluid directly, because it is protected by the dual element open hole sealing packer. In this way all forces/movement will be balanced, and the open hole anchor packer will be well set with reduced chance of erosion from the acid treatment. Second, as an added precaution to eliminate any communication between Stage 1 and Stage 2, it was discussed and recommended to place an extra dual element open hole sealing packer between the stages.

This investigation is part of a more detailed report currently being compiled with the evaluations performed on the MSF and completion efficiencies. High rate and high-pressure acid fracturing treatments test the completion equipment to its limit, and there

“In both unbalanced and balanced systems, an open hole anchor packer is needed to avoid any excessive movement of the liner and the open hole packer during the fracturing treatments.”

is much still to be learned about the equipment’s interaction with the carbonate formations. The well direction and resulting fracture orientation is certainly a major influencer on the fluid placement. This investigation focuses solely on the completion equipment set-up and configurations.

The completion that was run on Well #10 by Supplier B was an unbalanced system run with no open hole anchor used; anchored the completion was only at the top of the liner by the liner hanger. The lowest single sealing packer began to slide immediately when pressure was applied to it. A major pressure drop of ~1,700 psi was seen as soon as the SRT began pumping water at approximately 8,300 psi differential pressure (surface pressure less reservoir pressure).

With 8,300 psi differential pressure and 145,164 lbf applied to the lowest packer in the 5 $\frac{7}{8}$ ” open hole, with 5,284 ft of liner in total, the upward movement

can be as much as 12 ft. This movement could potentially damage the packer seal, allowing communication between zones.

The completion used on Well #6 by Supplier A did have an open hole anchor packer. It is believed, however, that due to acid erosion of the carbonate formation around the open hole anchor, the slips were compromised. The system moved upwards and the open hole packer seals were likely damaged. A pressure drop occurred following 3 days of pumping, which included an acid treatment designed to dissolve some of the barite mud away. The completion system, Stage 1, had been pressure cycled many times – up to its maximum differential of 9,600 psi – by the time the pressure drop was observed.

For future wells, it is recommended to run a balanced system with the open hole anchor packer toward the bottom of the completion, where it is protected by an

open hole dual element sealing packer. It is also recommended to use dual element packers with 100% redundancy, since they provide maximum success.

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1. Al-Jubran, H.H., Wilson, S. and Johnston, B.: "Successful Deployment of Multistage Fracturing Systems in Multilayered Tight Gas Carbonate Formations in Saudi Arabia," SPE paper 130894, presented at the SPE Deep Gas Conference and Exhibition, Manama, Bahrain, January 24-26, 2010. 📌

## Biographies



Mohammed A. Al-Ghazal is a Production Engineer at Saudi Aramco. He is part of a team that is responsible for gas production optimization in the Southern Area gas reserves of Saudi Arabia.

In 2010, Mohammed received his B.S. degree in Petroleum Engineering from King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia.



Abdulaziz M. Al-Sagris is a Supervisor in the Southern Area Production Engineering Department (SAPED). He has been very involved in the gas development program in the Southern Area to meet the growing global gas demand. Abdulaziz's experience covers several production optimization aspects, including acid stimulation, coiled tubing applications and fishing operations.

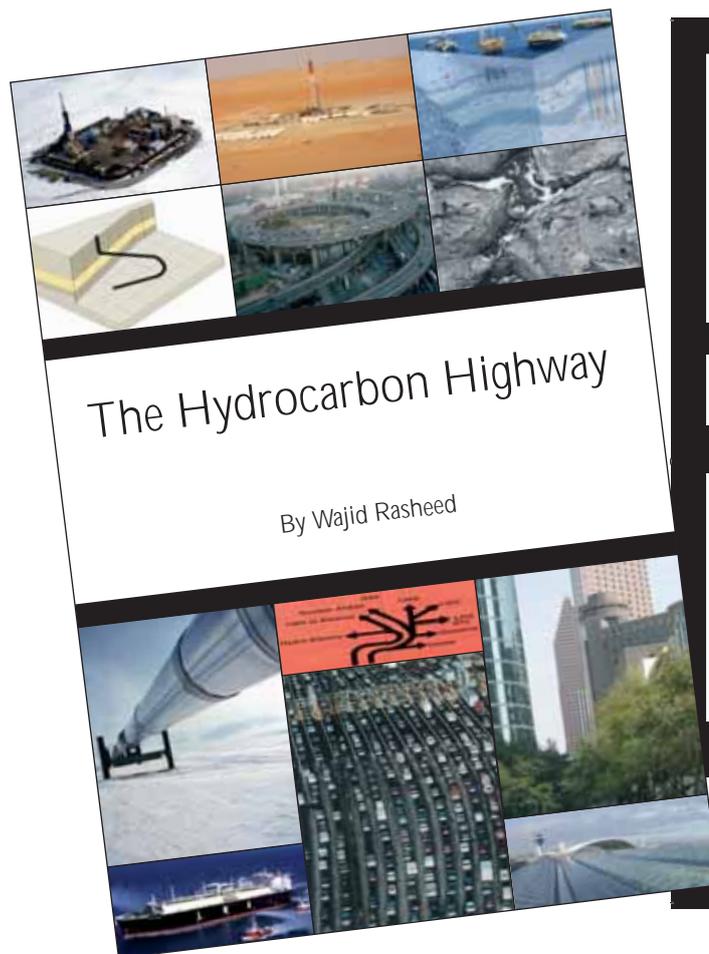


In 1995, he received his B.S. degree in Chemical Engineering from King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia.

Saad M. Al-Driweeshis is a Gas Production Engineering General Supervisor in the Southern Area Production Engineering Department (SAPED), where he is involved in gas production engineering, well completion, fracturing and stimulation activities. His main interest is in the field of production engineering, including production optimization, fracturing and stimulation, and new well completion applications.

Saad has 24 years of experience in areas related to gas and oil production engineering. In 1988, he received his B.S. degree in Petroleum Engineering from King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia.

# The Origin of Oil



"There have been many books concerning the oil industry. Most are technical, some historical (e.g. the Prize) and some about the money side. There are few, if any, about the oil industry that the non-technical person will appreciate and gain real insight from. Wajid Rasheed in this book, *The Hydrocarbon Highway*, has made a lovely pen sketch of the oil industry in its entirety. The book begins with the geology of oil and gas formation and continues with the technical aspects of E. & P. distribution, refining and marketing which are written in clear language. In particular, the process of oil recovery is outlined simply and with useful examples. There is a short history of how the oil companies have got to where they are, and finally a discussion concerning the exits—alternative energy. This is all neatly bundled into 14 chapters with many beautiful photographs and a helpful glossary. The book is intended to give an overture to the industry without bogging the reader down. I enjoyed the journey along the highway."

*Professor Richard Dawe of the University of West Indies, Trinidad and Tobago*

"A crash course in Oil and Energy. *The Hydrocarbon Highway* is a much-needed resource, outlining the real energy challenges we face and potential solutions."

*Steven A. Holditch, SPE, Department Head of Petroleum Engineering, Texas A&M University*

"I found the book excellent because it provides a balanced and realistic view of the oil industry and oil as an important source of energy for the world. It also provides accurate information which is required by the industry and the wider public. Recently, I read several books about oil which portrayed it as a quickly vanishing energy source. It seems that many existing books predict a doomsday scenario for the world as a result of the misperceived energy shortage, which I believe is greatly exaggerated and somewhat sensational. Therefore the book bridges the existing gap of accurate information about oil as a necessary source of energy for the foreseeable future. The *Hydrocarbon Highway* should also help inform public opinion about the oil industry and our energy future. It looks at the oil industry in an up-to-date and integrated view and considers the most important factors affecting it."

*Dr AbdulAziz Al Majed, the Director of the Centre for Petroleum and Minerals at the Research Institute at King Fahd University of Petroleum and Minerals*

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*This chapter is the foundation for understanding how oil and gas accumulations occur and what factors are involved in their discovery and development. A case history shows how analysis of oil and gas accumulations helps oil companies discover billion dollar assets.*

“Bathymetry, the science of mapping seabeds, can show the connection of islands to land masses and the influence of ancient river systems in carrying sediment downstream to what were once marine areas or those that are underwater today.”

If one looks at an outcrop or a core of the earth's formations, it's easy to see the natural beauty of differing rock types and deposited sedimentary layers. In the exploration for oil and gas, geologists or 'rock-doctors' often focus on 'ancient river deposits' or 'ancient marine reefs'. This refers to nature's legacy dating back through a geological timeline to when the continents were joined together in a single land mass known as Pangaea. Many sedimentary depositions and reservoir structures originated prior to continental drift when Pangaea was broken into separate land masses that form the continents we know today; for example, the western coastline of Africa and the eastern coastline of South America fit perfectly together. This explains the similarities found in oil and gas reservoirs in both areas today. Many millions of years ago, for instance, in the Jurassic and Cretaceous ages, eroded rocks, minerals and dead organic matter combined to form 'sediment' which was washed out onto seabeds. Imagine ancient heavy rainstorms at the top of a hill creating rainwater

channels that collect sediment—minute particles of rock, earth and other debris—and deposit it into rivers which finally run to the sea<sup>1</sup>.

Bathymetry, the science of mapping seabeds, can show the connection of islands to land masses and the influence of ancient river systems in carrying sediment downstream to what were once marine areas or those that are underwater today. Currents and waves spread sediment over many miles with larger heavier grains staying close to the river mouth, while lighter smaller grains are deposited further away. Combined with the dips, basins and platforms on the seabed, depositional patterns and dunes are created with certain areas accumulating massive organically-rich deposits of what was once marine life. It is for these reasons that marine sedimentary rocks interest rock-doctors (see Figure 1).

These sediments are often linked to river systems, either existing or ancient. This is the reason why so much

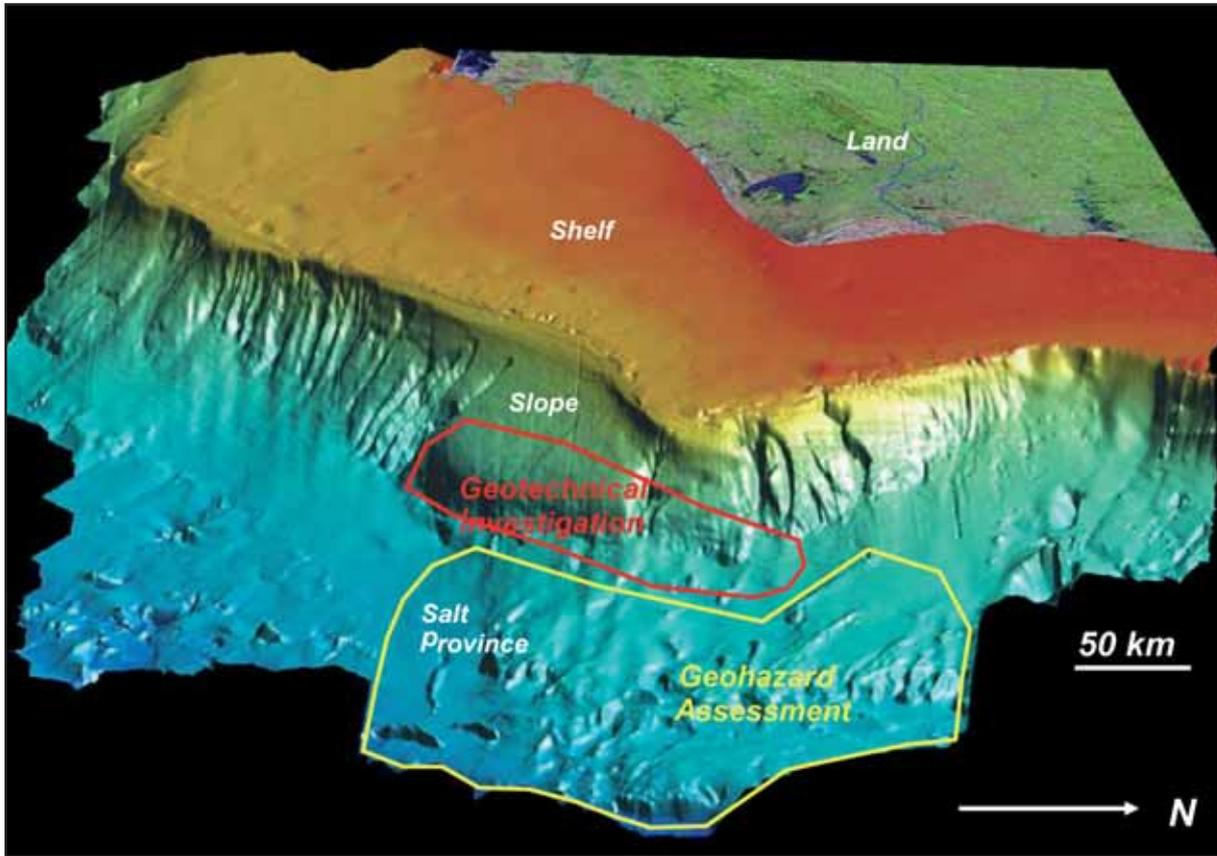


Figure 1 - Seafloor Under Investigation Offshore Brazil (Petrobras)

exploration is concentrated in the various offshore gulfs worldwide. Almost all of the easily accessed inland and deltaic reservoirs have been discovered<sup>2</sup>.

Wind can also erode, transport and deposit rock particles and debris. Wind is particularly effective in arid areas and where there is a large supply of unconsolidated sediments. Although water is much more powerful, Aeolian or wind-based processes are important in deserts where they can form vast sand dunes. Aeolian deposition occurs once a sand dune becomes compacted and hardened forming a consolidated sandstone. In the southern part of the Arabian Peninsula, a region called the Empty Quarter (Rub-al-Khali) because of its lack of life, vast dunes can be found that routinely reach 93 miles (150 km) in length and 1,000 feet (300 m) in height (see Figure 2).

The earth's surface and seabed is made up of two layers: the lithosphere and the asthenosphere. The lithosphere is the upper layer and it is quite rigid. It is broken up into numerous distinct tectonic plates (see Figure 3 opposite) which are moving, and this is exemplified by continental drift and seafloor spreading. Although solid, the lower layer or asthenosphere is considered to behave as a fluid over geological time. It is this fluidity that permits the movement of the tectonic plates in all directions creating earthquakes, volcanoes, mountains, and oceanic trenches along plate boundaries.

Over geological time, ancient river systems carried and deposited millions of tonnes of sediment as they ran their courses to river outlets, deltas or gulfs. In order for sediment to be deposited, a low-lying area called a ba-



Figure 2 - Exploratory Rig in the Empty Quarter, Saudi Arabia (Saudi Aramco)

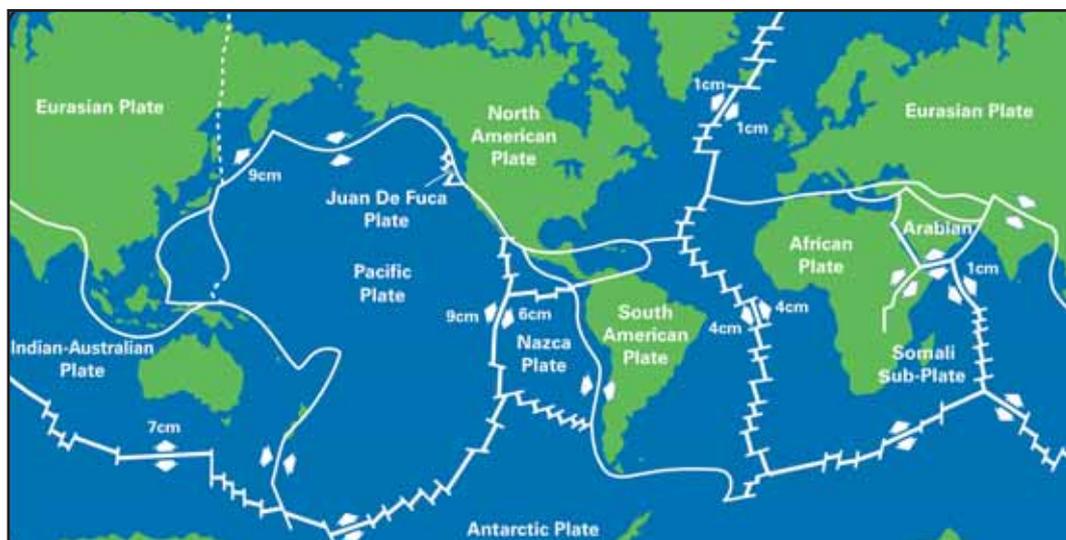


Figure 3 - Image of Tectonic Plates (Courtesy of British Geological Survey)

Name of Particle	Size Range	Scale	Loose Sediment	Consolidated Rock
Boulder	>256 mm	<-8	Gravel	Conglomerate or Breccia (depends on rounding)
Cobble	64 - 256 mm	-6 to -8		
Pebble	4 - 64 mm	-2 to -6		
Granule	2 - 4 mm	-1 to -2		
Very Coarse Sand	1 - 2 mm	0 to -1	Sand	Sandstone
Coarse Sand	0.5 - 1 mm	1 to 0		
Medium Sand	0.25 - 0.5 mm	2 to 1		
Fine Sand	0.125 - 0.25 mm	3 to 2		
Very Fine Sand	0.0625 - 0.125 mm	4 to 3		
Coarse Silt	0.031 - 0.625 mm	5 to 4	Silt	Siltstone
Medium Silt	0.016 - 0.031 mm	6 to 5		
Fine Silt	0.008 - 0.016 mm	7 to 6		
Very Fine Silt	0.004 - 0.008 mm	8 to 7		
Clay	<0.004 mm	>8	Clay	Claystone, Mudstone, Shale

Table 1 - Grain Sizes Table (After Prof. Stephen A. Nelson)

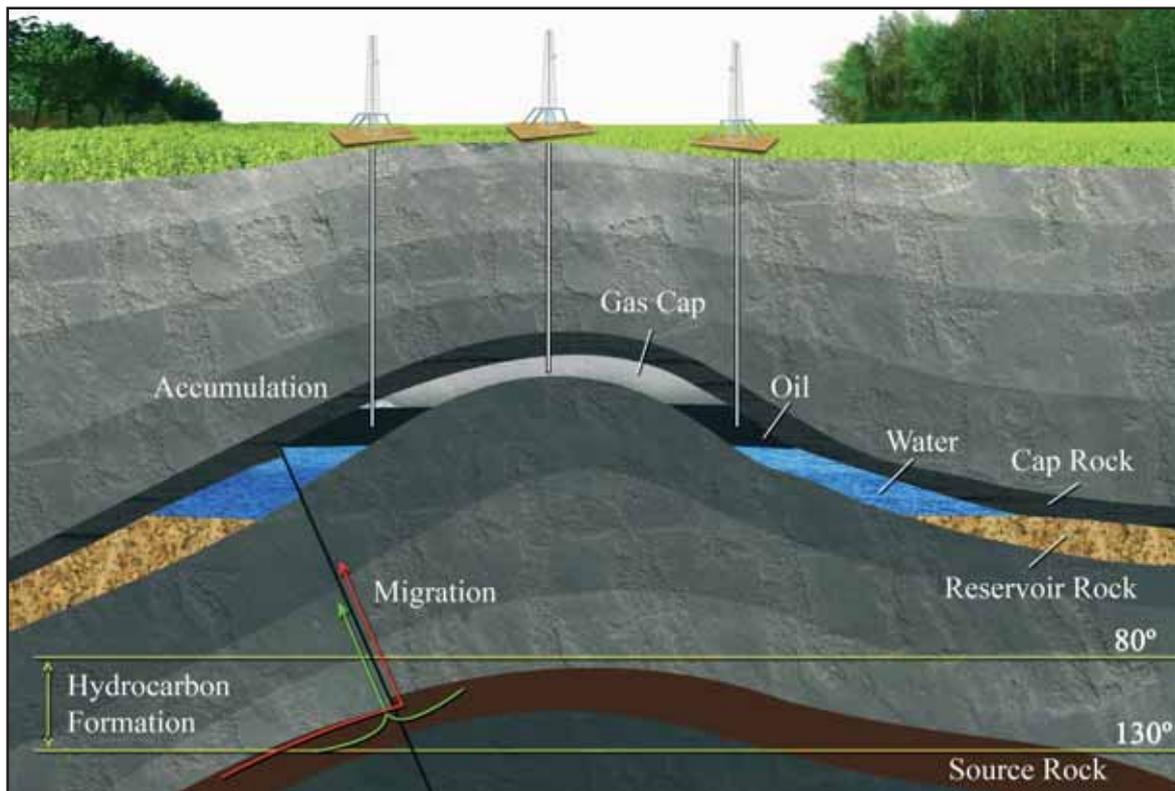


Figure 4 - The Window for the Formation of Oil and Gas

sin is required. The largest basins are the ocean basins, which currently cover about 70% of the earth's surface. In the past, however, the sea level often changed and the continents were covered by shallow seas (referred to as epi- or epicontinental seas). When sea levels rise to invade the continents, this is referred to as a transgression. Major transgressions occurred during the Cretaceous era, and from the early Cambrian through Mississippian eras. Plate tectonic movements create basins, and even the large transgressions appear to be related to tectonic factors, as increased spreading of ocean basins changes their configuration and leads to flooding of the continents<sup>3</sup>.

Over time, continuing deposits eventually formed numerous layers of sedimentary rock. These were pushed deeper and deeper under the seabed. Each successive layer (younger deposits) increased the pressure on earlier layers (older deposits) and tectonic plate movement deformed the layers creating folds, hills (anticlines) valleys (synclines), unconformities (eroded areas) and faults<sup>4</sup>.

Sedimentary rocks have an average thickness of about 6,000 ft (1,800 m) on the continents. This thickness is quite variable; for example, some areas such as the Canadian Shield, have no sedimentary rock cover, while other areas such as the Louisiana and Texas Gulf coasts, have more than 65,600 ft (20,000 m) of sedimentary rock cover. Generally, about 66% of all continental areas have a cover of sedimentary rocks.

The graph below illustrates that as sediment gets buried it avoids further erosion; hence, older sedimentary rocks show less exposed outcrop area than younger sedimentary rocks. More than 40% of the exposed sedimentary rocks are younger than Cretaceous in age.

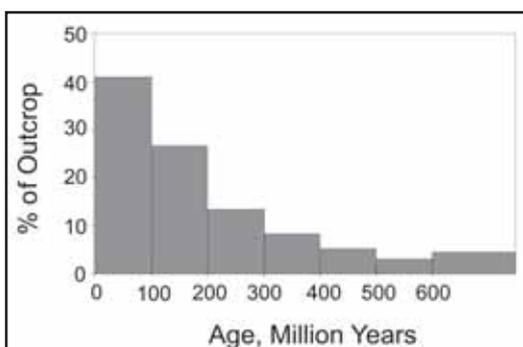


Table 1 shows typical rock grain sizes. There are three basic types of sedimentary rocks:

1. Siliclastic sedimentary rocks are formed by the accumulation of mostly silicate mineral fragments. These include most sandstones, mud rocks, conglomerates, and breccias.
2. Chemical sedimentary rocks are formed by direct chemical precipitation from water. While some limestones and cherts may form in this manner, evaporite deposits consisting of halite, gypsum, and other salts are the most common.
3. Biogenic sedimentary rocks consist of fragments of particles produced by precipitation from once-living organisms. Most of these rocks are limestones and cherts.

95% of all sedimentary rocks consist of sandstones (made up of sand-sized fragments), mudrocks (made up of silt and clay-sized fragments) and carbonate rocks (made up of mostly calcite, aragonite, or dolomite). Mudrocks constitute 65% of sedimentary rocks, while sandstones make up 20% to 25% and carbonate rocks 10% to 15%.

Carbonate rocks largely consist of two types of rocks:

1. Limestones which are composed mostly of calcite ( $\text{CaCO}_3$ ) or high magnesium calcite [ $(\text{Ca}, \text{Mg})\text{CO}_3$ ], and
2. Dolostones which are composed mostly of dolomite [ $\text{Ca Mg}(\text{CO}_3)_2$ ]

Because carbonate minerals in general are soluble in slightly acidic waters, they often have high porosity and permeability, making them ideal reservoirs for petroleum. It is for this reason they are well studied<sup>5</sup>.

Limestone can easily be recognised in hand specimens or outcrops because of its high solubility in hydrochloric acid (HCl). A drop of acid placed on the rock will cause it to fizz due to the generation of carbon dioxide ( $\text{CO}_2$ ) gas. A dolostone, on the other hand, will not fizz until a fine powder is made from the rock or mineral.

For oil and gas to form, the deposits of organic matter must be converted to hydrocarbon compounds. A

'window' or specific set of conditions is required for the formation of oil and gas (see Figure 4 opposite). Even today, the formation of oil and gas as a process is not fully understood but the prevalent theory is that time, pressure and heat convert decomposed marine life into elemental hydrocarbons. Within a given rock structure, the younger deposits or later layers form 'overburden' pressure conditions. Additionally, each layer has a given temperature profile according to the True Vertical Depth (TVD) at which it is located. The general rule is: the greater the depth, the higher the temperature. These factors combine to form oil and gas deposits in certain rocks known as 'source-rock', which can often be seen in certain oil and gas provinces in outcrops<sup>6</sup>.

From their origins deep within the source beds, hydrocarbon molecules are squeezed by immense pressures caused by the overlying sediments similar to water from a sponge. They migrate to water-saturated porous and permeable beds where, being lighter than water, they

start to rise. As they rise, they contact other hydrocarbon molecules and coalesce into droplets that keep rising until they encounter an impermeable layer called a cap rock. There, they accumulate, forming a reservoir.

Occasionally, the hydrocarbon makes it all the way to the surface without being trapped, forming a natural seep. It has been suggested that Christopher Columbus had moored off Trinidad to re-coat boats with pitch from La Brea (see Figure 5). The discovery well drilled by Colonel Drake in Titusville, Pennsylvania, US in 1859 was said to have been encouraged by a seep the Indians pointed out to the Colonel. The natives had been using the oil as pitch to waterproof their canoes and dwellings. Much of the tar blobs found on beaches have surfaced from natural subsea seeps.

For oil and gas to accumulate, and to prevent it from subsequently dispersing, a trap is required. Usually, this is an impermeable layer known as 'cap rock' that seals off oil and gas deposits ensuring that the oil and gas remains in place, until it is tapped by the drill bit, or subjected to other geological forces.



Figure 5 - Pitch Lake at La Brea, Trinidad and Tobago (EPRasheed)

“For decades now, reservoir pressures have been carefully controlled for health, safety and environmental reasons and not least due to the value of the oil.”

Climate changes, weathering, glaciers, volcanic eruptions, river flooding and other natural forces can change or erode surface rocks. Consequently, the depths, thickness and tilt of the layers vary from place to place. Buried layers of salt, created by the evaporation of seas and lakes, can be squeezed by pressure loads or made to flow with heat. Due to its relatively low density compared to other rocks, salt will flow and rise, often forming domes and distorting the overlying layers. Tectonic forces over time can cause upheavals that result in the rock folding, fracturing or faulting. These subsurface movements and changes can create or destroy traps, which, when combined with factors such as timing, temperature and pressure, will determine the existence of hydrocarbon reservoirs<sup>7</sup>.

Cap rock may be many layers higher than the original source rock, as oil and gas will always seek to leak or migrate upward unless it is stopped. Cap rock also plays a fundamental part in maintaining reservoir pressure. Pitch lakes are an instructive example of both reservoir

pressure and the tendency of oil and gas to ‘leak’ to the surface of the earth. In this case, a dense heavy bituminous form of oil which is chemically attracted to minerals such as clay has ‘flowed’ to the surface in channels. Pitch lakes, tar sands or oil and gas seeps, were well known to ancient man who used the oil for a variety of uses from medicine to basic lighting. The term ‘snake oil salesman’ arose from the early pioneers who attributed healing powers to the ‘surface oil’.

Underground pressure is the primary mechanism that drives oil and gas to flow to surface. The pressure of hydrocarbon reservoirs, prior to being tapped by the drillbit, is similar to that of an unopened bottle containing a fizzy drink. If you shake the bottle and immediately open it, due to the built-up pressure, a certain volume of liquid will be driven to the bottle top and spill-over. Known as a depletion drive, this is similar to the natural pressure of an oil or gas reservoir and can be exemplified by what were historically known as ‘gushers’. For decades now, reservoir pressures have been carefully controlled for health,

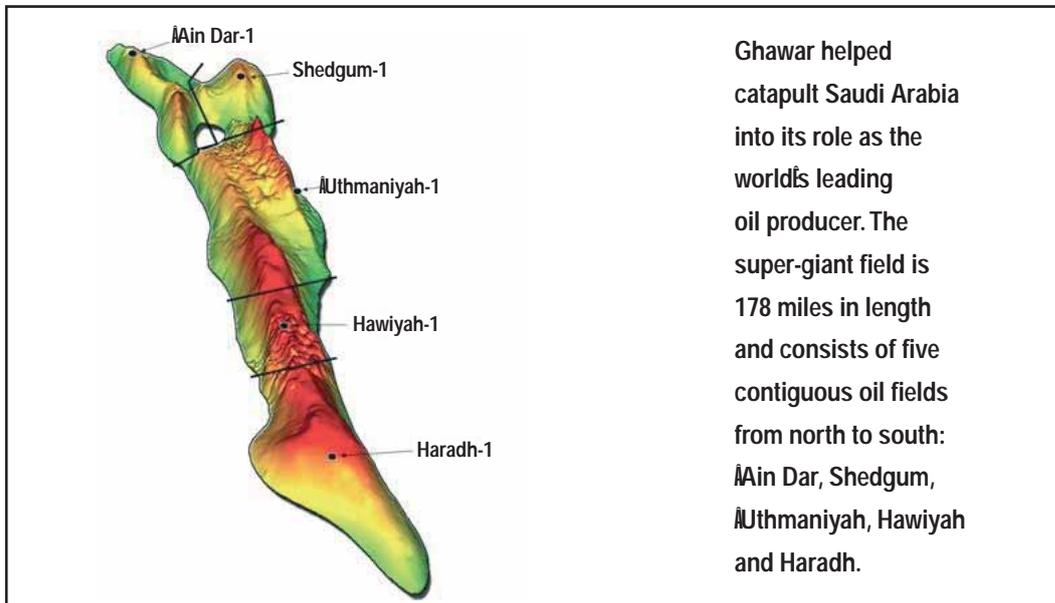


Figure 6 - Representation of Ghawar Field (Saudi Aramco)

safety and environmental reasons and not least due to the value of the oil. Primary pressure, however, cannot be maintained indefinitely. Depending on the rate of depletion, the reservoir's pressure will drop, requiring secondary means of production<sup>8</sup>. It is always the case that producing fields see a reduction in the natural pressure or 'fizz' that drives hydrocarbons to the surface.

However, other drive systems exist also. These range from water drive which is by far the most common and prolific, the combined water drive with an expanding gas cap and the gravity drive. The depletion drive is very short-lived whereas water drives can be near infinite.

The drive systems are detailed in *Chapter 9: Mature Fields*. Each one affects the production of oil and gas in a different way and this ultimately determines reservoir recovery factors.

Although people may perceive that there are large underground lakes or caverns of hydrocarbons, this is not true. Oil and gas is stored in tiny voids, called pores, within the reservoir rock which together may extend several hundred feet horizontally or vertically; for example, the world's largest oilfield, Ghawar in

Saudi Arabia, has a reservoir rock that is approximately 178 miles (280 km) long<sup>9</sup> (see Figure 6).

The three rock classes—source, reservoir and cap—help to explain two key concepts. Firstly, the sedimentary process explains why oil and gas are contained in minute rock spaces or pores (porosity) and not in caverns. Imagine a dry sponge placed over water. The water is drawn in and contained within the voids of the sponge. This is why porosity is defined as the percentage of 'voids' in a volume of rock. Secondly, sedimentation shows the ability of a fluid to 'seep' or 'flow' through a given formation (permeability). Minute channels are created in the formations and, due to the pressurised nature of oil and gas and their relative lightness, there is always a tendency for the oil and gas to rise. This is illustrated by the migration of oil and gas from a source rock to a porous reservoir rock<sup>10</sup>.

Permeability can be visualised by thinking of a coffee machine, and ground coffee being packed into an espresso chamber. Under pressure, hot water flows or trickles through creating coffee. The water-flow through

the porous coffee grinds is due to permeability, which is the relative interconnectivity of the pore spaces in the coffee pack. If we continue to pack in more coffee, a point is reached where the compaction (the equivalent being cementation in formation) is so great that it is progressively harder for coffee to flow through.

The ease or difficulty of ‘flowability’ is measured in ‘millidarcies’ (after Henri Darcy, a French scientist who promulgated Darcy’s Law governing fluid flow through porous media in 1856).

Although porosity and permeability are key attributes of reservoirs, they are the most misunderstood concepts in reservoir engineering. Low permeability can mean that large reserves may not be produced economically, or even physically. Tight reservoirs are those that have low permeability. There are rocks (oolites) that have lots of porosity, but no permeability. Conversely, there are fractured formations that have little porosity, but flow like a fire hose because of fracture permeability. Porosity also explains why we say that not all reserves are recoverable; for all oil and gas to be recovered, we would have to extract the rock itself, and literally squeeze out every drop. Given that vertical depths of reservoirs routinely exceed 5,000 ft (1524 m) and can reach more than 25,000 ft (7620 m), it may not always be economically possible to pursue such targets<sup>11</sup>.

Reservoir stimulation is a synthetic way to increase porosity and/or permeability. Due to their high solubility in hydrochloric acid (HCl), limestone reservoirs are often ‘acidised’. The acid pumped into the reservoir etches channels which improve production. For sandstone reservoirs, specialised fluids are pumped into the formation until it literally cracks open, thereby permitting better flow.

With the passage of time, the land and seas holding oil and gas accumulations became subject to territorial jurisdiction and were bid for as leases or exploratory blocks. Such blocks (see *Chapter 6: Properties, Players and Processes*) have led to the discovery of famous fields and formations such as the Austin Chalk, Brent, Ghawar and Shtokman. Commercial quantities of petroleum occur almost exclusively within sedimentary rocks (sandstones, limestones and, rarely, claystones). Some of these deposits became famous as they were associated with crude oil or gas production such as

the Kimmeridge clay in the UK North Sea, the Khuff limestone in Saudi Arabia and the Jurassic sandstone of the Shtokman field in Russia.

To summarise the origin of oil:

1. Hydrocarbons are formed by decomposing organic life subjected to temperature and pressure, while sealed by a layer of impermeable rock. This leak proof seal ensures that the hydrocarbon reservoir is maintained until it is tapped by the drill bit.
2. Source rocks need to be, or have been, in the right range of depths (and hence temperature) for sufficient time for the deposits to change into oil or natural gas. A source rock has massive organic deposits.
3. Porous reservoir rocks can exist above or below the source rocks.
4. Impervious cap rocks lie above the reservoir rocks.
5. Traps are required for the hydrocarbons to accumulate.

Geological mapping and geophysical surveys allow oil companies to characterise acquired acreage and the age and sedimentation patterns of the rock formation contained therein. This process of characterisation can be reconstructed as a visual earth model that delineates the position and shape of the structure including anticlines, faults-stratigraphy, structure.

It is useful to distinguish between the terms ‘reservoir description’ and ‘reservoir characterisation’. The former is the means by which the reservoir is described (using observable parameters i.e. models), while the latter explains how it will behave under production and includes petrophysical parameters.

Geophysics is the study of the earth by quantitative physical methods—principally by measuring the gravitational, magnetic, electrical and seismic-velocity properties of the earth’s surface and interior. The principle objective of geophysics is exploration, i.e. searching for subterranean structures that could trap and hold hydrocarbons. Recently, geophysics has been expanded to include characterisation of reservoir drainage patterns.

Measuring differences in rock properties provides information about the distribution and the structure of rocks at surface and at a given depth, and gives a three-dimensional (3D) picture of the earth’s crust. Scientists use this information to better understand the evolution



Figure 7 - A Stratigraphic Column in StatoilHydro Offices (EPRasheed)



Figure 8 - Outcrop In Bahrain Shows a Sedimentary Sequence (EPRasheed)

and structure of the earth, thus leading to more effective exploration for hydrocarbons, water and mineral resources.

The most common types of surveys include:

- Gravity surveys
- Magnetic surveys
- Electrical surveys
- Electromagnetic surveys
- Radiometric surveys
- Seismic surveys
- Radar surveys
- Thermal imaging
- Geochemical imaging, and
- Downhole electrical and calliper surveys.

Surveys are conducted for different purposes: at regional scales to cover large areas both on the ground and from ships or aircraft and at local scales to cover specific sites such as mineral prospects on the ground, with marine or airborne instruments, or by using underground wellbores<sup>12</sup>.

The stratigraphy of an area is obtained by measuring and describing the layers of rocks. This usually includes rock samples obtained using cores or cuttings or from outcrops (although this is becoming rarer due to the trend to deepwater and arctic areas).

Each rock sample is examined in the field and outcrop samples are taken to the lab where features are noted such as colour, grain sizes and mineral composition, fossil content, porosity and permeability. The samples are numbered and mapped so that their position in the sequence is known. They are then examined for small and large fossils by paleontologists.

In drill cuttings, only the microfossils are normally recovered since the large fossils are usually destroyed, although some may be recovered from cores. Sedimentologists will examine the samples to determine their nature and the environments in which they accumulated.

Geochemists will characterise changes in the organic material contained in rocks caused by time, heat and pressure. They will identify possible petroleum source rocks, assessing the burial history and hydrocarbon-

bearing potential of the sediments. Geochemists also use spectroscopy logs to determine the elemental composition of the rocks, and subsequently their mineralogy. This information provides important clues as to the origin of the rocks, and enables cross-correlation with similar rocks in adjacent or 'offset' wellbores.

Stratigraphy, and the study of fossils, will help determine the geological age of rocks. This in turn enables the correlation of a given formation with other areas, sections and boreholes. The stratigraphic sections are then correlated with each other for the area that is being mapped.

A stratigraphic chart of the types and age of rocks can be created and is presented in Table 2 which shows the data for the UK. Different nomenclatures have been used by different geologists to describe the same age and type of rock found in other parts of the world. The most important time periods are from the Carboniferous era (299-359 million years ago), the Permian era (251-299 million years ago), the Triassic era (199-251 million years ago), the Jurassic era (145-199 million years ago [Table 3]) and the Cretaceous era (65-145 million years ago). It should be noted that there are some accumulations that are much older. Each of these periods is divided into distinctive sub-period epochs and then ages. The rock characteristics can also be grouped by changes in rock type. In the early Jurassic period in the Middle East, for example, the Hith, Arab, Jubaila, Diyab and Hanifa formations can be found. They can be dated by the fossils, including pollens, found in them. The depositional environments, together with the diagenesis (changes after deposition), are reflected in rock characteristics (e.g. how grain sizes or permeability change with depth)<sup>13</sup>.

Distinctive rock types, known as facies, can be identified in the depositional layers. Changes occurring over a few metres within the reservoir provide clues as to the earth's history at that particular time and whether deposition occurred in a river delta, lagoon, seashore or desert. Each of these depositional environments creates unique properties of porosity, permeability and other reservoir characteristics which ultimately dictate hydrocarbon recovery.

Facies analysis is used by petroleum geologists to derive

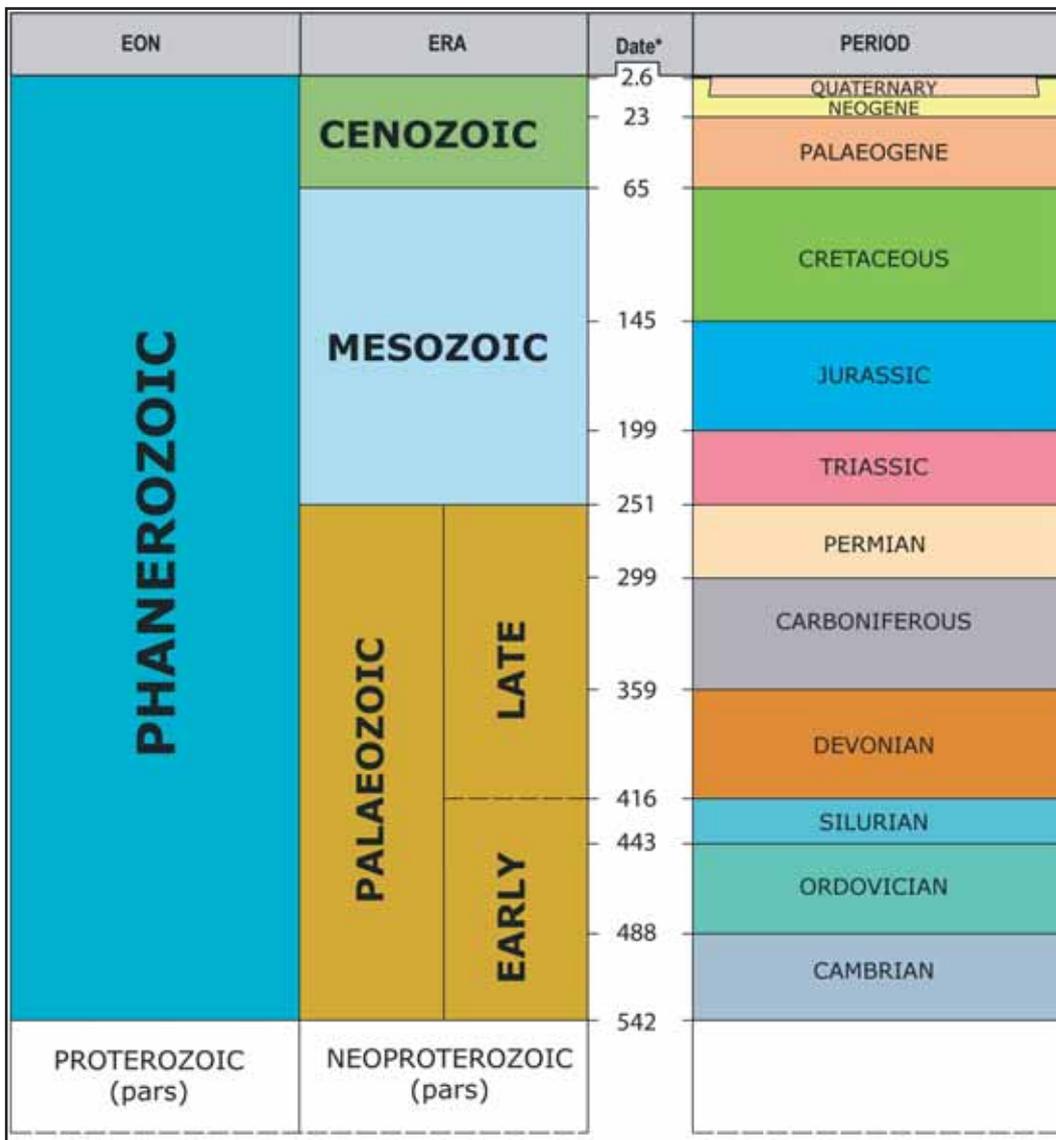


Table 2 - Stratigraphic Chart of Rock Types and Age in the United Kingdom. Courtesy of BGS (British Geological Survey)

a model of the subsurface, i.e. a reservoir description. This model of the multilayered reservoir is essential for the reservoir engineers when designing an optimum well completion or reservoir development and production policy. For instance, major intervals are often separated by seals of impermeable anhydrite or shale<sup>14</sup>. 'Marker beds' chronicle major events in the evolution of the earth; for example, huge volcanic eruptions blanketed huge areas of the earth's surface with characteristic ash that can be identified in cores and correlated with similar marker beds in other wells. This provides

an indisputable reference that fixes the rock's age in geologic time. Paleomagnetism studies the residual effect of magnetic polarity changes in the earth's evolution where the earth's magnetic poles swapped polarity back and forth over eons of time. By understanding these factors, wells can be constructed using techniques and know-how that have already been proven in similar formations. This saves time and money allowing oil companies to reach production faster.

There may be considerable doubt whether rocks, which

“The study of fossilised pollen and plant spores or ‘palynology’ has become an important means of correlating rocks to geological time as they are often identifiable in rocks that present no other fossil content.”

are similar in both chemical and physical nature, are of the same geological age. The doubt can only be removed, if at all, by detailed laboratory work. Initially, rocks are compared to see whether the constituent minerals are chemically and physically similar. Even if they are, the same types may be repeated during geological time and a study of the fossils (paleontology) will be essential to reduce the uncertainties. Most species of fossil organisms lived for a considerable span of geological time before becoming extinct.

The study of fossilised pollen and plant spores or ‘palynology’ has become an important means of correlating rocks to geological time as they are often identifiable in rocks that present no other fossil content. This is because spores and pollen remain remarkably well preserved over geological time due to their almost indestructible husks. The palaeontologist will use X-rays and electron microscopes to compare fossil assemblages rather than individual species which allows for accurate correlation of fossils within geological time-scales. The ultra-microscopic plates from the bodies of minute marine organisms have complex

shapes characterised by different geological periods and allow approximate geological dating of even small rock debris. Radiometric age-dating is also used and is based on estimates of the decay of radioactive isotopes of specialised minerals in the rocks.

When an area is being drilled, the rock cuttings from nearly all exploration and appraisal wells are examined. Analysis of the cuttings encompasses fossil and minerals content including clays, geochemical content and the physical appearance or description of the rock (e.g. shape and size distribution of rock grains). These elements provide important clues as to the rock’s age and depositional environment.

Most wells have petrophysical logs routinely taken. Petrophysical logs are measurements of various electrical, nuclear and acoustical properties recorded as a function of depth and are made with special downhole tools. Coring is conducted using a drill bit that employs Polycrystalline Diamond Compact (PDC) cutting elements and has a hollow centre. This allows the cutting element to obtain a core of the formation that is being

ERA	PERIOD	EPOCH	Date*	AGE
MESOZOIC	JURASSIC	LATE	145.5	TITHONIAN
			150.8	KIMMERIDGIAN
			155.7	OXFORDIAN
		MID	161.2	CALLOVIAN
			164.7	BATHONIAN
			167.7	BAJOCIAN
			170	
			171.6	AALENIAN
			175.6	TOARCIAN
		EARLY	183	PLIENSBACHIAN
			189.6	SINEMURIAN
			196.5	HETTANGIAN
			199.6	

Table 3 - Mesozoic Stratigraphy of the UK. Courtesy of BGS (British Geological Survey)

drilled. Cores are fragile and require special handling and storage techniques; however, they are not readily available. They are often used as a complementary method of formation analysis and can be used to help calibrate logs and provide information for reservoir modelling. Consequently, cuttings, logs and cores are the production geologist's primary sources of data and enable them to describe the nature of the rocks that have been drilled (the stratigraphy—the sedimentary sequence in terms of lithological characteristics and rock properties)<sup>15</sup>.

Despite development data being partial, and at times unreliable, key decisions to develop a prospect and spend millions of dollars have to be reached. Several appraisal wells are drilled to determine the size of the accumulation and to test the reservoirs for production

capacity and quality. At this stage, geologists must work closely with the well log analyst, the reservoir engineers and production engineers. Refinements, or even gross revisions of the original reservoir assessments, are made as new data are obtained.

To plan a development of an oil or gas field, information is needed about the structure of the oil and gas reservoir such as the:

- Shape, size, volume and connectivity of the accumulation
- Porosity, pore geometry and permeability of the rock
- Fraction of the pore space filled with hydrocarbons
- Nature of the hydrocarbons
- Cost of wells, facilities, pipelines, installations etc., and

- Health, safety and environmental matters<sup>16</sup>.

As a result of obtaining all the appropriate data, the oil company developing the field seeks to save millions of dollars and reach production faster by knowing how many wells to drill and where best to locate them. This is precisely what happened in the exploration and drilling project in the Dnieper-Donets Basin in the Ukraine as is indicated in the case history below.

Careful study of the geology of the Dnieper-Donets Basin resulted in the discovery and development of 12 petroleum fields with oil reserves equal to 1.4 billion barrels of oil equivalent, the major part of which is produced from the Precambrian crystalline basement. These fields were discovered in a narrow strip approximately 22 miles (35 km) wide and 250 miles (400 km) long near the Northern Marginal Deep Fault where the oil and gas-bearing rocks are Middle and Lower Carboniferous period sandstones and Precambrian granites, amphibolites, and schists of the crystalline basement complex. This exploration project also generated the discovery of a new gas-producing area near Kharkiv for which the proven gas in place has been calculated to be 100 billion cubic metres (Bm<sup>3</sup>).

The oil produced from all reservoirs was analysed for correlations of trace metallic elements; for example, the ratios of nickel and vanadium, and of either methane or nitrogen were measured. The abundance of the trace metals showed a clear correlation and it was established that the oil from different reservoirs shared a common, deep source characterised by diffusive separation (regardless of the age, type or circumstance of the particular reservoir rocks).

Paleontological analyses of the oil in the Permian and Carboniferous sandstone formations demonstrated the presence of spore-pollen and other microphytofossils of the Devonian and Proterozoic ages, thereby establishing upward migration from deeper formations. By examining micro-sized traces of pollen contained in the rock pores, scientists concluded that the oil migrated upwards to its present location from much older, deeper sediments.

The oil produced from the reservoirs in the crystalline basement rock of the Dnieper-Donets Basin has been examined particularly closely for the presence of either porphyrin molecules or 'biological marker' molecules, the presence of which used to be misconstrued as

'evidence' of a supposed biological origin for petroleum. None of the oil contains any such molecules, even at the parts per million (ppm) level. There is also research presently under progress, which has established the presence of deep, anaerobic, hydrocarbon metabolising microbes in the oil from the wells in the uppermost petroliferous zones of the crystalline basement rock in the Dnieper-Donets Basin.

These results, taken either individually or collectively, helped optimise the drilling and production strategy within the Dnieper-Donets Basin<sup>17,18</sup>.

Now that we understand how oil and gas is formed, it is time to ask two important questions: Are we running out of oil? And given that oil and gas reserves are miles below ground, how are they actually measured?

1. See Issue 1 TTNRG (2004) – Why does Trinidad and Tobago have Oil? By Wajid Rasheed. ([www.ttnrg.com](http://www.ttnrg.com))

2. Well known fact that the 'low-hanging fruit' or easy-to-produce reserves in land and shallow waters have been well characterised and produced.

3. The majority of world's oil is located in the Tethyan Belt, lying between the equator and mid northern latitudes; and running from Venezuela through the Middle East to China and Indonesia. Tethyan petroleum systems are characterised by facies deposited in tropical environments such as carbonate and evaporites, and prolific source rocks laid down in warm lakes and shallow epic seas. However, about a third of global petroleum is in the mid to high northerly latitudes of the Boreal Realm. Though some petroleum systems rely on Palaeozoic source rocks originally deposited in low paleo-latitudes (e.g. Late Devonian shales of Timan-Pechora Basin), most are sourced from marine Jurassic-Cretaceous shales deposited in restricted rift basins in high paleo-latitudes. These include the world class source rocks of the Neocomian of the North Slope of Alaska and the Late Jurassic of the North Sea, Eastern Canada, and West Siberia. See Bradshaw Marita et al Oil from the South.

4. See Sedimentation in standard geology texts or country geological surveys such as the British Geological Survey.

5. Not just for these reasons but also because carbonates hold much of future reserves.

6. See Issue 1 TTNRG (2004) – Naparima Formation which is the source rock is easily visible in Naparima Hill, Trinidad and Tobago. See AAPG Explorer June 2003 Long studied outcrops in Spain that may hold secrets to understanding deepwater reservoirs are providing new clues, thanks largely to new 3-D laser technologies.

7. Oil shales did not make it through the ‘Window’ for the Formation of Oil and Gas. Oil shale/sands were not subjected to the depth, pressure and temperature necessary to form crude oil. Therefore, their hydrocarbon content varies between that of coal and crude oil. Extraction efficiency depends on differing factors but generally 1 barrel of oil requires 1.5 to 2 tonnes of rock or sand. The total global resource of oil shales is order of magnitude greater than crude oil reserves. But extracting the energy value of oil shale is only valid at US \$50 to \$70. The industry is working on ways to reduce shale oil extraction costs.

8. See Horizontal Well Technology, Sada Joshi, p 49 Reservoir Engineering Concepts ISBN 0878143505. Drop a stone in a calm pond. As soon as the stone is dropped in the pond, one can see circular waves going outward. A similar phenomenon occurs when a well is put on production in a given drainage area. The pressure disturbance or loss is felt initially at the wellbore and it will take time before fluids furthest from the well start migrating to the well and as time progresses average reservoir pressure decreases. See Reservoir Engineering texts for detail of primary reservoir pressure curves and bottom-hole pressure.

9. See Saudi Arabia Oil and Gas Issue 8 2008 - Ghawar, Saudi Aramco. ([www.saudiaramcooilandgas.com](http://www.saudiaramcooilandgas.com)).

10. See Pirson S.J., 1950, Elements of reservoir engineering: McGraw-Hill.

11. Economic conditions are moving targets dependent on oil prices and production technology. Finding and lifting costs themselves vary, ultimately it is the oil price and the cost of production technology that determines what is cost effective. Nonetheless an average of 65% of conventional resources are left underground.

12. Surveys help reduce drilling risk.

13. See Diagenesis of Carbonate Rocks: Cement-Porosity Relationships Friedman ISBN: 0918985366.

14. In drilling wells sub-salt GOM and Brazil the occurrence of impermeable Anhydrite and Shale beds is commonplace.

15. Cores are just one of the geologist’s characterisation tools.

16. HSE will be statutory requirements set by lease agencies such as the Minerals Management Service (MMS) in the offshore US OCS or environmental authority IBAMA in Brazil.

17. Petroleum Geology and Resources of the Dnieper-Donets Basin, Ukraine and Russia, by Gregory F. Ulmishek. U.S. Geological Survey Bulletin 2201-E.

18. The Drilling & Development of the Oil & Gas Fields in the Dnieper-Donetsk Basin, by V. A. Krayushkin, T. I. Tchebanenko, V. P. Klochko, Ye. S. Dvoryanin Institute of Geological Sciences and J. F. Kenney Russian Academy of Sciences. 🛢️

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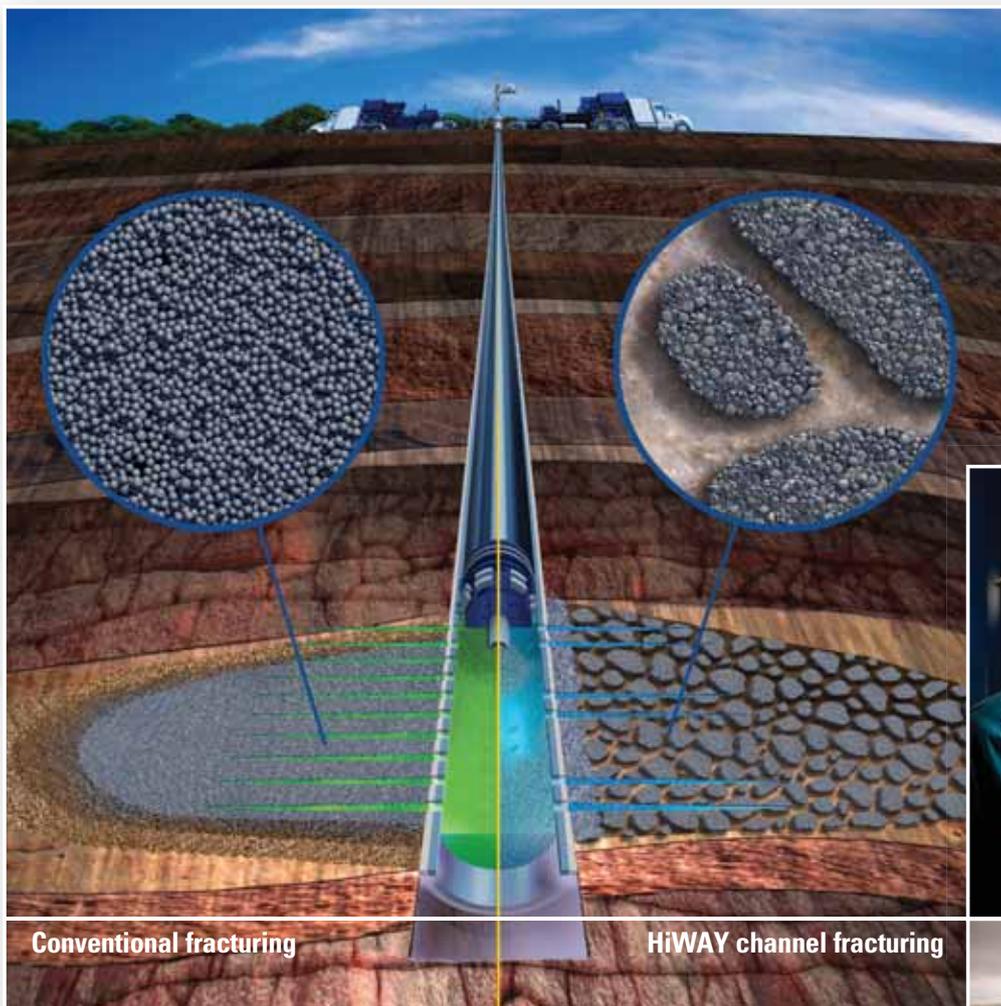
## Editorial 2011 Calendar

Jan/Feb	Mar/Apr	May/June	Jul/Aug	Sep/Oct	Nov/Dec
<b>Ad Closing:</b> 4 Jan 2011 <b>Materials Closing:</b> 11 Jan 2011	<b>Ad Closing:</b> 1 March 2011 <b>Materials Closing:</b> 4 March 2011	<b>Ad Closing:</b> 22 April 2011 <b>Materials Closing:</b> 29 April 2011	<b>Ad Closing:</b> 5 July 2011 <b>Materials Closing:</b> 12 July 2011	<b>Ad Closing:</b> 29 August 2010 <b>Materials Closing:</b> 30 August 2011	<b>Ad Closing:</b> 8 October 2011 <b>Materials Closing:</b> 15 October 2011
<ul style="list-style-type: none"> <li>• Saudi Aramco RTOC</li> <li>• Digitalization</li> <li>• While Drilling Technology</li> <li>• Telemetry</li> <li>• Production</li> <li>• OGEP II Review</li> </ul>	<ul style="list-style-type: none"> <li>• Khurais</li> <li>• Near Surface Modelling</li> <li>• Rotary Steerable &amp; Motor Systems</li> <li>• Drill Bits and Underreamers</li> <li>• Complex Wells</li> <li>• Geophysical</li> <li>• Drill Pipe Integrity</li> </ul>	<ul style="list-style-type: none"> <li>• Manifa</li> <li>• Remote Operation Centre</li> <li>• Drill-Bit Tech</li> <li>• Inflow Control Devices</li> <li>• Zonal Isolation (incl. Packers, Multi-Zone Completions)</li> <li>• Carbonate Reservoir Heterogeneity</li> <li>• Exploration Rub Al Khali</li> </ul>	<ul style="list-style-type: none"> <li>• Formation Evaluation</li> <li>• Wellbore Intervention</li> <li>• Casing While Drilling</li> <li>• Multi-Laterals</li> <li>• Lowering Drilling Costs in Tight Gas</li> <li>• Evaluating Tight Gas Formations</li> <li>• Increasing Productivity of Tight and Shale Gas</li> </ul>	<ul style="list-style-type: none"> <li>• Khursaniyah</li> <li>• Expandable Completions</li> <li>• Tubulars</li> <li>• Logging and Measurement WD</li> <li>• Electrical Submersible Pumps</li> <li>• Progressive Cavity Pumps</li> <li>• Novel Tight Gas Technologies</li> </ul>	<ul style="list-style-type: none"> <li>• Hawiyah</li> <li>• Smart Completions</li> <li>• I field</li> <li>• Geosteering</li> <li>• GOSP</li> <li>• Extended Seismic Feature (4D, OBC, Wide Azimuth)</li> </ul>
<b>Issue 18</b> <i>'OGEP II Review'</i>	<b>Issue 19</b> <i>'Innovation, IOC, NOC and Service Company Alliances'</i>	<b>Issue 20</b> <i>'Upstream Challenges'</i>	<b>Issue 21</b> <i>'Tight Gas Lowering Costs and Increasing Productivity'</i>	<b>Issue 22</b> <i>'Cost Effective Drilling and Completions'</i>	<b>Issue 23</b> <i>'Cooperation, Innovation and Investment'</i>
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