QATAR'S OIL AND GAS RESERVOIRS

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ABSTRACT

This paper discusses the oil and gas resources of Qatar from a reservoir point of view. It considers the discovery and development of the oil and gas resources of Qatar covering the past 60 years. It is concerned solely with the oil and gas reservoirs within the boundaries of Qatar.

Up to 1990, there were four major producing areas, one onshore, the Dukhan area on the west coast of Qatar (with three major oil producing reservoirs almost on top of each other and underneath these one non-associated gas reservoir), and two major offshore producing areas, one of three oil and associated gas fields, the Idd El Shargi, Maydan Mahzam and Bul Hanine Fields to the east of Qatar and the other, the giant North Field of non-associated gas to the north (figure 1). Qatar also shares with Abu Dhabi, the offshore Al-Bunduq oilfield to the south east of Qatar which straddles the Qatar-UAE sea boundary line. Although a number of other areas have been explored by seismic and by drilling, no further commercial oil has yet been discovered onshore. Since 1990 there has been much further exploration around the producing offshore areas and more fields have been discovered. Some have been considered commercial and are being developed even under the present economic climate (Al-Khalij, Al-Rayyan and Al-Shaheen). There are probably more finds still to be made, with some possibly straddling Qatar's territorial boundaries.

Footnote
Units
The petroleum industry uses a variety of units and conversion from one unit to another is often necessary. The major conversions are presented here for convenience.
b=barrel, MM=million (10^6), B= billion(10^9), T=trillion (10^{12}), d=day
$1m^3 \equiv 6.29$ b$\equiv 35.3$ scu.ft; 1 metric tonne oil $\cong 7.5$ b
MM represents 1 million.

- *Oil volumes*

1,000,000 b = 1 MM b = 159,000 $m^3 \approx 120,000$ metric tonnes
1 MM b/d $\approx$ 50 MM metric tonnes/year

- *Gas volumes*

1000 MM scu.ft gas = 1 B scu.ft = 28.3 MM sm^3
1,000,000 MMscu.ft = 1 T scu.ft
1 MM scu.ft/d = 10 MM sm^3 /year $\approx$ 7500 metric tonnes LNG/year

INTRODUCTION

Much of the Middle East has all the factors favourable for major oil accumulations; abundant source beds laid down in suitable environments; thick, permeable reservoir beds and very large anticline structures formed at the right time to provide traps (Alsharhan and Nairn, 1994; Alsharhan and Nairn, 1997; Selley,1997; Tiratsoo, 1984). The area around Qatar is a good example. Qatar occupies a peninsula of sedimentary limestone of about 11,500 sq. km. jutting from the west coast of the Arabian mainland northward into the Gulf. It is approximately 160 km long and 80 km wide at its widest point. It has four seaward neighbours, Iran, United Arab Emirates (UAE), Saudi Arabia and Bahrain and one landward, Saudi Arabia. (figure 1).

Oil was first discovered in Qatar near Dukhan in 1939. Oil and gas have been produced from these reservoirs since 1949. In 1960, oil was discovered offshore to the north east of the peninsula. This oil started to be produced in 1964. Then in 1971 large gas finds were discovered in the offshore North Field, which is also off the north eastern part of the peninsula. This gas is now being produced, part to be used for local consumption and the rest to be converted to liquid natural gas (LNG) for export. In 1997 contracts were signed to sell up to 10 MM tonnes LNG per year (1.3 B scu.ft/d) and shipments of LNG to Japan were started. Up to 1990, there were four major producing areas, one onshore, the Dukhan area on the west coast of Qatar (with three major oil producing reservoirs almost on top of each other and underneath these one non-associated gas reservoir), and two major offshore producing areas, one of three oil and associated gas fields, the Idd El Shargi, Maydan Mahzam and Bul Hanine Fields to the east of Qatar and the other the giant North Field of non-associated gas to the north (figure 1). Qatar also shares with Abu Dhabi the offshore Al-Bunduq oil Field to the south east of Qatar which straddles the Qatar-UAE sea boundary line. The remainder of the Qatar land peninsula is occupied by a large, north-south trending, gentle uplift which exposes Eocene beds at the surface. Although a number of other areas have been explored by seismic and by drilling, no further commercial oil has yet been discovered onshore. Since 1990 there has been much further exploration around these producing offshore areas and, as will be discussed later, more fields have been discovered and some have been considered commercial and are being developed even under the present economic climate (Al-Khalij, Al-Rayyan and Al-Shaheen). With modern production technology, particularly horizontal and multi-lateral wells and with improved reservoir management, Qatar's oil production has risen to over 700,000 b/d ($\approx$ 100,000 m^3/d, $\approx$35 MM tonnes/year). There are however, probably more finds still to be made with some possibly straddling Qatar's territorial boundaries. For these fields, after they have been discovered, there will have to be appraisal, evaluation and some agreement on efficient, fair, equitised, production plans.

The State of Qatar has full control of its hydrocarbon industry, as it created its own national oil corporation, Qatar General Petroleum Corporation (QGPC) in 1974. Clearly, because the hydrocarbon sector contributes over 90% of general revenue, the economic development of the State of Qatar will depend on how far its resources of oil and natural gas are exploited. The oil and gas selling prices are therefore very important factors when selling on the open market since these values can fluctuate dramatically and affect project viability and profitably.

The estimate of Qatar's proven crude oil reserves at the end of 1997, according to the 1998 statistics (Arab Oil and Gas Directory, 1998; British Petroleum Statistics, 1998; Qatar General Petroleum Corporation, 1997) are crude oil 3.7 Bb (about 0.4% of the world's known oil reserves). The average production in 1997 was 640,000 b/d (about 0.9% of the world's production), *footnote*(in March 1998 oil production was 735,000 b/d),* and the reserves production (r/p) ratio was about 16 (i.e. if the reservoirs continued to be produced at the current rate the reserves would last 16 years). Since 1949, Qatar has produced in total over 5.9 Bbbls from some 400 wells. The oil reserves are distributed approximately equally onshore and offshore. For gas, the reserves are quoted as at least 380 T scu.ft which is about 6% of the known gas reserves of the world. The 1997 production was 1.3 B scu.ft/d, which is 0.6% of the world's production, and the r/p ratio is over 100 years. Qatar could supply the whole of the world with gas for about four years. The gas production is currently planned to increase rapidly to perhaps 2.8 B scu.ft/d (Arab Oil and Gas Directory, 1998; Qatar General Petroleum Corporation, 1997). All these figures are approximate because the natural gas liquids, NGLs, which condense from the gas or evaporate from the oil are included and the statistics do not always identify them. NGLs are most important in the economics of gas sales, since they are the profit earners.

In Qatar, oil is converted into petrochemicals, refined to liquid fuels, or burnt for heating for industry or producing electricity. Particularly valuable, is the upgrading of the hydrocarbons to value-added products such as plastics and fertiliser, or the production of products needing a cheap and plentiful energy supply such as steel and cement. Natural gas is an environmentally friendly, safe and reliable important source of energy but has to be cleaned, desulphurised, processed to remove condensable components, and then exported by pipe, or liquefied. In Qatar, in the 1970's, much gas was flared but now most gas is used profitably (see note in Table 1). Gas is being used in desalination plants for boiling saline water to produce drinking water, producing LNG as a basic raw material for petrochemicals for polythene etc or chemical products such as urea for fertilisers, and soon, catalytic conversion into liquid fuels (Arab Oil and Gas Directory, 1998; Qatar General Petroleum Corporation, 1997).

In this paper there is no political comment or discussion of the reserves of other Arabian Gulf states. Technical details of what happens to the hydrocarbons once they leave the upstream production pipelines and travel to the refinery or processing plant are also not covered. These important and fascinating topics are dealt with elsewhere (Arab Oil and Gas Directory, 1998; Qatar General Petroleum Corporation, 1997).

GEOLOGICAL AND STRATIGRAPHIC SETTING

The tectonic history of the Middle East and the Arabian Gulf in particular has been well reviewed, (Alsharhan and Nairn, 1994, Alsharhan and Nairn, 1997; *Dukhan Field – Qatar, Treatise Of Petroleum Geology*, 1991; Murris, 1980; Tiratsoo, 1984). Qatar has the Qatar-South Fars Arch running north-south through the land mass and offshore and separates two basins where the eastern area is dominated by salt tectonics and the northern area is flat and featureless. The recent large volume by Alsharhan and Nairn, 1997 discusses every aspect in detail.

The typical stratigraphic chart for Qatar is presented in figure 2. (Different nomenclatures have been used onshore and offshore Qatar and by different geologists to describe the same age and type of rock in other parts of the Arabian Peninsular and elsewhere (Alsharhan and Nairn, 1997; Tiratsoo, 1984). The important periods for Qatar's oil and gas are from the oldest Permian, through Triassic, Jurassic to Cretaceous. Each depositional sequence affects the properties of porosity, permeability and reservoir continuity in different ways, which in turn affect reservoir performance and ultimate hydrocarbon recovery. Detailed facies analysis is used to derive a multilayered model of the subsurface to design an optimum reservoir development and production policy.

Most of Qatar's reservoirs are in massive carbonate beds with anhydrite and shale layers between them acting as seals. The hydrocarbon accumulations are widely dispersed throughout the stratigraphic column. All the fields have more than one pay zone horizon. Prolific oil and associated gas reservoirs are found in Qatar's Middle and Upper Jurassic Arab and the Lower Araej Formations at depths of 1565 to 2500 m and fair to good reservoirs, source rocks and seals are found in the younger and therefore shallower, Cretaceous Shuaiba and Kharaib carbonates, Lower Nahr Umr sandstones, and Khatiyah/Mishrif carbonates, at depths ranging from 940 to 1875 m (Saifaldeen, Jabber and Thabet, 1997). The deepest of Qatar's reservoirs are in the dolomitic carbonate Permian Khuff formation at around 3000-4000m and contain vast quantities of sour condensate gas. These beds range in thickness from 400m to 600m and have an average permeability of less than 30 md (Alsharhan and Nairn, 1997; Desautels, Hussain, and Al-Ansi, 1994; Tosdevin and Abdulla, 1991).

The Jurassic carbonate beds particularly the Hanifa-Jubailah and Hith Formations form a source rock-reservoir-seal triplet (Alsharhan and Nairn, 1994, Alsharhan and Nairn, 1997) that have created in the Middle East, the world's richest hydrocarbon habitat. Carbonate rock classification is difficult but the most widely accepted method concentrates on the features which control porosity and permeability, i.e. grain-matrix relationships and mud content. Thus the terms boundstone, grainstone, packstone, wackestone, mudstone are used. These terms describe the amount of visible grainy material that can be seen under the microscope, with boundstone and grainstone often being good reservoir rock with visible grains whilst mudstone is of poor porosity and permeability. Even so, carbonate rocks do not usually become reservoirs unless fractured or affected by dolomitisation. Dolomite is a highly-ordered mineral consisting of calcium and magnesium ions in separate layers alternating with carbonate ions. The chemical transformation of calcite ($CaCO_3$) into dolomite $CaMg(CO_3)_2$ results in a reduction in the volume of the rock by some 17 per cent. This commonly gives rise to fracturing and gaps in the rock which can significantly affect (often improve but can sometimes reduce) reservoir porosity and permeability. The conversion process may occur at any time in the diagenetic history of a rock sequence from soon after sediments have been deposited to long after deposition, when cementation has already affected the rock. Thus it can be difficult to predict the effects of dolomitisation without petrophysical examination of the rock itself (Selley,1997). In Qatar this is of major importance in predicting the productivity of all reservoirs.

The carbonates of the Cretaceous period are of shallow shelf facies with a cleaner, coarse and relatively more permeable carbonate at the top of each section. The Mishrif and Khatiyah Formations are generally poor, low permeability (0.1 to 5 md) reservoirs due to the way the formations were deposited and are covered by Laffan Shale (Alsharhan and Nairn, 1997; *Dukhan Field – Qatar, Treatise Of Petroleum Geology*, 1991). The carbonates of the Mauddud Formation offshore Qatar are slightly more promising with permeability from 0.1 to 70 md. The Nahr Umr Shale forms a good seal for the reservoirs of the underlying formations but it also has a good but relatively thin (3-5 m) sandstone reservoir which is oil and gas bearing. This is the only hydrocarbon bearing sandstone so far found in Qatar. The formation is of clean, well-sorted sands and is unconsolidated to slightly cemented. Its porosity is around 20% with permeabilities from 3 to more than 1000 md. The oil-bearing Shuaiba is of 0.1 to 2 md carbonate of microporous lime mudstones, but it is hydrocarbon-bearing only in the Idd El Shargi Fields. The Kharaib is oil-bearing but generally shows poor reservoir quality similar to the Shuaiba and is sealed by Hawar shale (Al-Maslamani, 1995).

The Arab C and D reservoirs are the most important reservoirs of offshore Qatar in terms of oil and associated gas production potential. The oil is of 28-32 ^{o}API and viscosity below 1 cp (Alsharhan and Nairn, 1997). These are again carbonates (Alsharhan and Nairn, 1997; Martin, 1997). There are four major reservoir sequences, Arab A –D (some geologists name them Arab I-IV) of the middle Jurassic period, with Arab D being the most prolific and Arab C the next. They are separated by thin seals of anhydrite. The Arab A and B reservoirs are heterogeneous dolomitic limestone, not in good communication, have low porosity ranges up to 20% with permeabilities from less than 1 up to 800 md and have not been very productive with vertically drilled wells. The Arab C dolomitic grainstones represents a major reservoir unit in some of the offshore fields. It can be over 100 m in places. The upper part of the Arab C is the most variable interval and consists of a complex of carbonate rock types. The porosity in the Arab C reservoir ranges from 1 up to 30% and permeability from less than 1 up to 1000 md. The Arab D limestone is one of the most productive carbonate reservoir horizons in the world. The Arab D can be further differentiated into four major cycles of facies of various dolomitic and lime mudstones representing different depositional and diagenetic environments, but is often regarded as a good uniform reservoir of thickness between 60 m to over 90 m with porosity ranging from 15 up to 30% and permeability from 100 to over 5000 md (Alsharhan and Nairn, 1994; Alsharhan and Nairn, 1997). The Middle Jurassic Araej Formation in Qatar contains only thin reservoir zones. The Araej is of general poor reservoir quality except for the central Uwainat member. The Uwainat limestone reservoir consists of relatively clean porous lime mudstones (Alsharhan and Nairn, 1994, Alsharhan and Nairn, 1997) and can be over 60 m in thickness. Overall its permeability is rather poor, and with increasing depth of burial the thin reservoir zones suffer from compaction and pressure solution. It is the deepest of the Jurassic reservoirs at around 2400m.

A separate set of thick reservoir horizons is in the Permian Khuff Formation between 3000-4000m. As mentioned above they are the deepest of Qatar's reservoirs. They are carbonate with ranges in thickness from 400m to 600m and permeability of average 30 md, and contain vast quantities of sour wet gas both on- and offshore. As the Khuff wells have not been extensively cored the Khuff stratigraphy has not yet been fully described although it is suspected that the bulk of the production comes from very discrete thin zones. The Khuff Formation is currently described as a fine to coarse crystalline dolomite with a few interbeds of limestone and anhydrite (Khalaf, 1997; Kasnick, 1987). There are 4 major Khuff horizons, generally numbered in the North Field from the top as K-1, K-2, K-3 and K-4. Each contains gas with a different composition and it is believed that the composition also varies across the field. K-1 is about 100m thick. This interval has an oomoldic porosity zone, about 7 m thick. Generally it has high porosity and low permeability. K-2 gross thickness is of the order of 160 m. There is extreme vertical variability in both porosity and permeability. For example, the porosity can change from 4 to 20% and the permeability from 3 md to 1800 md in an interval of one metre. It is though the major current producer. K-3 gross thickness ranges from 100-150m. It is somewhat similar to K-2. K-4 is the lowest zone with a gross thickness of around 300m. K-4 lacks any well developed porosity. Fractures constitute the only interconnected porosity in this zone. It still is poorly defined. The Khuff Formation is conformably overlain by the Triassic Sudair Shale and unconformably underlain by the Devonian Sandstone of the Haushi Formation (figure 2).

Seals

The reservoir seals are mainly anhydrite and shale. They occur in places both as complete layers of regional extent as well as smaller areas just covering the reservoir. In particular the Mishrif and Khatiyah Formations are capped by the Laffan Shale. The Khuff reservoirs are sealed by the dense lime mudstones of the Triassic Sudair Shale, figure 2 (Alsharhan and Nairn, 1994; Alsharhan and Nairn, 1997).

Tarmat

The presence of an almost immobile tar layer in the bottom of oil reservoirs is a common feature in the Gulf area. Most of the Qatar fields have a tarmat in at least one horizon. A tarmat poses several problems. It can act as a partial or a complete barrier to any aquifer influx, a sizeable portion of the recoverable oil can be sandwiched between the tarmat and the up-dip injectors and a tarmat at the base of the oil column can cover a sizeable area, which can represent in its own right a hydrocarbon reserve that could be very significant. However methods of economical recovery have not yet been developed (Al-Kaabi, Menouar, and Al-Hashim, 1988; Alsharhan and Nairn, 1997).

Aquifers, water injection and water dump flooding

Various aquifers are used as water sources for powered water injection. In particular the Nahr Umr sandstone, but also the Yamama, Sulaiy and the shallow Umm er Radhuma if the Nahr Umr potential is weak in the area. The handling and injection of the large quantities of water required has problems with zonation of the reservoirs requiring selective injection, including peripheral, mid-dip and crestal injection. Water dumping is practised in Qatar because it has operational and economic attractions, but the controlling and monitoring of how much water is being injected and where it is going is difficult and a challenge to the reservoir engineer (Alsharhan and Nairn, 1997; Nasrulla and Rana, 1991).

QATAR'S PETROLEUM FLUIDS

Qatar has much light oil with an °API of around 40 with two primary export oil streams, Dukhan (41 °API) and Marine (36 °API). Most of Qatar 's oil and gas is sour with up to 1.5% H_2S. The country exports a considerable tonnage of sulphur, mainly to the far East and Pakistan. Qatar's oil, both onshore and offshore, has gas-oil ratios mostly in the range 140-400 m^3/m^3 (700-2000 scu.ft/bbl) so produces substantial amounts of associated gas along with its oil. Energy supplies are sometimes quoted in Barrel of Oil Equivalent (boe). The energy of 170 sm^3 (6000 scu.ft) of gas is about equivalent to one barrel of oil. For Qatar, because its oil is volatile, the boe is about 25%, thus 25% of the produced energy from its oilfields is in the associated gas, and therefore has very important financial considerations. This gas has been used in Qatar since the 1960s to generate electricity and water for the city of Doha as well as the chemical plants at Mesaieed.*

*(footnote * originally known as Umm Said –both names are used in this paper)*

Qatar's non-associated gas lies in the Khuff Formation onshore in Dukhan at around 3,000-3,500 m underlying the oilfield, and offshore in the giant North Field. It is a rich, sour condensate gas with some 1% sulphur components. As will be seen later, Qatar has developed its natural gas liquids processing facilities in an attempt to make the production of its North Field commercial.

ADVANCES IN TECHNOLOGY

Qatar carries out many Improved Oil Recovery (IOR) operations. For instance reservoir pressure maintenance by water or gas injection is often adopted to avoid the problems of declining well production rates and increasing gas-oil ratios associated with the drop in reservoir pressure (Hearn, 1997). Suitable water may be injected into the reservoir by pumping from the surface. Alternatively in some fields a water bearing formation above the reservoir may be perforated to allow the water to flow directly into the oil layer after the pressure of the oil layer has been partially depleted. This process is known as water-dump flooding (Khalaf, 1989). In the past, water injection was often adopted late in the life of a field when primary production by natural depletion was about at an end. The term secondary recovery was often applied. Nowadays, water injection is often implemented much earlier in the life of an oil field and the term supplementary recovery is therefore more applicable. In Qatar, this is termed by some as 'Enhanced Oil Recovery'. Gas injection is less common than water injection, but is also carried out in Qatar, particularly if liquid condensation has occurred in the reservoir (gas recycling). The injected gas can dissolve in the oil/condensate and lower the oil viscosity and density and possibly the restraining capillary forces, so ultimately enabling more of the liquid in the reservoir to flow to the wellbore and be recovered, or in recycling for some of the condensate liquid to evaporate back into the gas stream to be produced. Sometimes gas injection has the aim of conserving gas in the reservoir for future recovery because it would otherwise be flared (burnt).

Over the last decade there have been many revolutionary developments in the industry. Because of improved drilling methods, particularly steerable tools and measurement-whilst-drilling (MWD) techniques, horizontal and now multi-lateral wells can be drilled. Consequently, it is now technically feasible to extract more of the STOIIP; thus the reserves credited to a field can be increased (sometimes by considerable amounts). Horizontal and multi-lateral wells are now the drilling norm both for new and infill wells in Qatar (Javed, 1995; Nasrulla and Rana, 1991; Scofield, Laney and Woodard, 1997) and cost little more than the earlier vertical wells (Saifaldeen, Jabber and Thabet, 1997). Seismic surveys are used to 'see' into the subsurface to identify possible hydrocarbon traps. Most of on- and off-shore Qatar has had (or is having) recent seismic surveys carried out (Qatar General Petroleum Corporation, 1997). The 3/4-D seismic methodologies and interpretations have dramatically improved in the last few years and have enabled clearer reservoir description, particularly the interpretation of geological detail for reservoir simulation (Jubralla and Hamam, 1991; Rubbens, Murat and Van Keulen, 1983). Computational techniques and reservoir modelling and flow simulation are continually being upgraded as management tools (DesAutels, Hussain and Al-Ansi, 1994; Tosdevin, and Abdulla, 1991). Additionally there have been gross changes in attitudes by the major oil companies with inter-company sharing of information and field development. The companies themselves have been restructured with downsizing of personnel and outsourcing of requirements. Finally there has been a much stronger attitude to public and world views on health, safety and environmental effects of hydrocarbon extraction. All these advances have been applied to the exploitation of reservoirs in Qatar.

However the varying (often downward) price of oil and gas greatly affect both exploration and exploitation plans as can be seen in oil company annual reports.

RESERVOIRS

Onshore -Dukhan

The first geological investigation of Qatar was undertaken in 1933 by British geologists. In 1935, the Qatar Petroleum Company (QPC), a consortium of companies including the IPC group (Anglo-Iranian Petroleum Company – now British Petroleum, and Shell), obtained a 75-year concession for exploration of the entire onshore territory of Qatar. The story of the negotiations for these concession rights and for others in the Arabian Gulf makes fascinating reading. They have been expertly summarised in Yergin's book 'The Prize' (Yergin, 1991), but the original sources themselves and other reviews are certainly not dull (for example, Records Of Qatar; Primary Documents 1820-1960, 1991; Al-Othman, 1984; Zahlan, 1979).

Drilling began in October 1938 on a site near Zekrit just north of Dukhan on the west coast. This area was chosen by the explorationists because the surface topography suggested a classical anticlinal structure, as indeed it is. In October 1939, the first slight show of oil was seen. In January 1940 an appraisal well at a depth of 5685 feet (1733 m) began to flow with oil, at some 5000 b/d (795 m^3/d) and the test was reported to have been 'highly satisfactory'. Oil had been found in the Arab C (named then as the Upper Jurassic Number 3 Limestone Member of the Qatar Formation). Two more appraisal wells were drilled, one 18 km south and 4 km east to confirm the size and quality reserves in order to ensure that production would be commercially viable (*Dukhan Field – Qatar, Treatise Of Petroleum Geology*, 1991). However, because of the Second World War, the company decided to halt all its operations in Qatar on 28 June 1942. The three appraisal wells were sealed and the company management and technicians left.

In 1946, the company returned to Dukhan to first create all the necessary services and infrastructure before the oil could be extracted. To quote from an eye-witness (Al-Othman, 1984),"The first priority was accommodation for staff and workers and storage facilities. Then there was the question of transport. There was no possibility of building an oil tanker terminal on the West Coast near the oil fields, because the water there is shallow and has an abundance of coral reefs. The company did build a small harbour at Zekrit to accommodate small supply boats from Bahrain, but the main oil terminal was built at Umm Said (now known as Mesaieed) where there is a natural deep-water harbour. Umm Said is on the East Coast south of Doha, and thus pipelines had to be laid to carry the crude oil 35 miles across the desert peninsula. Two pipelines of 14½ inch and 16 inch diameter covered the first 14 miles, converging into a single 20 inch diameter pipe for the remainder of the distance to the Umm Said terminal. A degassing station was constructed at al-Khatiyeh near Dukhan and a surfaced road was laid between Dukhan and Umm Said. To say a surfaced road was constructed will perhaps give a false impression, for by any normal standards this was a very bad road, though for Qatar, which had no paved roads at all, it was something special. The company road was not properly levelled, it followed every bump across the desert terrain, nor was it surfaced with tar or any other material, it was merely drenched in crude oil to compact the loose sand surface. With the port ready and two airfields in operation at Umm Said and Dukhan, the company was ready to turn on the taps and allow the oil to flow along the pipeline from Dukhan to Umm Said for export. The first shipment was made on December 31st 1949". Official statistics show that the Dukhan Field produced 80,307 tonnes (640,000 b) of crude oil in 1949. Also in 1949, oil was discovered in the Arab D (Number 4 Limestone Member), and later in 1954 a minor oil accumulation was also found in the Middle Jurassic Uwainat Member of the Araej Formation.

The Dukhan Field is the only oilfield so far discovered on land in Qatar. It is on the west of the peninsula, and geologically is a long, narrow anticline running north-south with a productive area in at least four producing horizons (Alsharhan and Nairn, 1997; DesAutels, Hussain and Al-Ansi, 1994; *Dukhan Field – Qatar, Treatise Of Petroleum Geology*, 1991). The field is large by world's standards (Alsharhan and Nairn, 1997; DesAutels, Hussain and Al-Ansi, 1994; *Dukhan Field – Qatar, Treatise Of Petroleum Geology*, 1991; Tiratsoo, 1984) with the overall area being about 60 km long and 25 km wide. Oil and associated gas, from three main (separate) upper Jurassic reservoirs, the Arab C, Arab D (depth about 1800 m) (Al-Dolaimi et al., 1989 [27-30] and the Uwainat limestones (depth about 2200 m) (Al-Dolaimi et al., 1989; *Dukhan Field – Qatar, Treatise Of Petroleum Geology*, 1991; Wilson, 1991; Sharshar et al, 1991) are separated at degassing stations at Khatiyah, Fahahil and Jeleha. These stations were initially commissioned in 1954-5. In 1992, oil was also found to the south in the now called Diyab area in the Arab D (Alsharhan and Nairn, 1997; Qatar General Petroleum Corporation, 1997). Currently oil reserves for the whole field are estimated to be in excess of 2,000 MM barrels and associated gas exceeds 7 trillion scu.ft. Some 370 wells have been drilled. 200 are oil producers, 20 are gas producing and 130 are used for water or gas injection to maintain pressure in the oil reservoirs. Since 1990, gas-lift projects and the drilling of horizontal wells have increased production rates and with upgraded production facilities the field has a production capacity of 335,000 b/d of crude and 310 MMscu.ft/d of associated gas. About 150 new wells will be drilled and 70 existing wells will be side-tracked to sustain production during the next 10 years. The oil is a high quality light oil of 41°API gravity (a relative density of 0.82), viscosity of 0.25 cp but with an average sulphur content of 1.1%. The oil is considered volatile with a formation volume factor of around 1.6 and an average gas-oil ratio of around 200 vol./vol. (1100 scu.ft/b). The oils from the different reservoirs vary but have similar properties. The initial reservoir pressure was about 20 bar (300 psi) above the oil's bubble point (around 200 bar (3000 psi) (Alsharhan and Nairn, 1997). It is exported as Dukhan export stream of 41 °API.

Dukhan crude along with separated dry gas and raw condensate/NGLs recovered during field processing is pumped to Mesaieed (an average of 2600 tonnes per day during 1997) in separate pipelines where the gas is further processed to produce stabilised condensate and NGLs (propane butane etc.) (Almarry and Al-Saadoon, 1985). The crude oil, condensate and NGLs are then exported through the Mesaieed Marine terminal. Gas is passed through the Gas Distribution System (GDS) to the various consumers in Qatar. The upgraded surface liquid crude handling facilities at Mesaieed can handle 340,000 b/d of oil, 800,000 b/d of gross liquids and 350 MMscu.ft/d of associated gas.

The Arab D is the main oil producing horizon. It is 70 km, long and 6 km wide, and averages 60 m in thickness but in places is much more. Because of the quality of the mudstones, the Arab D is commonly characterised as a uniform reservoir. Both water and expanding gas cap are major reservoir drive mechanisms (Alsharhan and Nairn, 1997; *Dukhan Field – Qatar, Treatise Of Petroleum Geology*, 1991; Wilson, 1991). Approximately 80 wells are producers. Dumpflood injection commenced in peripheral wells in 1970 with water from the Nahr Umr and was expanded to use 56 wells by 1986 (Sharshar et al, 1991). Many of these wells have now been converted to pressure water injection. Significant corrosion problems have been identified in recent workovers on dump-flood injectors and corrosion products are thought to contribute to plugging (Sharshar et al, 1991). A recycling of some of the produced gas is carried out to maintain pressure and recover any condensed liquids; for this some 34 gas production and injection wells are used. Some of the produced gas is reinjected into the top of the formation to add to the gas which has collected as a gas cap to push more oil to the producers.

The Arab C reservoir is the second major oil producing horizon. It is about 50 km long by 5 km wide and averages 30m in thickness (Alsharhan and Nairn, 1997; DesAutels, Hussain and Al-Ansi, 1994; *Dukhan Field – Qatar, Treatise Of Petroleum Geology*, 1991). The Arab C is a very complex, fractured and highly stratified carbonate formation with the reservoir rock being generally less permeable on the flanks. The upper reservoir section contains over 40% of the STOIIP but the lower section has 90% of the total production, and acts as a conduit through which most of the oil is produced. Production from the Arab C started in the late 1940's principally from the lower section. Initial production indicated a limited water drive because of stylolitic growths (thin impermeable layers) which have been dated as late Cretaceous, a time when the reservoir rock was already oil-permeated. As a result of these styloylites, much of the oil in-place is isolated in porous lenses which are surrounded by thin, water-saturated limestones and are consequently difficult to develop. Dump-flooding and powered waterflood injection schemes have been successful though with the Nahr Umr Formation being the main water source. Currently there are about 9 powered water injection and controlled dumpflood injection wells for Arab C pressure maintenance (Al-Dolaimi et al., 1989). A tarmat is present in the bottom of the formation which has not yet been fully mapped. Nevertheless, production has been prolific and with 3-D seismic and particularly horizontal wells, more reserves are being booked and production has been increased.

The Uwainat reservoir has a reservoir thickness of 60-100 m and lies deeper, at a depth of around 2200 m so that its reservoir temperature is 100 ºC (Hussain, 1993). The upper 44 m of the reservoir has an average porosity and permeability of 18% and 15 md respectively. The reservoir contains a relatively thin oil rim with an overlying gas cap. Poor well productivity led to a closing down of early production in 1975 but production was restarted in 1983 after water injection facilities were installed. Further oil was discovered in 1992 in the southern part of Dukhan, now called the Diyab area, in the Arab D and is produced at 50,000 b/d by water injection (Alsharhan and Nairn, 1997; Qatar General Petroleum Corporation, 1997).

In 1960 sour gas was discovered in the deeper Permian Khuff Formation of dolomite under the Jurassic reservoirs at a depth of about 3100 m. The initial pressure was around 400 bar (6000 psi). It was brought on stream in 1978. These reservoirs are discussed in the section on gas. In May 1997 two further gas reservoirs were discovered in the southern part of the field (Qatar General Petroleum Corporation, 1997) where the reservoir pay zones were intersected at 2,800 m and 3,333 m respectively and are stated to be of modest size when compared with the North Field, but nevertheless substantial. These discoveries will make the gas injection and gas lift programs for the southern part of the field more attractive (Qatar General Petroleum Corporation, 1997). Deeper drilling to test if there is gas deeper than the Khuff has been carried out, so far to a depth of 5,200 m (in 1985). Hydrocarbons have been found (Alsharhan and Nairn, 1997) but the reserves have not yet been disclosed.

In summary, the onshore Dukhan Field produces light crude oil, associated gas, condensate and non-associated gas in significant quantities. For the petroleum engineer a fantastic experience of so many different types of reservoir in one area!

Offshore

The first concession for offshore exploration to be awarded in the Gulf, was to the Shell Company Qatar (SCQ) who on 29 November 1952 and after much haggling, gained the rights to exploration dull (Records Of Qatar; Primary Documents 1820-1960,1991; Al-Othman, 1984; Zahlan, 1979). The concession was for a period of seventy-five years and the company in return was to pay the Ruler an annual fee of £231,976, a rental of £75,415 until exports began and £37,707 thereafter until the expiry of the Agreement, a royalty of 4 shillings and sixpence (in decimal UK currency 23p) per ton and 50% of the profits from oil exports (Al-Othman, 1984).

A gravity survey was begun in June 1953, followed by seismic reflection surveys six months later. The structural interpretation of the seismic record showed that the eastern area is dominated by salt tectonics, whereas the northern area is very flat and featureless. Shell decided to drill the salt tectonic area. Operational headquarters were set up at Ras Abu Abboud east of Doha. After the shore preparations were complete, the company brought out a special drilling platform rig for offshore exploration in water depths of around 70m. The first two appraisal wells produced no results; in fact today we know that the first well drilled between the two domes of Idd El Shargi 95 km east of the northern tip of Qatar in 30 m water-depth and was considered 'not commercial'. It reached a depth of 3714 m. Towards the end of 1956 Shell suffered a set-back when a heavy storm destroyed the rig. The company then acquired a much stronger structure capable of withstanding the rare but vicious Gulf storms. In January 1959 drilling operations resumed, and after many problems and an outlay of more than 100 million Rupees, in December 1959 a well was drilled on the northern dome of the structure to a depth of 2600 m. The well found oil in the upper Jurassic Arab C and Arab D Formations, the Middle Jurassic Araej Formation and also in the deeper Uwainat. The field covers 38 sq. km, and the reservoirs depths are from 1400 to 2600 m. In March 1961, well No. 4 on the southern dome proved oil in the lower Cretaceous Shuaiba formation. On 9 January 1964, the company started production from its Idd El Shargi Field from the Shuaiba, Arab C and Arab D Formations (*Arab Oil and Gas Directory,*1998; Alsharhan and Nairn, 1997; Wottge, 1998).

Also, in 1964, a second discovery was made 30 km to the north-east of Idd El Shargi at Maydan Mahzam, where the Arab D limestone was found to be the largest producing bed. Its discovery well, drilled in July 1963 to a total depth of 2811 m, had also found oil in the Arab C formation. Oil has now also been found in the Uwainat strata (Alsharhan and Nairn, 1997; Munn and Jubralla, 1987; Hamam, 1985). A third offshore field, Bul Hanine, was discovered in March 1969 and brought on stream in 1972. Bul Hanine has been the most prolific of the three offshore oil fields, producing from the upper Jurassic Arab D, middle Jurassic Araej and Uwainat formations (Alsharhan and Nairn, 1997 *Arab Oil and Gas Directory,1998*).

An operational base was established on Halul Island near the oil fields in 1965 (fig 1). The island was formed by salt extrusion pushing up the formations (Alsharhan and Nairn, 1997). It is some 1.5 km long and 1.0 km wide and has 9 storage tanks for 3.4 MMbs (enough for 2 weeks production), pumping stations and desalination equipment as well as staff accommodation. Oil exported from Halul is a high quality crude of about 36 °API (the Marine export blend stream) and a sulphur content of 1.5%. It is created from a blend of the crudes produced from Idd El-Shargi, Maydan Mahzam and Bul Hanine with oil gravities of 30, 38, and 35 °API respectively (Alsharhan and Nairn, 1997) and now also oil from Al-Khalij. The reservoir oils are volatile with gas-oil ratios over 150 sm^3/sm^3 (<700 scf/b), so there is also substantial condensate and associated gas production which is separated in the fields and piped to Mesaieed.

The open literature only discusses isolated problems associated with these large fields, so in the section below only selected aspects are mentioned.

Idd El Shargi

The Idd El Shargi Field consists of two domal structures separated by a saddle. The traps were created by a rising salt plug The North (ISND) and South (ISSD) Domes have four major productive reservoirs, those in the Shuaiba, Arab C and D and in the Uwainat Formations but have somewhat different structural and sedimentological features (Alsharhan and Nairn, 1997; Hearn, 1997; Khalaf, 1989; Scofield, Laney and Woodard, 1997; Wottge, 1998). The ISND Field is estimated to have a STOIIP of 3.8 billion bbl but from 1964 to 1994 only 6% had been recovered. The ISSD formations have complex geology, particularly considerable fracturing, and are estimated to have 1.1 billion bbl STOIIP but have only recently been considered commercial, as discussed later.

In 1995, ISND was handed over to Occidental Petroleum of Qatar Ltd. in a Development and Production Sharing Agreement (DPSA). With improved oil recovery and refurbishment of existing facilities the production rate has been raised from 30,000 b/d to over 120,000 b/d (Wottge, 1998). With the field's main reservoirs being redrilled with horizontal wells (up to 80 wells), the rate should increase to a plateau of 160,000 b/d. Dual openhole laterals have been employed to simultaneously exploit the Shuaiba A and B oil reservoirs. Full field reservoir models for the Shuaiba and the Arab C and D reservoirs have been prepared and with new well data and pilot results, long term field development plans are being optimised (Hearn,1997; Wottge, 1998).

The Shuaiba reservoir is the shallowest of the current producing reservoirs in the field and lies at between 1500-1700m (4500-5100 ft ss) and contains an estimated STOIIP of 2.3 billion bbl sour oil, trapped in predominantly tight, chalky reservoir rock, with the central crest area containing 1.2 billion bbl and the flank a further 1.1 billion bbl. It covers an area of 16000 acres, and averages 120 m in gross thickness. It is multi-layered with low permeability zones between some productive layers. Well productivity, except for crestal wells, is poor because of the poor formation permeability, despite relatively high average porosity ranging from 18 to 26% across four distinct reservoir members (A, B, C, and D) which contain 41%, 32%, 15% and 12% STOIIP respectively. The permeabilities and heterogeneity vary over the reservoir with variations in the crestal area from 50 – 200 md and in the flank areas from 5 – 50 md. The whole reservoir is thought to be extensively fractured with variable degrees of fracture/fault sealing (Rubbens, Murat and Van Keulen, 1983) hence, to date, only 2.3% STOIIP has been recovered, and three-quarters of this from the crestal area, meaning that the reservoir is difficult to deplete (Scofield, Laney and Woodard, 1997; Wottge, 1998). The initial reservoir pressure and temperature were 2380 psi and 71^{o}C (160 ^{o}F) respectively and as the bubble point pressure is 1660 psi the reservoir was initially 720 psi (49 bar) undersaturated. The reservoir fluid is asphaltene rich, 27 ^{o}API oil with a solution gas-oil ratio of 300 scf/bbl and has an oil viscosity of 2.5 cp (0.0025 Pa s*)* (Alsharhan and Nairn, 1997; Wottge, 1998).

Originally the reservoir was produced under a form of gas/oil gravity drainage. Individual wells showed variable rates, but in general production rates were low, <1000 b/d. Due to the faulting, waterflooding vertically was considered unlikely to be of great benefit, but after simple matrix acid jobs the crestal wells showed some improved production performance (Jubralla and Hamam, 1991). Since the Shuaiba reservoir has low permeability and is multi-layered with very low permeability sealing sections between some layers, the newly developed retrievable multi-lateral system should prove very beneficial for production, because this allows completion of a single well with two or more horizontal wellbore sections. Such advanced drilling and completion technology should enable cost effective optimization of ultimate recovery by providing closely spaced horizontal well bores throughout reservoir. This drilling and completion method provides adequate flexibility to produce both sections simultaneously or each section individually, particularly for production monitoring purposes. Thus horizontal and now multi-lateral wells are therefore proving to be very beneficial for simultaneously producing the Shuaiba A and B layers. Additional production from the Shuaiba C and D is however unlikely due to the water saturations being in excess of 65%, making these zones non-commercial over much of the field area (Wottge, 1998).

Since 1994, there has been intense upgrading of facilities, with the installation of Shuaiba gas and water injection pilot projects. The gas injection pilot, which includes one gas injector and three surrounding producers, uses gas from the Arab A zone (at a depth of 2200m) flowing naturally into the upper Shuaiba layer (1300 m) through the same producer/injector well. The producers are one deviated well and two short reach horizontal wells. The performance of the gas pilot is being closely monitored for pressure, gas breakthrough and production to determine its effectiveness. The water injection pilot includes two long reach horizontal injectors and two adjacent horizontal producers that have up to 2900m long open hole pay zones. Source water for this project comes from the Yamama and Sulaiy Formations which are considered the best water sources. The water is lifted by a subsurface jet pump and reinjected, after extensive filtering to assure high quality. Once the results of both Shuaiba injection pilots are evaluated, installation of the optimum improved recovery scheme for the reservoir will be carried out (Wottge, 1998).

The Arab C reservoir has an oil column averaging 30m and is estimated to contain 250 MM bbl STOIIP of 27 °API oil with a gas-oil ratio of 700 scf/bbl. By year end 1997, 9% of STOIIP had been produced. The initial reservoir pressure was around 3500psi (hydrostatic) but production has now lowered the reservoir pressure to below the bubble point. The production mechanism is gas cap expansion and solution gas drive. Extra horizontal producers are planned to optimise oil recovery from this reservoir (Wottge, 1998).

The Arab D reservoir depth is around 2500m and reservoir thickness is 40-70m. It contains an estimated 1 billion bbl STOIIP of sour 33 °API oil with a gas-oil ratio of 750 scf/bbl. By year-end 1997, 18% of STOIIP had been produced. The reservoir's primary production mechanisms are gas cap expansion and solution gas drive. This is currently being supplemented with water injection via dumpflooding and approximately 90,000 barrels of water per day are being injected via 14 injector wells and produced by horizontal producer wells (Wottge, 1998). This is because there is a massive tar column over 90m thick zone which prevents significant aquifer influx (Al-Kaabi, Menouar, and Al-Hashim, 1988).

The upper Araej/Uwainat reservoir is found at 2600-2700m at an initial pressure of 3500psi and temperature of 110^{o}C and reservoir thickness of some 50m with porosity varying between 5 and 20% and permeability between 1-1600 md (Alsharhan and Nairn, 1997). Its STOIIP is estimated at 220 MM bbl and some 21% had been recovered by year end 1997. The oil is light at 39 ^{o}API with a gas-oil ratio of 1070 scf/bbl and has a low viscosity of 0.2cp. It has a very active natural water drive and is being produced through four producers (Wottge, 1998).

Oil has also been found in two further zones, the Kharaib and Nahr Umr reservoirs, with a potential STOIIP of perhaps 500 MM bbl. These have not yet been produced, but the drilling of appraisal horizontal wells is currently underway.

Bul Hanine

Both the Bul Hanine and Maydan Mahzam Fields are now at their mature stage. Production peaked in 1973 so that by 1981 output was down to little more than 200,000 b/d and 110,000 b/d in 1997 when Bul Hanine produced at 70,000 b/d and Maydan Mahzam at 40,000 b/d. Remaining reserves are estimated for Bul Hanine at 690 MMb and for Maydan Mahzam at 550 MMb. They have some 4.4 trillion scf associated gas between them. Their production facilities are being upgraded with the installation of enhanced recovery systems to prevent further declines in flow rates and maximise recovery rates. IOR was first brought into use at Bul

Hanine in 1978, when three water dumpflood wells and three additional producers were completed, increasing the field's production potential by 40,000 b/d. The application of dumpflooding techniques has since been extended to the Maydan Mahzam and Idd El Shargi Fields. Gas injection was installed at the Bul Hanine Field in 1987-88 with modified equipment on existing platforms, then installing a new platform for housing a booster compressor, and finally adding another gas production platform. Current development of the fields to maintain recovery rates includes the revamping of production facilities, the installation of water injection systems to maintain reservoir pressure as well as drilling a number of horizontal wells (Simpson and Laitiff, 1997).

The structure of the **Bul Hanine** Field is a dome of 11.5 km by 6 km with the crest at about 2800m ss. (Alsharhan and Nairn, 1997; Hamam, 1985; Munn and Jubralla, 1987). It has sour oil in the Arab C and D, the Upper Araej and the Uwainat. The oil in the Arab D is 35 ^{o}API with a viscosity of 0.5 cp and in the Uwainat 37 ^{o}API and 0.4cp. Some 40% of its STOIIP of 2.3 billion bbls has been extracted and is currently producing at around 70,000 b/d. The Arab D reservoir in the Bul Hanine Field has been the most prolific of the offshore reservoirs. It consists of a number of distinguishable layers. The lowermost section of mudstones (from 140m to 170m thick) generally having permeabilities ranging from 0.1 to 40md and interbedded dolomites (predominantly occurring at specific horizons, in the northern part of the field), which have permeabilities ranging from 1 to 500md. These mudstones and dolomites are overlain by grainstones and muddy sands (packstones) usually 20 to 30 m thick. Above this, grainstones form the dominant reservoir intervals and have permeabilities ranging from 1 to 3.5 darcies with occasional values as high as 11 darcies. A tar mat is present at the base of the reservoir. In 1980, contrary to earlier predictions, water-breakthrough occurred along discrete intervals of the reservoir in a crestal well. The Upper Araej reservoir is relatively thin and overlies the more significant Uwainat reservoir sequence. It has a low to moderate porosity and low to very low permeability no more than tens of millidarcies. It is gas bearing. The Uwainat is some 55m at 2800 m depth, has a porosity of 10-23% with permeabilities between 30-300 md.

Field redevelopment is being carried out particularly in the relatively tight upper units of the Arab D reservoir and the Uwainat rim reservoir through the drilling of horizontal wells (Munn and Jubralla, 1987; Simpson and Laitiff, 1997). By the year 2002, 75-80 new wells are to be drilled, up to nine new wellhead jackets and a gas recycling project installed for developing the Arab C condensate gas cap to boost condensate reserves by 100 MM barrels in a manner similar to the Dukhan Arab 'D' Recycling Project mentioned earlier.

Maydan Mahzam

In the Maydan Mahzam Field (Alsharhan and Nairn, 1997; Hamam, 1985) about 80% of the STOIIP is located in the Arab Formations particularly the Arab C and Arab D (84%) with most of the remainder in the upper Araej and the Uwainat. The field is interpreted as an elliptical dome 8.5 km by 6.0 km. Tar exists at the bottom of the oil zone in the Arab D horizon. The upper Araej reservoir has a low to moderate porosity and low to very low permeability of no more than 30 md. It contains gas but producible oil was found in 1983. The crest of the Uwainat is around 2650m with an oil column of 85 m. Because of the structure in the Uwainat, the oil is in a rim of 55 m thickness and has an oil-water contact at about 2735 m depth. This reservoir has a porosity of 10-23% with permeabilities between 2 and 300 md. The average net offtake per well from the thin oil rim was less than 800 b/d of 38 ^{o}API oil. An estimated 40% of the field's reserves have been extracted, and the ultimate recovery is expected to reach 55% through the continued use of water injection. Other improved oil recovery techniques are to be applied in order to maintain output above 40,000 b/d.

Al-Bunduq

The Al-Bunduq Field is a domal structure of 6 km width and 11 km length with a minor elongation trending northeast to southwest. It is located offshore to the east of Qatar and straddles the Qatar-Emirates sea boundary line. The Al-Bunduq Field was discovered in 1968 and, after a border adjustment agreement in 1969 between Qatar and the United Arab Emirates, it was agreed with Abu Dhabi that they should have an equal interest in the production. Thus, Qatar is entitled to half the oil produced (Bashbush, 1983; De La Cruz and Takizawa, 1985; Honda, 1989).

The Arab D Formation is the main reservoir. It mainly consists of 100 to 150 m of carbonates (lime mudstone). There are two distinct dolomite layers of high permeability and a complex facies which greatly affect the reservoir properties. It is overlain by 7m of anhydrite. A continuous bitumen zone exists above the present oil-water contact in the Arab D Formation and acts as a barrier to aquifer ingress, as evidenced by a pressure difference above and below the bitumen zone of over 15 bar. Above this the Arab C zone is also oil bearing, but is complex and can be further subdivided into layers with the bottom one being the most permeable. The Arab A and B Formations consist of several cycles of anhydrite, limestones and dolomite beds. The carbonate layers are thin, mostly less than 7 m, but are hydrocarbon bearing zones but of very low permeability, often only a few md. The overlying Hith Formationis composed mainly of anhydrite acts as its seal.

The field went into production in 1976 at an initial rate of 30,000 b/d, but output declined to only 4,000 b/d early in 1979. Production was then halted as a result of continued difficulties with an increasing oil/gas ratio and poor reservoir pressure. However, at the end of 1980 $330 million was invested in a secondary water injection programme to improve recovery from the Arab D reservoir and bring the Arab C reservoir into production. Production started again during 1983. The development of the Arab C reservoir required the drilling of two producing wells and four water injectors. Production from the Arab C started towards the end of 1987 increasing the field's total output to 30,000 b/d in 1988 and around 50,000 b/d in 1989, at about which level it has remained since. The oil produced from Al-Bunduq is exported via the Das Island Terminal in Abu Dhabi waters.

GAS PRODUCTION

The story of Qatar's gas is in two sections, before and after the full scale development of the North Field, which was brought into service in 1997. The key watersheds for gas have been the world's attitude towards gas from, initially (the early days), a by-product that had largely a nuisance value and requiring disposal (flaring), to a fuel for local application (1970-85) and now to a sought-after export product. However, economists express a note of caution since gas requires a far greater capital investment per unit of production when considering the whole supply chain. This means that, unlike oil which is almost always economic at market prices and is heavily taxed, gas development is driven by economics (the selling price of gas) and not taxation policy. Gas economics are complicated but gas cannot be regarded as a great currency earner that some might first think it will be (Stauffer, 1997). Huge investments are needed in the infrastructure of a processing plant and pipelines etc. There is rarely a huge surplus 'economic rent' available for the producing country so it has to derive any benefit from the exploitation of its gas by accumulating secondary benefits – development of infrastructure such as steel, plastics etc. or from the liquid NGL's and sale of sulphur (Qatar General Petroleum Corporation, 1997). The case of Qatar illustrates the importance of gas liquids. Gas from the North Field is "wet" i.e. has condensable components(Almarry and Al-Saadoon, 1985), so that the impact of NGL recovery upon the project economics is profound - the net value of the NGL's may possibly be greater than the probable income for the (liquid) methane from the LNG plant. However, for Qatar, the development of this gas potential, particularly the use of gas as a cheap and plentiful source of energy is paramount in any argument.

Associated gas

When crude oil is produced from a reservoir, gas comes out of solution- this is associated gas. Thus, associated gas has been produced in the Dukhan region ever since oil production began in 1949, but it was originally used solely in field operations. The gas began to be used for power generation when the first gas pipeline across the country was completed in 1962, enabling 25 MMscu.ft/d of gas to be carried from Dukhan to Doha. Gas is now separated and compressed at field degassing and compressor stations then flowed to Fahahil where there is a stripping plant (capacity 340 MMscu.ft/d). After the heavy ends are liquefied and removed, the lean gas (228 MMscu.ft/d) is passed to the gas distribution system. The raw natural gas liquids (NGL) stream separated at Fahahil were separately piped to a fractionation plant in Masaieed (see the pipeline layout in Figure 1). Here LPG and condensate for export, as well as raw material and feedstock for the petrochemical and fertiliser industries and fuel for the seawater desalination plant and power station at Ras Abu Abboud are produced. This plant can produce some 1,400 tonnes/d of ethane-rich (58%) gas, 1,300 tonnes/d of propane, 850 tonnes/d of butane and 600 tonnes/d of natural gasoline. The ethane-rich gas is used as feedstock to the petrochemical complex, and the other products exported. Associated gas is also produced along with the oil from the off-shore fields. It is separated from its crude oil and then compressed on the Idd El-Shargi, Maydan Mahzarn, and Bul Hanine platforms and brought ashore through an 85 km under-water common-carrier pipeline to a second NGL plant at Masaieed. The fractionators at Masaieed are interconnected so that each can process liquids from either the onshore or the offshore system.

Reserves of onshore and off-shore associated gas are estimated at about 5.5 and 4.5 trillion scf respectively.

Non-associated gas

Onshore non-associated (Khuff) gas

In 1960, gas was discovered in the Permian Khuff Formation under the Dukhan oilfield at a depth from about 3100 m. This reservoir started producing non-associated gas in 1978 and was the main source of supply for Qatar's domestic gas fuel requirements and used by local industry for its power and desalination complexes. The reservoir is capable of delivering 800 MMscu.ft/d from its 10 dual purpose injection/ production and 7 production wells. Dew-point reduction and drying is carried out by low temperature separation plants located at the wellhead and the gas then passes to one of three separation plants at Khatiya, Fahahil and Jaleha. Over 1,500 billion scf have been produced, but the Dukhan Field has stopped regular gas production because of the North Field, (discussed below). It is now used as a buffer store for any unsold (surplus gas) from the North Field and as a strategic reserve if the North Field has problems. It will now only produce to Qatar's gas distribution system if the North Field supply is interrupted. Thus the average production in 1996 was only 40 MMscu.ft/d. The volume of North Field gas injected in 1996 was 290 MMscu.ft/d. The remaining reserves are however about 0.6 trillion scf (being increased with new drilling) *(Arab Oil and Gas Directory, 1998;* Qatar General Petroleum Corporation, 1997).

North Gas Field

The North Field, discovered in 1971 by Shell, lies mainly offshore to the north-east of Qatar's Peninsula towards the Iranian sector of the Gulf in water depths ranging from 15 to 70 metres (figure 1). It covers an area of more than 6,000 square kilometres, which is about half the State of Qatar's land area. The field contains unassociated sour gas trapped in the carbonate series of the Permo-Triassic Khuff Formation in four beds between 2500 and 3900 m sub-sea (Kasnick, 1987; Martin, 1997) with pressures up to 5,800 psi (390 bar). The recoverable reserves are estimated to be about 380 trillion scf (35 trillion scf in Khuff 1, 150 trillion scf in Khuff 2-3, and 195 trillion scf in Khuff 4) and total gas in place exceeding 500 trillion scf, so that the North Gas Field is considered to be the largest single gas reservoir in the world thus far discovered. As stated earlier, it has about 6% of the worlds gas reserves, sufficient to supply the whole world for about four years at current gas usage. The sour gas is rich in hydrocarbon condensates, which adds to its value in terms of potential revenue. In fact it may even be a retrograde condensate, which, if so, care has to be taken on pressure depletion because some of the condensate (perhaps as high as 45 bs/MMscf) could drop-out within the reservoir matrix and is unlikely to be produced (Almarry and Al-Saadoon, 1985). A pressure maintenance or dry gas injection (CH_4 or N_2) scheme may then have to be implemented. Other challenges include the handling of the fairly noxious gas which contains corrosive and poisonous constituents such as 1% H_2S, 4% CO_2 and the brine, all at reservoir pressures exceeding 300 bar (4500 psi), (Al-Maslamani, 1995; Martin, 1997).

The massive reserves of the North Field and the merits of natural gas as clean, safe and reliable source of energy has created from 1987 a spirit within Qatar to develop the North Field, so far in two stages.

North Gas Field before 1997

The first development project started in mid-1987 with the construction of facilities to produce non-associated gas to serve local industry and re-injection into the Dukhan Khuff reservoir, as well as allowing for the export of 40,000 to 50,000 bpd of LPG and condensates stripped from the gas output at Mesaieed. The design capacity was for 800 MM scu.ft/d of wellhead gas yielding 750 MM scu.ft/d of lean gas and about 50,000 b/d of liquefied petroleum gas (LPG)-naphthas for export. This phase became operational in September 1991, *(Arab Oil and Gas Directory,1998;* Qatar General Petroleum Corporation, 1997).

North Gas Field after 1997

The field has now been further developed in stage 2 and on 24th February 1997, Qatar became a major LNG gas exporter. The aim is to produce dry gas for export by pipeline and/or as liquefied gas to neighbouring or world markets. The ultimate production capacity will be dependent on the availability of export markets *(Arab Oil and Gas Directory,1998;* Qatar General Petroleum Corporation, 1997). The offshore facilities section are located about 75 km from Ras Laffan, and currently comprises six platforms including two well-head platforms, each with eight producing wells and an additional well. Special care is needed in the design of wellbore and equipment to take into account the sour nature of the gas [18]. The average production capacity of each well is around 50 MM scu.ft/d. The remaining four platforms include a riser platform for receiving the production pipeline, the surface valves and the gauges; a production platform; a utilities platform; and an accommodation platform. The pipeline section consists of two main pipelines: one for dehydrated gas and the other for the condensates, and transports these two products separately from the offshore complex to a landfall at Ras Laffan and then to Mesaieed. There is another pipeline from Mesaieed to the Dukhan area, for reinjecting into the Khuff reservoir in Dukhan Field the lean gas which is surplus to domestic requirements.

The facilities onshore at Ras Laffan include a plant for processing the gas and condensates produced from the North Gas Field. Here sulphur impurities and acid components are removed, and liquid components such as naphtha, gasoline, propane and butane separated and treated. The dry gas is also piped for use in energy generation and for operating electricity plants. *(Arab Oil and Gas Directory,1998;* Qatar General Petroleum Corporation, 1997). Phase 2 became operational in early 1997 with shipments of LNG to Japan in specially constructed ships taking 135,000 m^3 (3.1 billion scf) of LNG per load. The downstream industrial projects of petrochemicals, fertiliser, methanol etc are being developed rapidly at Mesaieed. The design life of the offshore production complex is at least 50 years. In essence, this massive project has had ten years of planning, five years of construction and some $3.5 billion of investment. A fuller discussion of the facilities being developed both offshore and at Ras Laffan for the production of liquefied natural gas (LNG) production, the negotiations for selling the gas in the future converting it to chemical products particularly liquid fuel by the Sasol or the ACG-21 Exxon process can be found elsewhere *(Arab Oil and Gas Directory,1998;* Qatar General Petroleum Corporation, 1997).

EXPLORATION, APPRAISAL AND DEVELOPMENT OPERATIONS FROM 1990

New Oil Discoveries

In the 1970's and 80's although finds were announced, no commercial discoveries were made in Qatar, and between 1970 and 1990 no new oilfields were brought into production. However since 1991, three oilfields have been developed.

Al-Khalij

The Al-Khalij oil Field was discovered by wildcat drilling after extensive 2-D seismic activity in January 1991 and confirmed by further drilling on 1st June 1991 *(Arab Oil and Gas Directory,1998;* Alsharhan and Nairn, 1997; Qatar General Petroleum Corporation, 1997). It was the first discovery in Qatar for 20 years. It lies to the east of the North Field and runs along Qatar's maritime border with Iran. Seven exploratory/appraisal wells were drilled by September 1993 to appraise the stratigraphic trap. It is 41m thick in the Mishrif Formation (Upper Cretaceous) at a depth of 1,200 metres. It is of wide ranging quality carbonate rocks. The results of three wells led to estimates of the field's probable recoverable reserves of 200 MMbbls with the field producing at 30,000-50,000 b/d. Appraisal was completed during 1995/1996 and the field brought onto production by mid 1997 with the production rate reaching 30,000 b/d of 28 °API sweet crude with nine production wells. The crude oil is pumped the 42km to Halul Island in a 12" subsea pipeline, uses the process facilities there and is mixed in with the Marine export blend. Power for the field is generated on Halul Island and transmitted by subsea cable. This is evidence of the recent attitudes to cost reduction by careful field management and using available resources.

Al-Rayyan

The Al-Rayyan Field was discovered in 1976 is located approximately 70 km north-northeast of the Qatar peninsula where the water depth is 33m. It is an oil-bearing reservoir in the Jurassic Arab A and Arab C formations in a zone above the North Field that was thought to be essentially gas-bearing *(Arab Oil and Gas Directory,1998;* Alsharhan and Nairn, 1997; Qatar General Petroleum Corporation, 1997). The layers are thin, probably not much more than 20m thick. An appraisal well drilled to confirm the find was tested in September 1995 and produced around 10,000 b/d of a heavy, sour crude (24 ºAPI and 3.4% sulphur). The Arab A and Arab C zones were cored, logged, and tested in a vertical pilot hole. Three more production wells were drilled into the Arab Formation using horizontal well technology and low invasion drilling fluids. The low invasion, good quality core played a vital role in understanding the reservoirs properties (Rathmell et al, 1997). Estimates of STOIIP vary but may be as high as 1.3 billion bbl and 40 trillion of recoverable associated gas. The field was brought on stream in mid-November 1996 at a rate of around 10,000 b/d. Production rose to 32,000 b/d by mid 1997 using horizontal production wells through the Arab A and C zones. Output is scheduled to level off at 30,000 b/d for the next few years when the jack-up rig and offshore tanker loading facilities may be replaced by permanent production platforms and onshore tanker loading facilities at, probably, Ras Laffan.

Al-Shaheen

The Al-Shaheen Field was discovered whilst appraising the North Field in 1974 on the edge of the field at a depth of 1,100m in the mid Cretaceous Kharaib Formation *(Arab Oil and Gas Directory, 1998;* Alsharhan and Nairn, 1997; Qatar General Petroleum Corporation, 1997). The structure is flat and on further appraisal, oil was also found in smaller volumes in the Khatiyah, Mauddud and Shuaiba carbonates as well as the Nahr Umr sandstone. All five reservoirs are complex thin low permeability oil bearing layers of 4-12m thickness. Due to these thin layers, horizontal wells are being used to gain maximum oil production with minimum water coning and fines production. The field started up in late 1994 and was the first new oilfield to have been brought into production for 20 years in Qatar. It produces a heavy sour 30 ^{o}API crude with 1.9% sulphur and is due to produce at least at 100,000 b/d by 2000. The drilling programme is now developing the production and water injection wells as well as delineating the five Kharaib thin formation layers in the field to maximise both oil and gas production. 70 producing wells are being drilled as part of the full-field development. Considerable directional steering is needed to keep the wells in the oil horizons. The Al-Shaheen 2 well set a world record for lateral drilling, since it included a horizontal section of 4120m, and in September 1995, another appraisal well drilled to further test the Kharaib Formation, included a horizontal section of 4,200m at a continuous deviation of over 86^{o}. The crude is exported directly by tanker from single point mooring facilities.

Export Terminals

Crude oil, oil products and gas are exported from Qatar, particularly to the Far East. Oil and condensates are shipped from terminals on Halul Island, Mesaieed, some refined products from Ras Abu Abbud and, since 1997, from the terminal built in Ras Laffan for LNG exports from the gas liquefaction plant in the Ras Laffan industrial zone for the gas from the North Field development *(Arab Oil and Gas Directory, 1998;* Qatar General Petroleum Corporation, 1997).

THE FUTURE

Qatar is rich in hydrocarbons and for the next 25 years is comforted by the fact that the alternatives for many of the products from oil, including renewable energy, are not yet viable.

There are new exploration targets, particularly the small, satellite reservoirs which exist near the current producers, including the development of the geologically difficult heterogeneous South Dome of Idd El-Shargi (ISSD) and the Al Karkara area west of the Al Bunduq Field. The ISSD oil field offshore Qatar, lies about 24 km south of the Idd El Shargi North Dome (ISND) field. The ISSD Field is of complex geology, with much of the formations being of poor quality fractured reservoir carbonate rock (Alsharhan and Nairn, 1997). It is estimated to hold 1.1 billion bbls of oil in place with ultimate gross recoverable reserves put at 200 to 300MM bbls. A development investment of some $450MM in capital over the life of the project is planned. The ISSD Field will be operated as a satellite of the ISND in order to keep overall per unit bbl operating costs down, probably with unmanned platforms. The current development plan has the drilling of 36 wells from three platforms, including 21 producers, 13 injectors and 2 water-disposal wells. Two pipelines, one for oil and one for gas, linking the ISSD Field to the processing facilities on the main ISND production platform will be built. Clearly such activities depend on the continued existence of a parent platform for economic success.

Since 1993, there has been much offshore exploration activity. More offshore fields have been discovered and appraised. Also developments in seismic interpretation using 3-D are growing at a very rapid pace and are giving much clearer images of the reservoir architecture. Such seismic and geophysical work has enabled seismic maps of the whole of Qatari territory to be made, including unified seismic maps illustrating the thickness of geological strata. These studies suggest the possible existence of stratigraphic traps between the North Field and other known offshore structures. Much drilling activity in recent years has been carried out to this end. With developments in horizontal and multi-lateral well technology more of these fields will become commercial and come on onstream. For these fields, after they have been discovered, there will have to be appraisal, evaluation and some agreement on efficient fair equitised production plans if they cross an international boundary. New field production systems will use new and cost reducing ideas, with offshore lightweight jackets, integrated topsides, and greater use of floating and subsea systems tied into existing facilities and unmanned platforms. All these technologies have been tested elsewhere in the world. Safety features have increased and are being incorporated into every new and upgraded development plan.

CONCLUSIONS

The Qatar petroleum industry is 50 years old and in that time there have been tremendous achievements. The consequence of these activities is that production of oil from Qatar is expected to achieve production levels of light oil from onshore and offshore fields of over 700,000 b/d and over 2 B scu.ft/d of gas and NGL products for at least 30 years. Since 1978 Qatar has been producing value-added products including fertiliser, steel, cement, power, desalinated water, petrochemicals, plastics and NGLs all based on oil, associated gas and its huge non-associated gas reserves.

Horizontal drilling with multi-lateral features is becoming common in all the development plans so that a smaller number of wells, and consequently a smaller number of well slots on the platforms, and yet greater productivity from each well is expected. This keeps operating costs down, but much depends on the oil price and whether the hydrocarbons can be lifted and then sold to market at a commercial margin.

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Fig 1. Map of Qatar
Fig 2 Generalised Stratigraphic column of Qatar

Appendix

Historical Data Production (compiled from Arab Oil And Gas Directory1998; British Petroleum Statistics,1998; Qatar General Petroleum Corporation, 1997)

Year	Oil mb/d	Gas MM scu.ft/d
1950	34	
1961	177	
1962	186	
1963	191	
1964	215	
1965	231	
1966	291	
1967	323	363
1968	339	330
1969	355	330
1970	362	340
1971	430	410
1972	483	500
1973	570	560
1974	518	515
1975	437	520
1976	497	450
1977	444	410
1978	487	450
1979	508	600
1980	471	610
1981	415	560
1982	332	556
1983	269	540
1984	325	560
1985	290	550
1986	314	564
1987	230	646
1988	292	649
1989	360	727
1990	405	780
1991	390	810
1992	450	1240
1993	420	1310
1994	390	1250
1995	420	1210
1996	510	1310
1997	649	1400

Much gas was flared until 1979. In 1967 96% was flared; in 1975, 75% was flared and in 1982 less than 2% was flared. Now it is used for heating and refinery purposes. Flaring in 1997 is less than 5%; this flaring is necessary from a safety point of view. The figures here are total gas (associated and non-associated).

~TVD, m	Age	years/ MM years	formation	lithology	field
0					
	Eocene		**DAMMAM**		
		60	**RUS**		
400	**Paleocene**		**UMM ER RADHUMA**		
			SIMSIMA		
			FIQA		
1000	**Upper Cretaceous**	80	**HALUL**		
			LAFFAN	anhydrite seal cap rock	
			MISHRIF	carbonate	*oil **AK**,AS*
			KHATIYAH	carbonate	*oil AS*
			MAUDDUD		*oil AS*
	Middle Cretaceous	100	**NAHR UMR**	sand/shale	***oil** D, I, AS*
			SHUAIBA	carbonate	***oil D, I***
1200			**HAWAR**	shale seal	
			KHARAIB	chalky limestone	***oil D,** I,**AS***
		120	**LEKHWAIR**		
			YAMAMA		
	Late Cretaceous		**SULAIY**		
	Upper Jurassic	150	**HITH**	Anhydrite seal/ carbonate	
1500			**ARAB A,B,C,D**	carbonate with anhydrite seals often thick formations	***oil D(C+D), I (C+D), AB(C+D), AR (A+C) BH(C+D), MM(C+D),***
			JUBAILA		
			DIYAB	carbonate- source	***oil** D*
		180	**HANIFA**	Mudstone - source	
2000			**UPPER ARAEJ**		***oil** D,I,MM*
	Lower Jurassic		**UWAINAT**	carbonate	***oil B,BH,D,I,MM***
		210	**LOWER ARAEJ**	thin zones	***oil** D,I*
2300			**IZHARA**		*oil BH*
	Upper Triassic		**GULAILAH**		
	Lower Triassic	220	**KHAIL**	anhydrite seal	
2700			**SUDAIR**		
3000	**Permian**	250	**KHUFF KI TO K3**		***gas D, N***
			UPPER ANHYDRITE		
			KHUFF K-4		***gas D, N***
3500		260	**HAUSHI**	anhydrite	

Figure 2. Generalised Stratigraphic Column for Qatar. **Bold**-major pay zones
AB=Al-Bunduq, AK=Al-Khalij, AR=Al-Rayyan, AS=Al-Shaheen, B=Bul Hanine, D=Dukhan,
I= Idd El Shargi, M=Maydan-Mahzam, N=North Field.