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2009 – Issue 14

# Brazil oil & gas

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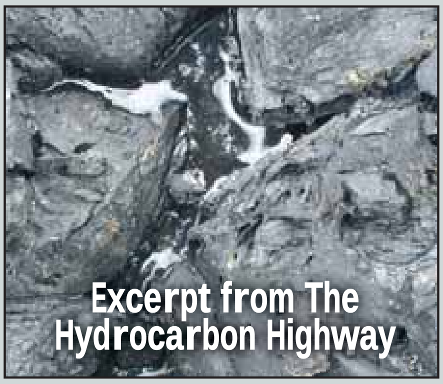
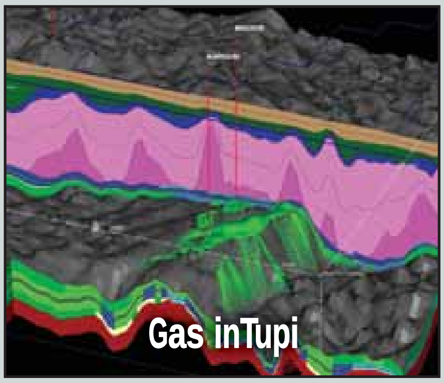
## Inside

Water Solutions



Excerpt from The Hydrocarbon Highway



Gas inTupi

Image Courtesy of Liderroll
– see page 21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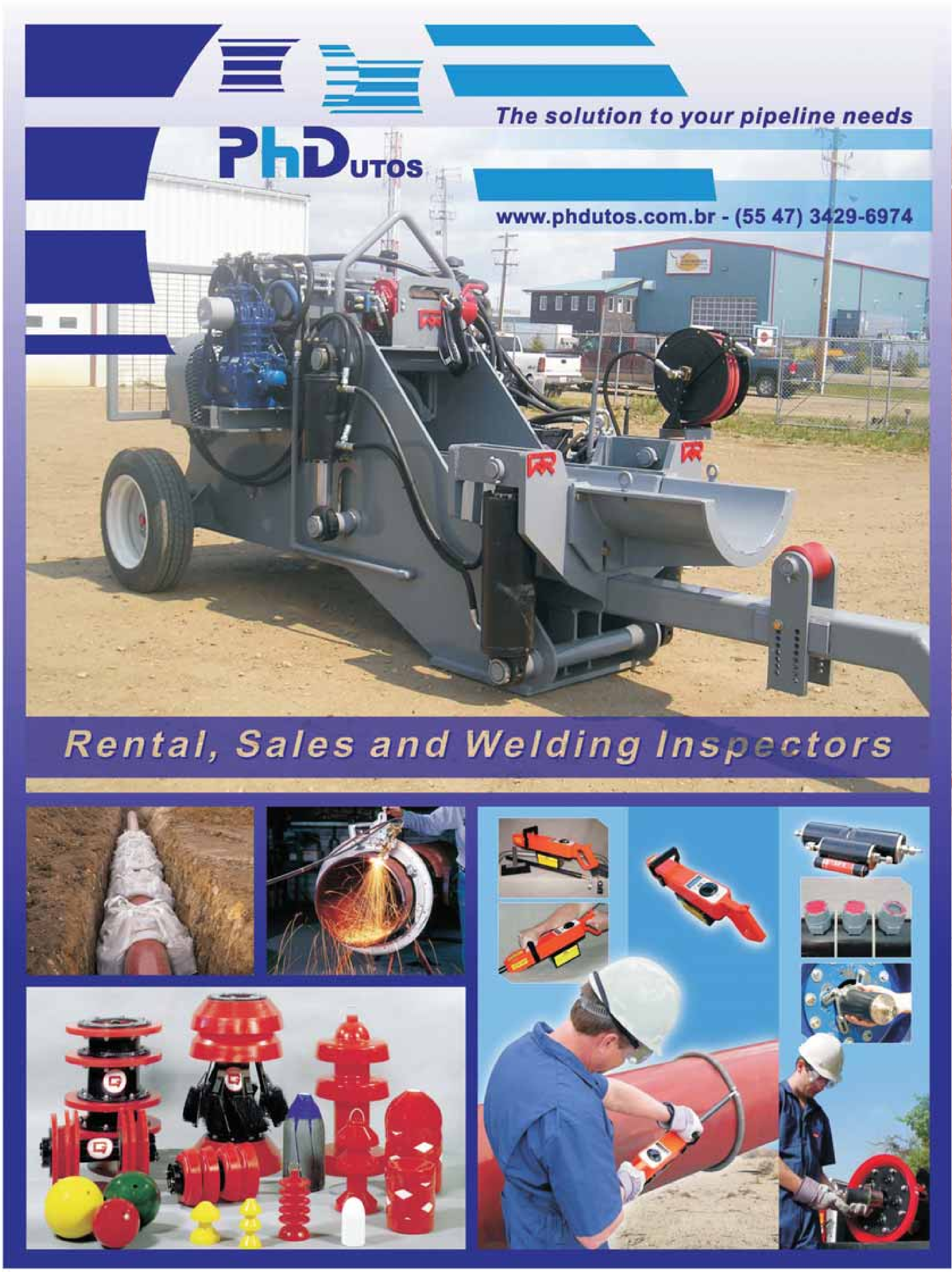
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# Contents









# CEO Gabrielli delivers keynote speech at the Brazilian Geophysical Society's International Congress

By PETROBRAS News Agency


Petrobras CEO, José Sergio Gabrielli de Azevedo.

Petrobras CEO, José Sergio Gabrielli de Azevedo, participated in the opening session of the 11th International Congress of the Brazilian Geophysical Society, at the Salvador Conventions Centre. In his address, Gabrielli highlighted the important role the work done by geologists and geophysicists plays in Petrobras' success.

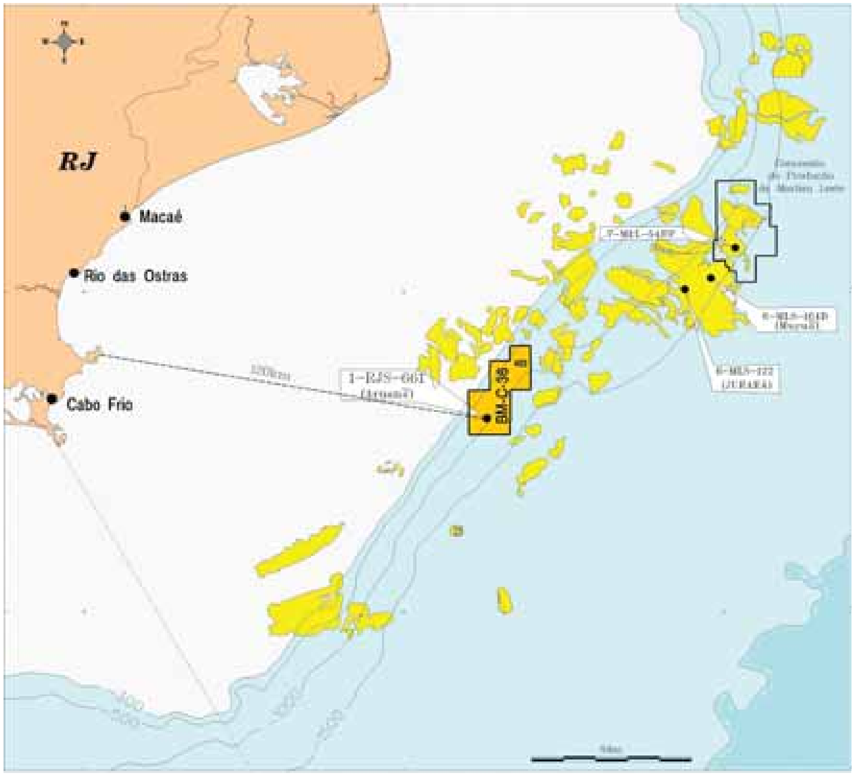
"Geophysics is fundamental for oil prospection. We could not be doing what we are doing without Geophysics," said Gabrielli. To him, oil exploration and production results, essentially, from practical knowledge. "You learn by doing, as long as you have the theoretical base for that. Geophysics helps us anticipate locations, guide investments and avoid waste."

The main purpose of the Brazilian Geophysical Society's biannual International Congress was to update information and exchange technical knowledge in the area of geophysics. During the congress, which lasted until 08/28, Brazilian and foreign scientists presented the results of their research projects, in addition to new technologies or case studies.

The pre-salt was one of the congress' main themes. In addition to the technical sessions, a workshop designed especially to discuss the challenges associated to exploration and production in this area was also scheduled. Other themes discussed were 4D seismic and onshore operations. A novelty in this edition of the event was also an exhibition called "What geophysics is", which was aimed at high school students, who may learn, in the form of experiments, the several applications of geophysics.

# Petrobras discovers more light oil in the Campos Basin

By PETROBRAS News Agency




Petrobras announced a new oil discovery, the Campos Basin post-salt layer (carbonate reservoirs), with the drilling of well 1-BRSA-713-RJS (1-RJS-661), informally known as Aruanã, in Exploratory Concession BM-C-36 (block C-M-401), which is operated exclusively by Petrobras. Preliminary analyses indicate not only the presence of recoverable volumes of some 280 million barrels of light oil (28° API), but also good productivity. Block BM-C-36 was acquired in the seventh round of bidding held by the National Petroleum Agency (ANP) on October 17 and 18 2005.

The discovery well is located nearly 120 km off the coast of Rio de Janeiro and at a water depth of 976 meters. The discovery was proved based on assessments (lined well formation test) in reservoirs located at depths ranging from 2,993 to 3,123 meters. The discovery will then be the object of an Assessment Plan to be submitted to the ANP.

## Marlim Sul

Also in the Campos Basin, in the Marlim Sul Field, in reservoirs geologically similar to this discovery, Petrobras drilled wells 6-MLS-122-RJS (Jurará) and 6-MLS-146 D-RJS (Muçuã), in 2007 and 2009 respectively, at water depths of 1,200 meters. These wells allowed for joint estimations of 350 million recoverable barrels of 27° API oil. The development of these projects has been foreseen in the 2009–2013 Strategic Plan, and early production is being deployed at platform P-51, which already produces oil in the area, and, in 2011, at platform P-56, which is currently under construction.

## Marlim Leste

Also regarding this type of reservoir, it is important to keep in mind that knowledge has already been amassed in the exploration of the Marlim Leste field, by means of well 6-MLL-14-RJS, informally known as Jabuti (2005). In waters at a depth of 1,300 meters and at 120 km off the coast, this well identified a reservoir with a recoverable volume of some 345 million barrels of recoverable 28° API. The first oil of this reservoir was produced in 2008 with the FPSO Seillean platform.

The joint production of these areas is expected to make short- and medium-term contributions to the Company's production curve, as production and drainage structures are already installed there.

# The Super Giant Pre-Salt Hydrocarbon Province in the Deep Water Santos Basin, Brazil

By Márcio R. Mello, Nilo C. Azambuja, Eduardo de Mio, André A. Bender, Carlos Luciano. C. de Jesus and Priscila Schmitt – HRT Petroleum




## ABSTRACT

Recently, HRT, in cooperation with CGGVeritas, finished a very important study over Brazil's pre-salt giant oil province: the 3D Petroleum Systems Modeling of the Deep Water Santos area, covering the BM-S-8, BM-S-9, BM-S-10 and BM-S-11 Cluster Blocks and surroundings (Fig. 1). This area encompasses the five most important, recent worldwide discoveries including the supergiant fields of Tupi, Jupiter and Iara and the successfully tested prospects of Bem-te-Vi, Guará, Carioca and Parati. Volumes are surprisingly large, which may reach 18 Bbbls of reserves. This summary article includes a partial view of a very detailed petroleum system 3D model of the Cluster area, deep water Santos Basin, in which oil and gas generation, expulsion and migration pathways are showed as well as the impressive prediction of hydrocarbon volumes and composition of the oil and gas accumulations.


## METHODOLOGY

A 3D integrated petroleum system modeling using a geological and geophysical framework was built based on very detailed mapping using a 20,000 km$^2$ PSDM seismic data (provided by CGGVeritas). The 3D basin

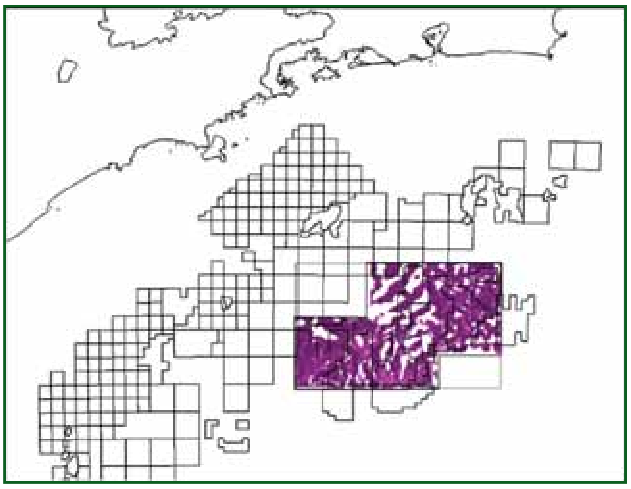


Figure 1 - Location of the study area in deep water Santos Basin. This area contains the Tupi oilfield announced as having up to 8 BBbls of oil reserves.

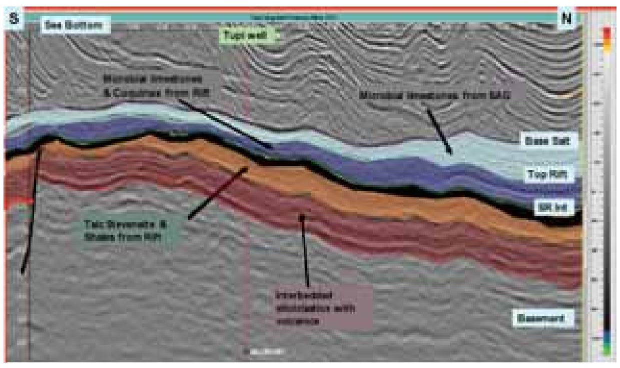



Figure 2 - North-south geological section across the study area showing the main pre-salt sedimentary facies mapped in the area of the Tupi well. Note the distribution of the main carbonate reservoirs and their association with the source rock sequences (HRT-CGGVeritas).

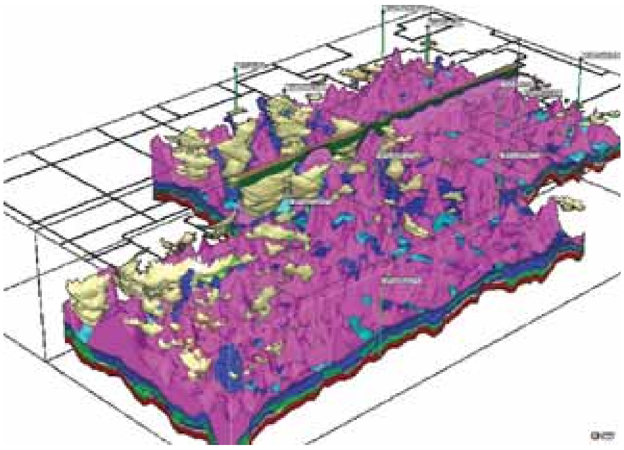


**Figure 3 - Detailed facies distribution in Sag and pre-salt section built using Petromod software and based on well data, conceptual geological model and seismic attributes. The view presents the salt layers (in pink), the carbonate reservoirs in the upper part of Alagoas SAG sequence, the source rocks and the basement.**

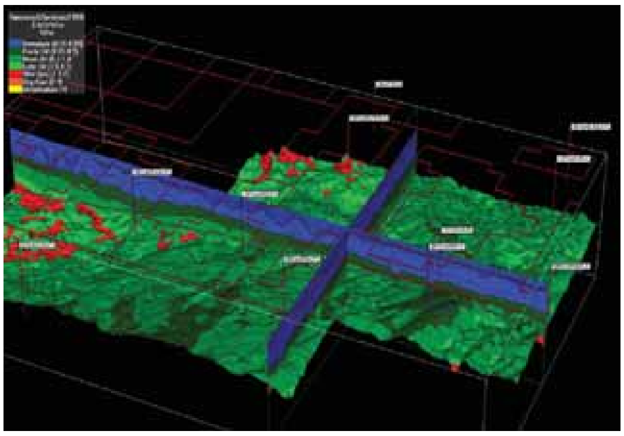


**Figure 4 - Vitrinite data prediction over the studied area suggesting an oil prone condition for the whole pre-salt area in deep Santos Basin. Present time conditions.**

model used information about source rocks richness, thickness, distribution, kerogen kinetics, reservoirs quality, sealing rocks and trap geometries. An integrated 3D petroleum system simulation with PetroMod (provided by IES) allowed an evaluation of the interplay among the elements and processes of the petroleum system to assess source rock potential (vertical and horizontal distribution), thermal evolution of the source rocks, transformation ratio, hydrocarbon generation and charge, timing of migration, oil origin, quality, and a volumetric quantification of the accumulated petroleum in the main reservoirs (Fig. 2). A detailed facies model from pre-salt section was built based on well data and conceptual models from seismic interpretation associated with previous knowledge of the tectono-sedimentary sequences of the Santos basin (Fig. 3).

## RESULTS

The Santos Basin is considered today the most important frontier of exploration in Brazil to hold giant to super giant hydrocarbon reserves in the pre-salt sedimentary sequences (Melo. *et al.*, 2009).

The main results of the 3D Petroleum system modeling of the Cluster area of the Santos basin indicate that transformation of the main depocenters of the Barremian source rock systems in the area reached almost 80%

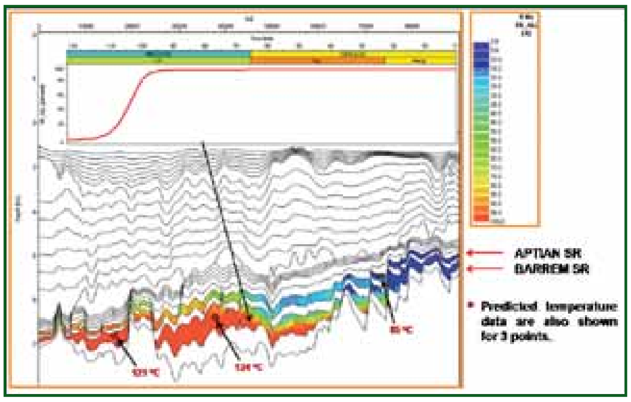



**Figure 5 - Transformation ratio values in a cross section through the Tupi High. Note the low temperature values in rift section.**

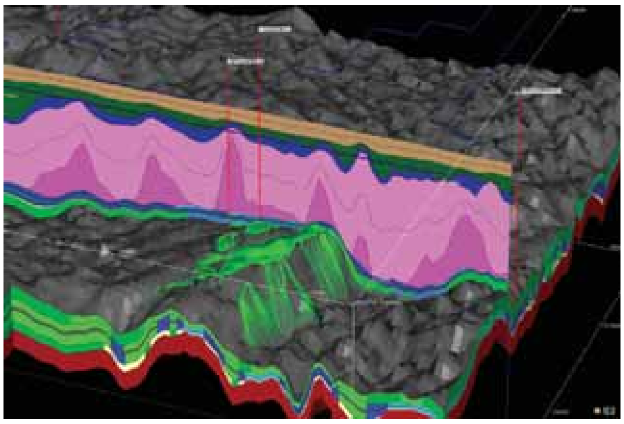


**Figure 6 - Accumulated hydrocarbons in the Tupi Area. Announced reserves can reach up to 18 Bbbls of oil reserves.**

at present day. On the other hand, the Aptian lacustrine source rock is partly transformed in the depocenters (70% in average) and it is not expelling in the highs (<20%) where the main accumulations were discovered up to today (Mello *et al*., 2009). The predicted vitrinite reflectance data suggested that most of the Aptian source rock systems, deposited in a lacustrine brackish to saline alkaline lake environment, are inside the early to peak oil generation stage in the mapped area (Fig 4).

Two physical parameters are mainly responsible for the adequate thermal conditions for the oil generation and its preservation: the heat flow history and the high average thermal conductivity of the evaporitic layers. Contrary to the prediction of high heat flow values in ultra deep waters by theoretical models (e.g. McKenzie type of models), the heat flow peak never reached values higher than 120 $mW/m^2$. Additionally, the vulcanoclastics that occur stratified in the pre-salt sequences so far do not represent a risk neither in terms of high temperature intrusion nor for reservoir or source rock quality (Mello *et al*., 2009).

Predicted temperature values in the main source rock systems deposited in a lacustrine saline alkaline lake environment, such as the Aptian calcareous black shale, section (e.g. Coquinas section in the Campos Basin; Mitsuro, 2008) and the Barremian black shales, deposited in a lacustrine brackish alkaline lake system (e.g. Talk Stevensite section in the Campos Basin; Mello *et al*., 1995 and 2009; Dias, 2004) range from 92° to 130°C in the deepest part of the basin, and 70° to 90°C in the shallowest areas (Fig. 5). Such values are critical in, not only preserving the oil prone nature of the whole area, but also preserving the permoporosity and reservoirs temperatures (Mello *et al*., 2009).

In general the pressure behavior seems to reflect the structural discontinuity of the halite salt core of the evaporitic sequence, which allowed pressure release in the pre-salt layers reaching this way normal pressure values for most of the area. Excess pressure is surprisingly low in the pre-salt rocks. The highest excess pressure values are less than 0.2 MPa in local depocenters and are at hydrostatic state over most of the area (Mello *et al*., 2009.

However, it is important to mention that the main exploration and production risk lies in the nature and petrophysical characteristics of the reservoir rocks, composed by stromatolites, coquinas and volcanoclastics

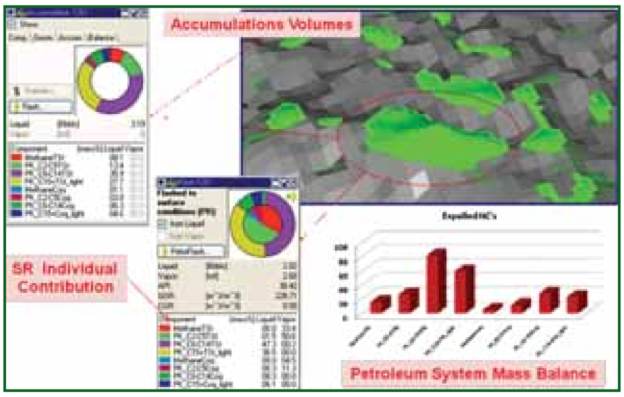



**Figure 7 - 3D petroleum system accumulation simulation model, only for the pre-salt province, suggests a potential reserve, in the Cluster area of the Santos Basin, much larger than reported, in excess of 60 Billion bbls of oil reserves.**

that occur alternating themselves and sum more than 400 m in thickness and extend for more than 1500 km, from Southern Santos up to Northern Espírito Santo Basin, presenting porosities ranging from 8% to 20% and permeability ranging from 20MD to 500MD (Mello *et al.*, 2009).

The charge and accumulation simulation model, only for the pre-salt province, suggest a potential reserve, in the Cluster area of the Santos Basin, much larger than reported, getting numbers over to 60 Billion bbls of oil reserves (Figs 6 and 7).

The discoveries of low sulfur, pre-salt, lacustrine origin light oil (31° to 37° API), occurred in carbonate reservoirs called stromatolites and coquinas. The petrophysics of such reservoirs are unique and made possible to preserve permoporosity in very deep conditions (over 5,000 meters).

The supergiant accumulations of light oil, condensate and gas found in the study area, involving the Tupi, Carioca, Parati, Guara, Iara, Bem-Te-Vi and Jupiter are trapped below a huge evaporitic sequence that was able to hold significant hydrocarbon column heights, becoming a key success factor in establishing one of the most prolific petroleum systems of the world: The Great Lagoa Feia (!) Petroleum System (Mello, *et al.*, 1995 and 2009).

It is important to mention that all volumetric estimations are based on premises that consider the same permoporosity distributions for all the stromatolites, coquinas and clastic basal reservoirs.

## ACKNOWLEDGEMENTS

The authors would like to thank CCG-VERITAS who provided the whole 3D Seismic Data for the 3D Petroleum System and Exploration Risk Assessment Multiclient study performed by HRT & Petroleum in association with CGGVeritas. The authors also thank gratefully the geophysicists Alexandre Coelho and Paula Kale Brazão and all the HRT personnel which worked together in this project. We also thank IES that provided the PetroMod 3D for the simulations.

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# Water Solutions

Interview with Henrik Friedenberger of RWO GmbH

**Brazil Oil and Gas:** What are the major challenges in water treatment and how can they be overcome?

**Henrik Friedenberger:** Bremen-based RWO GmbH – Marine Water Technology is a leading and globally active supplier of systems for water and wastewater treatment aboard ships and offshore installations with more than 30 years' experience in the sector. The product portfolio encompasses all types of water treatment technologies, from oily water, ballast water, wastewater to drinking and process water treatment. The company is part of Veolia Water Solutions & Technologies, a subsidiary of Veolia Water, the leading builder of treatment plants and supplier of technical solutions for water treatment. Beside RWO's own R&D capabilities, the company also makes use of the company's network of R&D centres supporting our technology development.

From a technological point of view, there are no real challenges and we have products for all types of water and wastewater treatment. Current and future key aspects of our activity are to enhance our existing processes even further with the aim to a) additionally boost efficiencies and b) further reduce energy consumption, both from an OPEX and a carbon footprint point of view. Moreover, we also aim to convince customers who are considering more a total water management concept with, for example, re-use of existing wastewater streams for conversion into, say, process or potable water.

Challenges, however, sometimes do arise on the operation side due to frequent changes of crew and even no or imprecise training – RWO offers a complete range of services to ensure productive and reliable systems, on the one hand by robust and reliable products that are easy to handle and operate, and on the other by combining them with comprehensive and easy-to-understand documentation and proper training. Since, for example, the installation of RWO's oily water separators aboard the P-43 and P-48, all training courses for Petrobras have been especially tailored to its staff, including specifically produced videos, manuals and site training on board.

**Brazil Oil and Gas:** How has RWO's water treatment engineering capability developed over the past five years? How have these treatment facilities performed so far?

**Henrik Friedenberger:** Throughout its history, RWO has successfully launched many new products on the market and enhanced its processes to meet the stringent performance requirements of the IMO or local authorities, such as for oil/water separation, ballast water treatment, sewage treatment and also for potable and technical water production.

In the field of oily water separators RWO is the worldwide market leader, with more than 10,000 installations, and the latest range of products not only complies with the current IMO Resolution MEPC.107(49), which came into force in January 2005, but also processes best bilge water quality far below a 5 ppm limit. These SKIT/S-DEB oil/water separators use the combination of highly-effective open porous coalescer with automatic backflushing, together with a second-stage emulsion-breaking oil and hydrocarbon polisher. More than 12 custom-made oily water separators have to date been supplied to Petrobras according to their technical standards.

RWO is also one of the leading suppliers of reverse osmosis desalination plants for the production of process or potable water for the offshore field. Several multinational oil and gas companies are putting their faith in our technological know-how and experience. Just a few days ago RWO supplied such a desalination plant to one of the world's largest FPSOs to produce excellent water quality with very low maintenance effort and thus provide a reliable and independent water supply.

With MEPC.159(55) coming into force for ships with keel-laying/new installation from January 2010, RWO's family of sewage treatment systems will be complemented by two more types: the new "SMT" and the new "WWT-LC" series. While the SMT works with submerged membrane technology, the WWT-LC is based on RWO's top-selling BIOPUR wastewater treatment system together with an additional treatment step. Both series feature easy-to-operate, compact plug & play units meeting the requirements of the new IMO standard. Type testing of the SMT has been already successfully completed and testing of the WWT-LC is expected soon.

For ballast water treatment, RWO has developed the innovation product CleanBallast, a compact modular system covering all ballast water capacities and qualities. The system and process technology designed and developed over several years provides benefits to shipowners, shipyards and the environment and is regarded as the most forward-looking system solution in ballast water treatment and stands out as an economical-ecological duplex system. RWO is not only a technological front-runner in the field of ballast water treatment, but also has more than 40 units on order and with the increased levels of interest in the product from the marketplace it looks like it's 'full steam ahead!' for the CleanBallast system.

**Brazil Oil and Gas:** What are the future challenges for RWO from a Latin American market perspective, plans to export RWO's success further with Latin America, and major contributions that RWO has made to water treatment?

**Henrik Friedenberger:** RWO has operated successfully in the Latin American market for more than 25 years and has supplied several hundreds of commercially and ecologically sustainable water treatment systems and

**Oily water separator type SKIT/S-DEB 10.0 for FPU P-56**

equipment to the local market, both for ships and offshore installations. At present, RWO's network in South America consists of five qualified sales/service stations to ensure customer benefit from short communication links and rapid response times. Companies such as Petrobras, Transpetro, Detroit, Rebras, the Chilean Navy and many others are using our products and technologies. But, of course, one of our goals is to increase our success further within Latin America, whether in Argentina, Chile, or Venezuela, but especially in Brazil, where Petrobras is mounting a huge expansion programme.

RWO's customers also benefit from the world-class backing and know-how of its large parent company, Veolia Water Solutions & Technologies, the world's leading concern in water treatment. With more than 130 subsidiaries in over 57 countries, the group specialises in water and wastewater treatment technologies for local authorities and industries and generates a turnover of more than €2.5 billion per year. RWO's sister companies, VWS-Brazil and VWS-Westgarth, are also successfully active in Brazil, providing a range of water and wastewater treatment solutions and technologies to the refinery and upstream Oil & Gas markets. Offshore, VWS-Westgarth for example specialises in the design & build of produced water treatment and seawater treatment and injection systems and is the world's leading supplier of the membrane-based sulphate removal process (SRP).

*Henrik Friedenberger is a Senior Area Sales & Project Manager of RWO Marine Water Technology and responsible for the Latin American market.*

# CTDUT – A Model for Sharing Facilities and Costs in Research and Development

The pipeline industry has special characteristics related to the difficulty of testing and researching pipeline activities. These are related to the risks represented by the tests, the difficulty of simulating extreme conditions in an operational pipeline and also due to the permanent online nature of transport and distribution operations of vital products, which makes stops and changes in line operating conditions a difficult task.

Moreover, any facility dedicated to testing in the pipeline industry has high costs of construction, operation and maintenance, and few companies can afford this structure without imposing excessive costs. It is also important to consider that the availability of well trained researchers inside the company, in all areas of expertise where they are needed, leads to the formation of a research and development structure of high cost. Moreover, the growing technological challenges created by the need to exploit new fields lead the companies to undertake research and development activities as a means of remaining competitive and with an outstanding performance in the market.

Created with the objective of attending such needs, working as a shared research center and available for use by all companies in the sector, members or not, the CTDUT – Center for Technology in Pipeline – has increased its offer of services to the pipeline community, seeking to fill gaps and to act as an independent institution and as discussion forum for the industry.

Created as a nonprofit association and open to any company active in the pipeline industry, its model came from an initial audacious and original concept that is performing perfectly adjusted to the reality and producing excellent results. Inaugurated on May 10th, 2006 as an initiative of its three founding partners, Petrobras, Transpetro and PUC – Rio, CTDUT now has 45 members, including several prominent institutions in their fields of actuation.

Within this innovative concept, CTDUT has facilities dedicated to testing and training, available for use by the whole pipeline community. It also has operating personnel, specialized and trained to meet all the tests demand-

ed in such facilities. The structure of CTDUT counts on managerial capacity to coordinate the research and development projects in which the institution participates. However, this model wisely does not rely on a permanent team of researchers located at CTDUT. The maintenance of these researchers would burden excessively the payroll of the institution, which counts on associates, but not with supporters committed to its financial sustainability.

The sustainability of CTDUT has to be attained with the results of the technological services offered, and here is important to understand that the word "service" at CTDUT has not its usual meaning, but it must be understood as a technological task which is part of a big research and development project being executed in another institution or company. The services of CTDUT are, in fact, portions of other institution research projects which are ordered to CTDUT because it has the facilities and the capacity of bringing together the necessary people and partners for attaining such objectives. The audacity of the model is in the conception of an institution of Science and Technology which does not house its researchers on its staff, but in a vast network that consists of researchers from other institutions, public and private, which are invited to join a working group whenever a research project that requires expertise in their respective areas of specialization exists. This model of a Brazilian Network of Competence in Pipelines overtakes the borders of institutions and strongly encourages the collective and participatory work by aggregating researchers from different research groups in a common goal. Gather what's best, are laboratories or persons, without competition, but in a complementary manner in order to optimize results with economy of resources.

This model, different from traditional standards of Science and Technology institutions, is being gradually accepted, the extent to which demonstrates its feasibility as a solution and its qualities whenever adopted as a complement to the traditional models, which have their excellence centers inside the universities and other specialized institutions. It had never been the proposal of CTDUT to replace or prove better than other already adopted solutions, but before that, complement what already works, acting like a catalyst of capacities, with evident advantages both for the ones who have and the ones who need the specialized knowledge in pipelines. In such model, other

laboratories and specialists are never perceived as "competitors", but as important partners in the technological initiatives CTDUT may be involved with.

Through this network activity, which includes the main actors in the pipeline sector, CTDUT provides the participation of the community in its projects in several segments of the industry, creating opportunities for interaction between them. As an example, CTDUT participated in drafting the proposed Safety Rules of Operation for Pipelines, being prepared by ANP – National Agency of Oil, Natural Gas and Biofuels, is a reliable indicator of such participation, which brought experts with large experience for its preparation, and also of CTDUT wider mission of action, that can provide valuable services far beyond the tests and experiments required for the development of new equipment. Once established and accepted this model of partnership, the possibilities for action are increasingly more diverse and challenging.

According to its original purpose, CTDUT now offers facilities that permit a series of tests to support research and training, such as Loop 14, Pigódromo (for testing PIGs) and Laboratory of Structural Integrity, among others.

The 14" diameter and 100 meter length testing pipeline of CTDUT is equipped with aerial flanged spools and inserted with mapped defects. It allows the assessment of performance of any kind of PIGs, including ultrasonic and MFL (Magnetic Flux Leakage).

It offers the possibility of operators training in all procedures involving the launching and receiving of PIGs, such as operation of control and lock valves, opening and closing launcher traps and receivers of PIGs. It also allows training for intervention operations of pipelines in charge, for maintenance.

The Pull Test Rig for PIGs, a testing assembly consisting of pipelines with diameters ranging from 6" to 16", contains well known and mapped defects. It is equipped with a traction engine with controlled speed. It is suitable for tests that evaluate the detection and calibration efficiency for instrumented PIGs, or other equipment for the detection of defects such as acoustic inspection of long reach guided waves. It can receive the addition of pipes with different diameters, according to the test.

The Structural Integrity Laboratory offers an adequate area for integrity tests (destructive or not) in carbon steel or composite material pipes, of any diameter, or equipment like valves and similar. It is equipped with a crane capable to support 10 tons load, hydrostatic pressurizing pump of up to 1000 bar, "Bunker" with high impact protection, monitoring cameras for tests and masonry windows without glasses, appropriate to the test environment. The area reserved for the tests has 74.21 m² (4.10 wide x 2.55 high x 18.10 m length) with steels plates for superior protection.

Among the activities being developed these days, there are seven projects of research and development with financial support from CTPETRO – Oil Sector Fund – through an agreement with FINEP – Financer of Studies and Projects – and financial counterpart from Petrobras. These projects are related to researches for the detection of leaks, studies of transients in pipelines, reduction of drag, georeference and the development of techniques for internal lining of pipelines and are being conducted trough partnerships with universities and research institutes (UFRJ, UFF, IME, PUC-Rio, UERJ and INT).

CTDUT is also offering technological consultancy, by forming specialized teams, for attending specific sector needs, promoting high level training for the community, personnel education and consultancy in the implementation of pipelines for ethanol, geotechnical studies for pipeline risk analysis, handling plan as a function of the geotechnical risks previously identified, among others.

Such facilities are also fully adequate for training activities, qualification and certification of equipment and personnel, being able of playing important role in the activities for pipeline quality and reliability improvement, reducing the risks associated with its use, which even smaller than risks related to other transportation systems, are still present.

As an example, we can mention the recent PIG passage practical training organized by Clarion Technical Conferences and by Scientific Surveys Ltd. In partnership with Rosen and CTDUT, which took place at the 14" Test Pipeline – Loop 14.

A person who works in Science & Technology must keep, for sure, one eye looking at the future and CTDUT has this feature. Several projects for equipping the Center with new laboratories and installations in order to attend other sectors which can not be attended by present facilities are under construction. Such new facilities will bring a new dimension to CTDUT capacities for attending the needs of the pipeline industry, whilst in the meantime will bring new challenges to the sustainability of the institution, faced to its fast growth.

In this line, we have the project of the flow calibration laboratory for liquid and gaseous hydrocarbons on an industrial scale, which is under development and will have as main purpose to provide the country's basic infrastructure for the implementation of technology and knowledge in metrology for measuring the production of oil and natural gas. Therefore, it will function as a support for Research, Development and Innovation activities (R, D & I) in this area and should become the national reference laboratory for measurement of oil and natural gas of INMETRO, thus meeting the needs of the local industry and sector regulation agencies in ensuring the traceability and metrological quality practiced in different measurement systems used in the oil industry. With the implementation of the project in CTDUT, Brazil will join a select group of countries that have flow laboratories using their own working fluid in the tests and calibrations, which certainly will provide autonomy and meaningful development of this area in the country

Another important infrastructure being constructed is the 12" Test Pipeline. This test circuit was designed to support the research and development of new equipment, tools and systems for inspection and protection of pipelines, flow tests under various operating conditions to validate the developed simulation software, testing and certification of equipment and control systems , protection, monitoring, inspection and maintenance of pipelines, beyond the certification of processes and operating procedures, inspection and maintenance of pipelines and the training and qualification of operators and technicians of pipelines.

With 2.5 Km length and 12" nominal diameter, the pipeline leaves CTDUT area, joins a group of pipelines already existent on a right of way and returns to the Center, forming a loop. The tanks park designed for the pipeline allows its operation with oil, derivatives or water.

With the same objective, but dedicated to the transportation of Natural Gas we will also have a Test Gas Pipeline with 16" diameter. Such circuit will have properties similar to the ones of the Test Oil Pipeline, contributing with the formation of gas pipeline operators and technology tests applicable to this important system of transportation. It will be 2.5 km long and will be placed in the same area of the oil pipeline, with compression segment and guns located in an area near CTDUT.

# METROLOGY LABORATORIES – OIL AND GAS FLOW (LABLIQ AND LABGAS)

The ANP/INMETRO #1 – 2000 joint Regulation and the INMETRO # 64 Regulation, from year 2003, legislates on the determination of the quantities of oil and gas produced and handled in Brazil and on the legal metrological control of measuring instruments and volumetric totals respectively. However, since the promulgation of such regulations, the lack of a laboratory structure in the country that could allow its full applicability became clear. A project proposed by Petrobras and CTDUT, in partnership with INMETRO, aims at the construction of two laboratories of flow determination, one for oil and liquid hydrocarbons (LABLIQ) and the other for natural gas (LABGAS), capable of supplying Brazil with the necessary infrastructure to meet current legislation requirements. The implementation of such lab infrastructure, besides allowing the metrological control of liquid and gaseous hydrocarbon flow measurements, will also contribute for the global development of the area, including the training of human resources, the technical-scientific exchange, the achievement of studies, tests and Research & Development for new measuring methodologies and technologies.

The projects are very audacious in technical terms, aiming at uncertainties low enough to meet the requirements for the model approval. See below a summary of the information of the laboratories that will be built.

In the global scenario, one can say that with these laboratories, Brazil will be at a level reached by very few countries.

**LABLIQ Project Data**

| Parameter | High Flow | Low Flow |
|---|---|---|
| Maximum Flow (with working standards) | 5000 $m^3/h$ | 300 $m^3/h$ |
| Maximum Flow (with tester) | 2500 $m^3/h$ (tube-ball tester) | 340 $m^3/h$ (plunger tester) |
| Minimum Flow | 80 $m^3/h$ | 5 $m^3/h$ |
| Larger diameter | 24” | 4” |
| Smaller diameter | 4” | 2” |
| Target Uncertainty | 0,04% (with reference standards) 0,1% (with working standards) | |
| Viscosity Range | 1 to 120 cSt (44 < Re < 2,9 x106 ) | |

**LABGAS Project Data**

| | |
|---|---|
| Primary Standard | Plunger Tester |
| Calibration Fluid | Processed Dry Natural Gas |
| Calibration Pressure | 30 to 70 bar |
| Flow Range | 8 $m^3/h$ to 8.000 $m^3/h$ |
| Diameters Range | 2” to 16” |
| Target Uncertainty | 0,20% |

It is still important to highlight that the construction of these laboratories meets the Strategic Guidelines for the Brazilian Metrology 2008-2012 of CONMETRO, which, for the dynamic measurements of fluids, recommend “to increase the country laboratorial infrastructure, in order to promote the traceability in the measurements of custody transfer and in the inspection measurements of oil and its derivatives, natural gas and biofuel” and in the targets for legal metrology foresees “to expand and seek for the continuous improvement of the services of legal metrology in order to meet the demand and the incorporation, in the metrological system, of new strategic areas, particularly in the oil, gas and biofuels sectors for tax and custody transfer purposes”.

With this in view, and given the relevance of this structure for the country, it was celebrated in set/2008 a cooperation agreement between CTDUT and INMETRO aiming at technical and scientific cooperation between the institutions, which is essential for the success of these ventures.

# Pipeline Handling Innovation

Brazil Oil and Gas spoke with the President of Liderroll, Paulo Fernandes, about his company's plans and operations

**Q: Brazil Oil and Gas** – Which projects have Liderroll been involved with?

**A: Fernandes** – In the past few years we have been a part of many projects, like the TEBIG, the TEBAR and the PECEM, which are pier pipeline projects. Our products were installed and are working very well. We also supplied all of the rollers for Petrobrás's BGL 1 boat. The rollers will also be installed in the Stinger that is currently being assembled. In January BGL 1 will be ready to launch ducts in deeper waters. Right now we are involved with the Gasduc III, a project that is a great challenge for Brazilian Engineering because we will have to launch ducts of large diameters in confined locations.

**Q: Brazil Oil and Gas** – How has the company's wider organization benefited the local operation?

**A: Fernandes** – Our main office is located at the center of Rio de Janeiro, and we have a factory at the heart of the Brazilian oil industry, as well as a commercial office in Houston, the heart of the American oil industry. We employ people that are trained and ready to execute the special endeavors that our line of work requires.

**Q: Brazil Oil and Gas** – How has the company improved its performance locally?

**A: Fernandes** – We seek to revolutionize run of the mill


methods, with the application of innovative geometry and materials. To go beyond the commonplace. Through this practice we have achieved excellent results in our activities. Liderroll is a company of engineering solutions that pursues creative, practical, modern and cost efficient answers for our clients.

**Q: Brazil Oil and Gas –** Which training initiatives have been implemented?

**A: Fernandes –** We are constantly training our employees, making them more capable of developing the techniques necessary for the execution of our projects. This is one of our permanent preoccupations. It is our philosophy.

**Q: Brazil Oil and Gas –** Has the company maintained a high level of Safety and Quality Assurance?

**A: Fernandes –** The best way is to have external auditing. They are examples that attest to our quality. We have the entire structure necessary to fulfill ISO 9000 requirements and we need this external evaluation. We have the quality and we need to show it.

**Q: Brazil Oil and Gas –** How does the company plan on staying ahead of the curve?

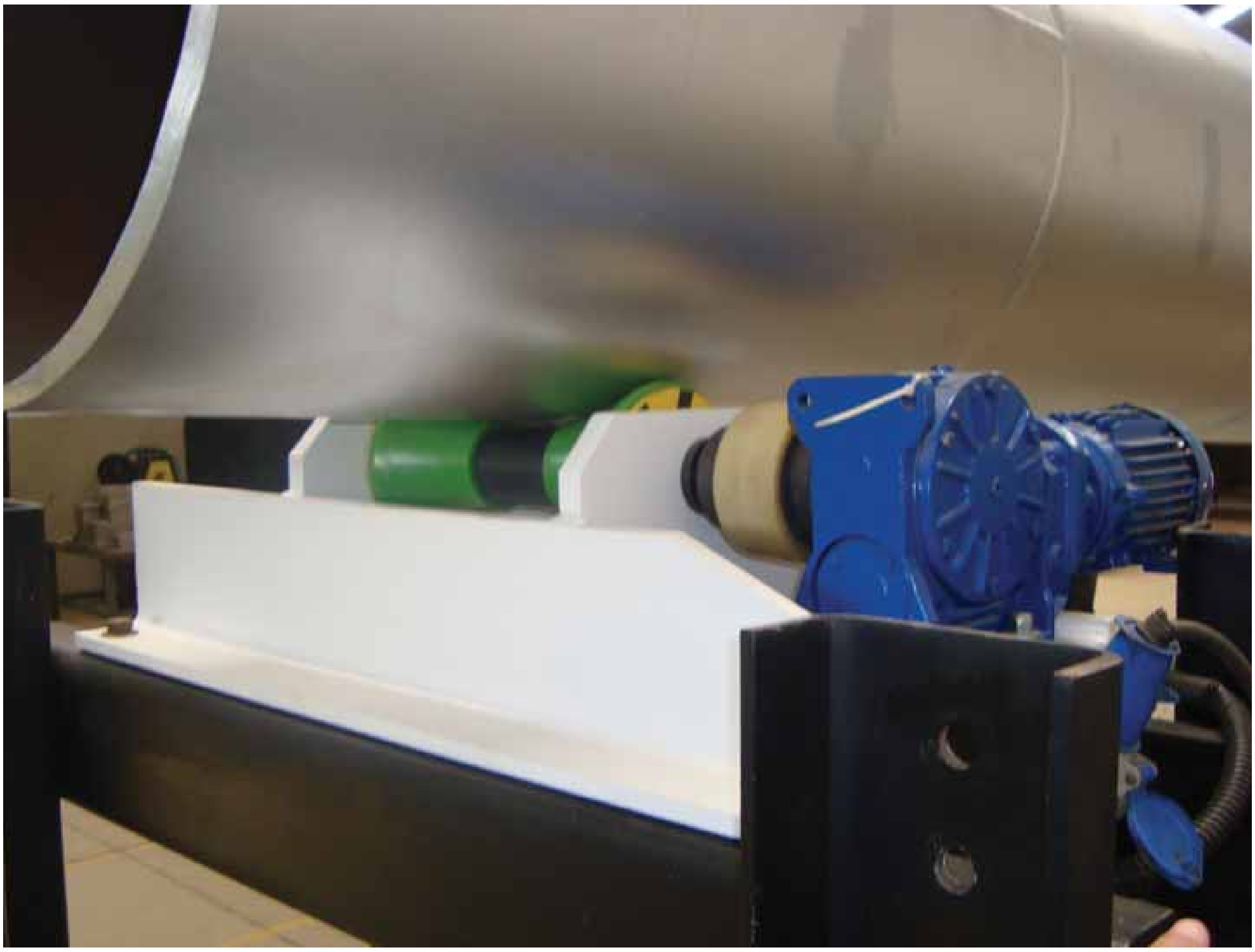
**A: Fernandes –** We like to work with partners. Always. We do this in Brazil, in the United States (where we will be working towards making possible the use of probes in Brazil) and also with Belgian companies, which can open the European market for us. Partnerships, fidelity, and competence. These are the words that define us. We search for partners that share with us this philosophy. Executing projects with us or not, we learn together.

**Q: Brazil Oil and Gas –** What investments have been made and what investments are planned?

**A: Fernandes –** We invest in the human being, in training, in new materials, and in equipment. We now see the pre-salt possibilities in Brazil, as an incentive for our capabilities. What do we see ahead of us? Success.

**Q: Brazil Oil and Gas –** Can you describe your current R&D projects and your objectives?

**A: Fernandes –** As I've said before we invest in the human



being, i.e. the community around us. It is our philosophy. We stimulate cultural and sports related activities in the Brazilian communities. We believe in this and Liderroll invests in it. Today's small boy is tomorrow's great man. This is not an exclusive view of ours. It is a point of view cherished by many Brazilian companies.

**Q: Brazil Oil and Gas –** What are the company's latest developments?

**A: Fernandes –** We have been doing research in new materials and in the development of new equipment. We have five patents registered in over 52 countries. We believe in research and development. In the oil and gas industry it is necessary that we think big, like Petrobrás company. If it hadn't developed itself we would still only be looking for oil in our beaches. Today we search for oil in the sea, in depths of up to 7,000 meters. And not only do we search, but we also find oil in these locations.

**Q: Brazil Oil and Gas –** What are the company's future plans?

**A: Fernandes –** We are working on one of the new challenges of Brazilian engineering. The Gastau. It is a gas duct of over 100 kilometers in length. It will have to cut through a mountain range in which tunnels of up to eight kilometers will have to be built. This makes Gasduc II, where we plan to cut a four-kilometer long tunnel, a mere appetizer. But an appetizer that makes us grow, develop and think nonetheless. And these are all things that we wish to do more and more. We are ready once again to conquer our challenges.

We believe in a bright future for us of Liderroll, and for Petrobrás, who doesn't stop showing the world quality and competence. Let us wait and see what the future holds. Through our ideas we will develop, feel and improve the good ideas that other Brazilians are capable of creating and developing.

# Tomography Inspection and Leak Detection

Brazil Oil and Gas speaks to Morken Brasil's Chief Engineer, Leonardo Fiorini, a Mechanical Engineering graduate of UNICAMP, State University of Campinas.

Lothar Edelmuth established the Morken Group over 12 years ago in Buenos Aires. Mr. Edelmuth has more than 40 years of experience in the corrosion industry. Today Morken has offices in Argentina, Bolivia, Brazil, and Peru, and also conducts business in Chile, Venezuela, Colombia, Ecuador and Uruguay.

Morken SA specializes in providing equipment, materials and services, aimed to improve the transportation of gas, oil, petrochemicals and their derivatives. The company offers a wide range of options for inspection, repair, maintenance or rehabilitation of pipelines, surface structures or subsurface pipelines and/or pumping plants, focusing on providing solutions for the early detection of corrosion.

**Q: Brazil Oil and Gas** – Which projects have the company been involved with?

**A: Fiorini** – Morken is involved in the technical and operational base establishment to provide non-contact tomography inspection services and Leak detection systems in Brazil. Morken Brasil offers pipeline exclusive inspection technologies and leak detection systems, not only for pipelines, but for tanks as well.

Our previous experience gained in other countries, not only applied to the Oil Market, but also to the Steel, Natural Gas, Water and other markets, which made market entry into Brazil easier. Morken Brasil has already provided services in process and fire fighting water, natural gas, oil and derivatives pipelines. The variety of products and pipeline diameters makes the application broad allowing Morken to apply services in all kind of pipelines.

Currently Morken Brasil is under contract with Transpetro, the transportation company of Petrobras.


**Q: Brazil Oil and Gas –** How has the company's wider organization benefited the local operation?

**A: Fiorini –** By transferring technical know-how obtained through four decades of experience in the Oil & Gas Market. Exclusive Non-Contact Pipeline Inspection for Underground, Submerged and Non-Piggable Pipelines

The inspection technology offered was commercially launched in 2002 worldwide and now has been successfully applied to over 20,000 kilometers of pipelines. Developed in Russia, this technology is currently in use on several European, Asian and American projects.

This Non-Contact inspection is named Magnetic Tomography provided by IGP, an Argentinean company, also part of the Morken group. It enables the survey of pipelines of all configurations, exposed, underground and submerged.

The inspection occurs by walking over the pipeline surface using specialized equipment called SKIF. This equipment records magnetic field data to verify the "hazard scale" of the anomalies found. This scale is divided in three; green, yellow and red, from the lither to the harder in order. It enables the location and classification of the anomalies, giving a proper idea of the pipeline's situation.

Not only does it offer a complete view of the structural condition, it's very cost effective, while the pipeline remains working at normal operating pressures and doesn't require preparation procedures needed by in-line intelligent pig techniques, for example.

**Q: Brazil Oil and Gas –** How has the company improved its performance locally?

**A: Fiorini –** The performance was improved through the exchange of experience between all of Morken's working groups.

**Q: Brazil Oil and Gas –** Which training initiatives have been implemented?

**A: Fiorini –** We have, as a standard procedure, local continuous training programs in all of the offices and an annual meeting where we share our different results and businesses cases.

**Q: Brazil Oil and Gas –** Has the company maintained a high level of Safety and Quality Assurance?

**A: Fiorini –** Yes. We work according to all of the Brazilian and international regulations regarding safety procedures.

In this kind of Market, quality assurance is a question of survival. Morken has always worked to exceed the customer's expectation.

**Q: Brazil Oil and Gas –** How does the company plan on staying ahead of the curve?

**A: Fiorini –** We are always developing technological innovations for safer, cheaper and more precise applications of inspection and detection tools. Also we have as priority the dynamic training programs.

**Q: Brazil Oil and Gas –** What investments have been made and what investments are planned?

**A: Fiorini –** Morken has made sizeable investments in infrastructure, logistic and technical capability of the workgroups.

**Q: Brazil Oil and Gas –** Can you describe your current R&D projects and your objectives?

**A: Fiorini –** Our target is to promote the integration of new and traditional inspection technologies, and than be able to offer our clients more complete and accurate results and reports. It means safety and productivity to the clients. For example, our new inspection technologies offer benefits to our clients. Morken provides inspection solutions for all kinds of pipelines. To make that possible the group continuously search for new technologies.

The latest technologies available are Pipescan MFL, Spectrum XLI, MMM and others.

With this wide application is possible to perform services not only in pipelines. Heat exchangers, boilers, condensers, tanks and some metallic structures can also be inspected by Morken.

Inspection results can also combine multiple techniques, besides Ultrasound, Eddy Current and other common results, Morken can provide A-Scan, B-Scan, C-Scan, CIS, DCVG and a contact technology called Metal Magnetic Memory (MMM).

This combination provides details about the coating, cathodic protections and the metal structure, intern and externally. Metal loss, cracks, dents, corrosion of all forms and coating flaws can be detected, and major damage can be prevented.

**Q: Brazil Oil and Gas –** What are the company's latest developments?

**A: Fiorini –** We are continuously improving innovative features to our tools and services such as the exclusive non-contact pipeline inspection for underground, submerged and non-piggable Pipelines

The inspection technology offered was commercially launched in 2002 worldwide and was until now successfully applied to over 20,000 kilometers of pipelines. Developed in Russia, this technology is currently in use on several European, Asian and American countries.

This non-contact inspection is known as 'Magnetic Tomography' and is provided by IGP, an Argentinean company, also part of the Morken group. It enables the survey of pipelines of all configurations, exposed, underground and submerged.

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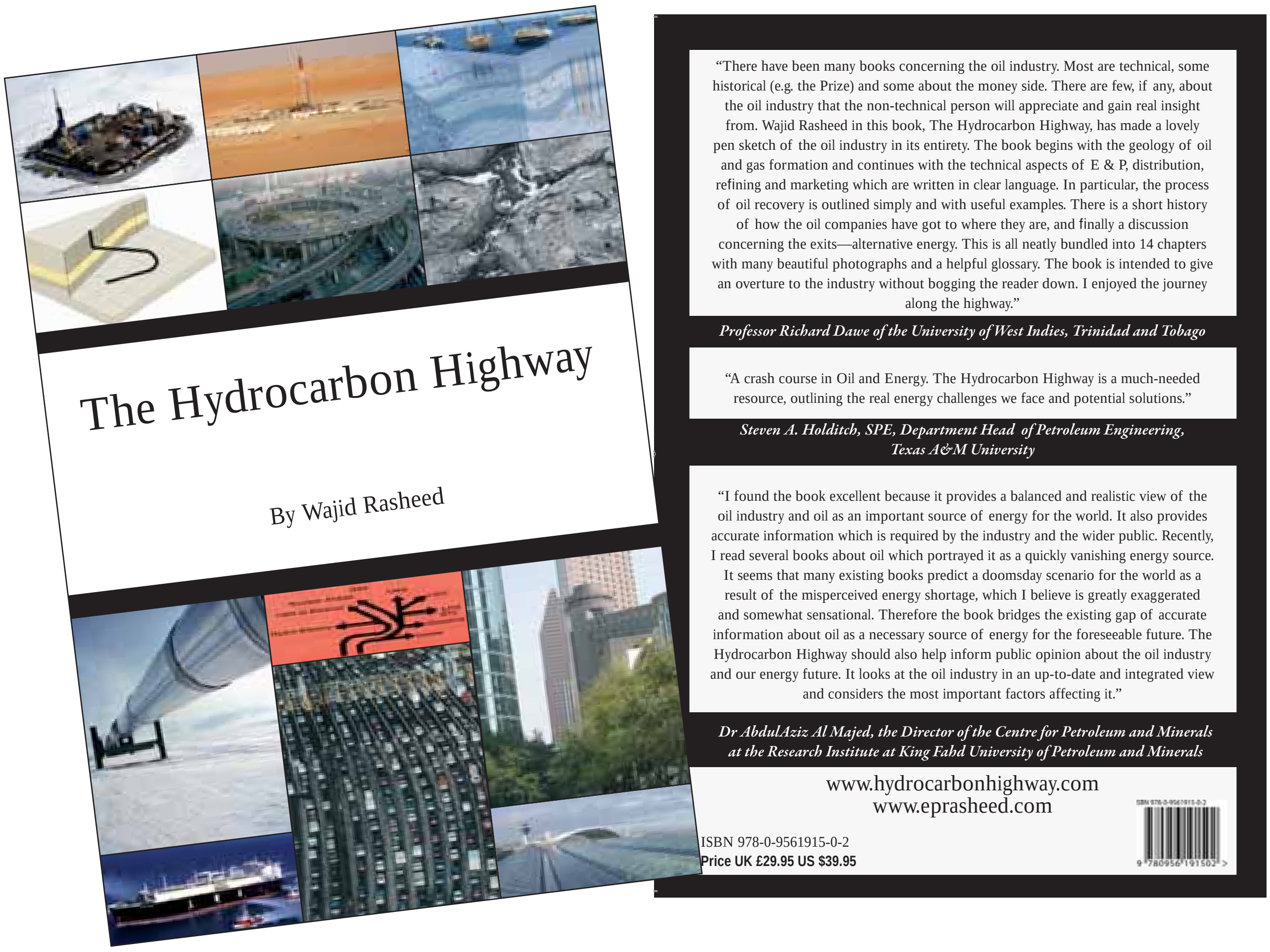
Not only does it offer a complete view of the structural condition, it's very cost effective, while the pipeline remains working at normal operating pressures and doesn't require preparation procedures needed by in-line intelligent pig techniques, for example.

**Q: Brazil Oil and Gas –** What are the company's future plans?

**A: Fiorini –** To remain focused on our current targets and promote vertical company growth to respond to market demands.

# What's In a Wet Barrel?

## *A chapter from The Hydrocarbon Highway, by Wajid Rasheed*




*Oil and gas asset production can be maximised through an understanding of petroleum and reservoir types.*

When crude oil first came into large-scale commercial use in the 19th century, it was stored and shipped in wooden barrels with one barrel equal to 42 US gallons or 159 litres. The term 'wet' barrel denotes a physical barrel of oil that is actually delivered or consumed as opposed to a futures or other paper barrel that is traded.

Asphalt, bitumen and crude are common terms describing different forms of petroleum that can be found in a typical 'barrel' of oil[1].

The term comes from the Latin petra—"rock" and oleum—"oil". For lay people, petroleum itself is a generic term that covers all naturally occurring hydrocarbons as well as refined products or derivatives.

For purists, however, petroleum refers to chemical compounds made up of hydrogen and carbon atoms; consequently, the classification hydrocarbon is more appropriate. Definitions aside, hydrocarbons in their 'unproduced' state are found in underground accumula-

**HRH Prince Andrew looks through The Hydrocarbon Highway at the MEOS Conference, Bahrain.**

**Figure 1 - Nature's Best Is Sweet and Light (EPRasheed)**

**Figure 2 - Heavy Oil Is Unable to Flow at Atmospheric Conditions (EPRasheed)**

tions or reservoirs of oils, gases, water and impurities located at depths ranging from 2,000 ft (610 m) to 25,000 ft (7620 m). Petroleum naturally seeps to the earth's surface along faults and cracks in rocks gathering in tar, asphalt, pitch or bitumen lakes. Shortly, we will consider the make-up of reservoirs but first of all, what's in a barrel of oil?

Nature's best orange juice is sweet and light, as is its crude; however, not all of the 200 or so naturally occurring varietals of crude oil are so blessed and this affects their commercialisation. Sweet crude has less than 0.5% sulphur content—increase this figure and it turns 'sour'. Light crude has a density of 20° or more using the American Petroleum Institute's (API) specific gravity scale and has light hydrocarbon fractions. Heavy crude has more complex fractions with higher densities and lower API gravities[2].

## The Colour of Oil

Generally speaking, the colour of crude oil intensifies with its density and viscosity. While black oil is hard-to-pour and has high density and viscosity, green to yellow oils are runny and have low density and viscosity. The term 'crude' refers to petroleum straight from the

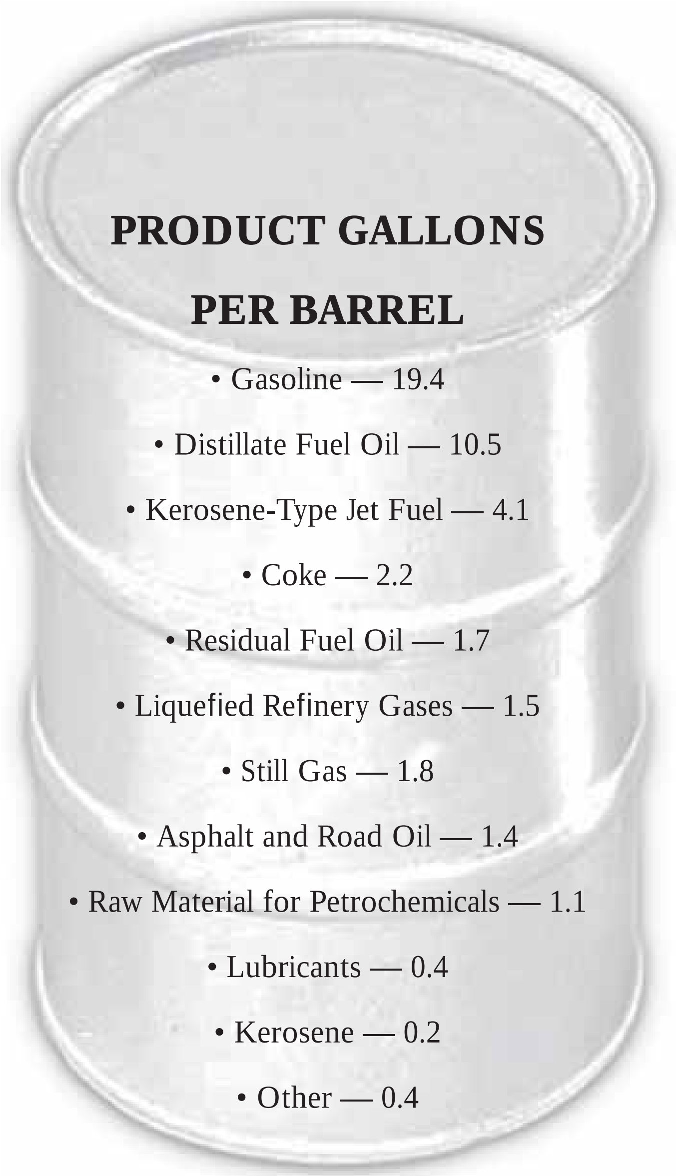



**Table 1 - Products Per Barrel of Oil (in Gallons).**

**Note: Distillates includes both home heating oil and diesel fuel. Residual fuel oil refers to heavy oils used as fuels in industry, marine transportation, and for electric power generation. Figures are based on average yields for U.S. refineries in 2005. One barrel contains 42 gallons of crude oil. The total volume of products made is 2.7 gallons greater than the original 42 gallons of crude oil. This represents 'processing gain.' (After API)**

wellhead in its 'unrefined' state that can generally flow in atmospheric conditions. Where petroleum is unable to flow in atmospheric conditions, it is often referred to as heavy oil, tar or bitumen[3].

Technologists quibble on when crude gets heavy; some say this happens at 25°API or less and others say 20°API or less. This is important because heavy oil trades below its lighter counterpart. For our purposes, the definition of heavy oil is 20° API or lower and further detail is found in *Chapter 8: Extreme E & P*. Finding heavy or light crude oil depends entirely on the presence of cap rock and permeability, as these will prevent or permit oil and gas to leak to the surface and be dispersed. In

| Component | Boiling Point °C | Black Oil | Volatile Oil | Gas Condensate | Wet Gas | Dry Gas |
|---|---|---|---|---|---|---|
| Methane, $CH_4$ | -161 | 49.0 | 64.0 | 86.0 | 87 | 96.0 |
| Ethane, $C_2H_6$ | -88 | 2.8 | 8.0 | 4.4 | 5 | 2.8 |
| Propane, $C_3H_8$ | -42 | 1.8 | 4.5 | 2.4 | 5 | 0.3 |
| n-Butane, $C_4H_{10}$ | -1 | 0.8 | 2.0 | 0.8 | 0.6 | 0.2 |
| i-Butane, $C_4H_{10}$ | -11 | 0.8 | 2.1 | 1.0 | 0.6 | 0.2 |
| n-Pentane, $C_5H_{12}$ | 36 | 0.7 | 1.5 | 0.3 | 0.5 | 0.1 |
| i-Pentane, $C_5H_{12}$ | 27 | 0.5 | 1.5 | 0.5 | 0.5 | 0.1 |
| n-Hexane, $C_6H_{14}$ | 69 | 1.6 | 1.4 | 0.6 | 0.3 | 0.1 |
| Colour of liquid at surface | | black | brown | straw | white | - |
| Liquid Specific Gravity | | 0.853 | 0.779 | 0.736 | 0.758 | none |
| °API | | 20-35 | 38-50 | 50-70 | 50-70 | none |
| GOR scf/bbl | | 50-1500 | 2000-40,000 | 3000-18,000 | >100,000 | none |

**Table 2 - Crude Oil and Natural Gas Varietals, After Professor Richard A. Dawe**

Venezuela's Orinoco Belt, for example, heavy oil deposits are found close to the surface with the lighter fractions of oil having migrated or dispersed over the years, leaving only the heavier residue.

## Sour as a Skunk

Sour crude with its high sulphur content sells below its sweet counterpart—the gap can be US $5 or more and is likely to increase in the future. The gap exists because sour crude requires specialised refining treatment before it can be sold; however, there are more sweet than sour refineries worldwide. Consequently, a refining preference for sweeter crude exists[4].

The naturally occurring sulphur compounds or 'mercaptans' present in sour crude are powerfully smelly and are also found in garlic oils and skunk secretions. The malodorous mercaptans are by-products of decaying organic matter and they must be treated which adds to refining costs; however, mercaptans have a market value. They are used to imbue an odour to commercial natural gas so the general public can easily be alerted to a gas leak. Untreated natural gas is odourless, and without the tell-tale smell of the mercaptan additive, the public could be unaware of a gas leak until it was too late and someone was asphyxiated or an explosion occurred. Getting rid of sulphur, water, chlorides and other such impurities improves quality, increases value and stretches the world's oil reserves but it also adds to cost.

Table 2 shows a series of oil and gas compounds and their respective molecular weights and common names ranging from methane gas (CH4), petrol (C5H12 to C7H16) to asphaltene (C80H160). Many characteristics such as density, viscosity and flammability are determined by molecular weights and greater detail is available in *Chapter 11: Refining*.

The range of oil varietals is illustrated by extremely light oil, which has a relative density and viscosity below that of water, to extremely heavy oil which has a relative den-

**Figure 3 - Checking Crude Samples (Saudi Aramco)**

sity close to that of water and high viscosity that can be 100 to 100,000 times that of water.

## Molecular Weight

Typically, oil has a carbon content of 84 to 87% weight and a hydrogen content of 11 to 14% by weight[6].

Table 2 shows that hydrocarbons exist with varying densities and viscosities. Viscosity is a prime determinant of the ability to produce and refine oil. It is worth noting that the number of hydrocarbon compounds increases dramatically due to isomers, differing arrangements of the same number of atoms. In the case of hexane (C6) there are five isomers, for decane (C10) there are 75 and for C30 there are more than four billion. Although laboratory analyses of reservoir hydrocarbons can profile all compounds containing as many as 20 carbon atoms, it is usually sufficient to profile compounds containing up to six or seven atoms, with a general number being used to represent the total proportion of heavier molecules that are present[7].

The general trends depend on the ratios of methane (CH4) and the heavier components. The intermediates, C2-C6, control the GOR and API grade. The percentages shown are representative only and each category can be considered as flexible. Additionally, once production starts from a reservoir, the state of equilibrium that has been established over geological time is destroyed. Pressure gradients are created and the chemical composition and the physical properties of the fluids in the reservoir change. This happens as the pressure exerted on the fluids changes from the reservoir to the wellbore to the surface and, over time, as the fluids constituting the reservoir change.

Analysis is usually presented in terms of C1, C2, Cn+ with n often being 7, 12 or 20. Compounds that are not expressed in this way are usually treated as a composite fraction characterised by a molecular weight, density and/or a boiling point.

For E & P purposes, physical properties such as colour, API grade, viscosity, bubble point pressure, Gas-Oil Ratio (GOR), pour-point, and kerosene content are characterised. For downstream purposes, actual hydrocarbon compositions and fraction descriptions are required. Traditionally, the analysis of produced fluids was performed in the laboratory and could take weeks or more to obtain. Nowadays, real-time formation testing tools can provide analysis of produced fluids in near real-time at the wellsite.

## Saturated Oil

Produced oil will always contain a certain amount of dissolved gas. The exact amount depends on reservoir conditions such as temperature and pressure as well as the composition of the oil. If the oil cannot dissolve any more gas under the prevailing conditions, it is termed saturated; the excess gas has moved to the top of the reservoir and formed a gas cap. If the oil can dissolve more gas, it is termed undersaturated, and no gas cap will be initially present on production. The GOR is the ratio of the volume of gas produced to the volume of liquid and may be expressed as cubic feet per barrel depending on the units used for measuring gas and liquid. For gas wells, the inverse ratio is sometimes used and the liquid-gas ratio is expressed in barrels per million $m^3$ (or million cubic feet)[8].

## Impurities

Reservoir characteristics depend on the interplay between the molecular arrangements of the hydrocarbons, the extent of liquid and gas phases as well as the existence of impurities. Aqueous impurities are caused by differing levels of salinity and mineral salts within water that were present within rock pores before hydrocarbons migrated into the reservoir rock, displacing a certain volume of this water. The volume of water that remains after migration is known as 'connate water' and it is common for large volumes of water to be produced in conjunction with oil and gas.

## Water

Water is present at all stages of oil production. Connate water found in the reservoir at discovery can occupy 5

| API Gravity<br><br>(°API) | Classification | Specific Gravity<br><br>(g/cc) |
|---|---|---|
| 10° to 20° | Heavy Oil | 1.0 to 0.93 |
| 20° to 30° | Medium Oil | 0.93 to 0.87 |
| >30° | Light Oil | less than 0.87 |

**Table 4 - A Rough Classification of Crude Oil Is Sometimes Used Based on API Gravity**

to 50 % of the pore volume and it is common for large volumes of water to be produced in conjunction with oil and gas (it is not always the case that a reservoir has reached maturity simply because it is producing water. See *Chapter 9: Mature Fields*—Water Management). It is also usually very salty, often more concentrated than seawater. Levels of water saturation can be accurately measured by well-logging, surface monitoring as well as permanent downhole monitors. Water breakthrough causes production problems including corrosion and scale, particularly as reservoir water often contains salts up to 250,000 mg/l, in comparison to sea water which contains 35,000 mg/l of salts.

Water and oil also create emulsions which are difficult to break and disposing of produced water can generate an environmental burden as it must be disposed of adequately. Further, any incompatibility between injected water and connate water can create chemical scale[9].

Water is nearly always present in gas reservoirs and reservoir gas is often substantially saturated with water vapour at the temperature at which it enters the wellbore. With the change in temperature and pressure from the subsurface to surface, the gas will not be able to hold as much water and it will condense both within the well during the upward travel of the gas and in surface equipment. Much of this condensed water is carried in the flow lines into the separator as entrained droplets. Water can form hydrates with natural gas, which can create production difficulties, rendering metres and valves inoperative and, on occasions, causing disasters. Low temperature separators are needed to remove the entrained water close to the wellhead before the gas arrives at trouble points. In many cases, appreciable amounts of water will settle to the bottom of the well and can, in time, saturate the zone surrounding the wellbore so that the permeability to the flow of gas may be materially reduced. This reduction can result either from water blocking or clay swelling and can be responsible for a gradual decrease in deliverability and periodic remedial work-overs[10].

Other impurities can be metallic such as vanadium or non-metallic such as hydrogen sulphide ($H_2S$). If there is any measurable sulphur content (more than one part per million), then the sulphur components, $H_2S$, can cause considerable damage to the production facilities unless they are designed to handle sulphur. The sulphur components are also poisonous to humans hence lowering the commercial value of the oil or gas. They therefore have to be extracted, but can be converted to sulphur and sold on as a useful product. The production equipment has to use special quality steels to prevent rapid corrosion. Getting rid of sulphur, water, chlorides and other such impurities improves quality, increases value and stretches the world's oil reserves but it also adds to cost[11].

## Releasing Hydrocarbons

The production of underground hydrocarbons is based on the release of trapped and pressurised fluids. Production involves a reduction in pressure and temperature from downhole reservoir conditions to at mospheric or surface conditions. As a result, hydrocarbons originally present as only liquid underground will separate into liquid and gas on their way to the surface, as soon as well pressure declines below the 'bubble point'.

In a mixture of liquids, the bubble point occurs when the first bubble of vapour is formed. For single component mixtures, the bubble point and dew point are the same and are referred to as the boiling point.

Hydrocarbons originally present as gas underground will generally produce some liquid at the surface due to condensation, which occurs when the pressure and temperature are reduced*. The point at which natural gas components start to condense out of the gaseous system is known as the hydrocarbon dew-point and refers to the temperature (at a stated pressure) at which this occurs. Both bubble point and dewpoint are useful data when designing distillation refinery systems.

Surface facilities will mechanically separate gas from liquid using gravity separators or de-gassing facilities after which the volumes of liquid and gas are measured separately.

## Gas

Natural gas volumes are reported in standard cubic metres [(s)$m^3$] or standard cubic feet (scf). Quantities of natural gas are usually expressed in cubic feet; a cubic foot is equivalent to approximately 0.028 $m^3$ at standard conditions[12]. For reserves valuation, gas is usually expressed in thousands ($10^3$) of cubic feet (Mcf), millions ($10^6$) of cubic feet (MMcf), billions ($10^9$) of cubic feet (BCF) or trillions ($10^{12}$) of cubic feet (TCF).

Methane is the most abundant component of natural gas and has numerous fuel applications. These range from liquefaction, compression, and Gas to Liquids (GTL). For further details, see *Chapter 13: Renewable*

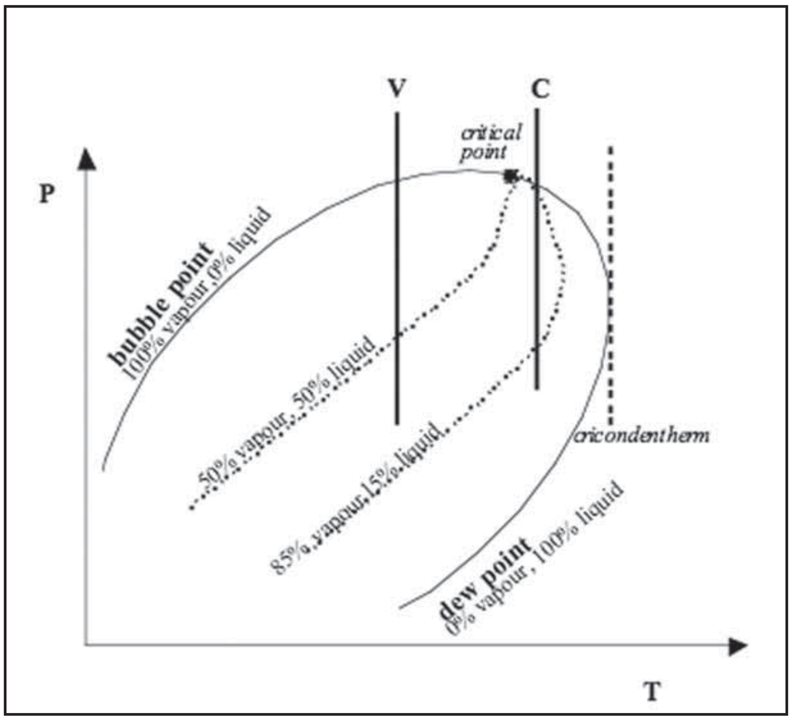



**Figure 4 - Cricondentherm, After Professor Richard A. Dawe**

*Energy*. The second largest component is ethane which can be liquefied and sold as fuel, but is mostly used as a petrochemical feedstock. Propane and butane are also found in natural gas, albeit in smaller amounts, and are commonly separated and sold as Natural Gas Liquids (NGLs). This commercial value stems from their comparatively high-energy content. On a cubic foot basis, methane renders just over 1,000 Btu, while propane renders 2,500 Btu and butane 3,250 Btu[13].

## Gas Condensate

Gas condensate or 'wet-gas' reservoirs are an important class of hydrocarbon accumulation and describe hydrocarbons which are gaseous in the underground reservoir. When the temperature and pressure of gas condensate are reduced to dew point, however, they partially condense to yield liquid condensate. Condensates are often characterised by low-density and high-API gravity (45° and above) and co-exist with natural gas.

Natural gas condensate is typically composed of pentane, hexane, heptane and octane. Liquids that condense are almost transparent or light yellow and can be refined in a way similar to very light crude oil[14].

Condensate-bearing reservoirs pose further production challenges due to the effect changes in reservoir pressure have on the hydrocarbons. Gas may be converted to liquid if its pressure drops below the dew point during production. If gas is preferable to liquid production, reservoir pressure can be maintained by fluid injection. Reservoir fluid composition determines:

• Fluid type—dry gas, condensate gas, volatile oil, black oil

• Method of fluid sampling, laboratory tests

• Surface equipment (type and size)

• Calculation procedures for determining oil and gas in place

• Techniques for predicting oil and gas reserves

• Prediction methods for future production rates, and

• Depletion plan and secondary or enhanced oil recovery methods.

## Common Types of Petroleum

There are several common types of petroleum:

**Associated Gas:** Is the natural gas and NGLs, which under reservoir conditions, are dissolved in the crude oil or are present as a gas cap above the oil in the reservoir.

**Condensate or Distillate:** Is the pale straw-coloured liquid with an API of 45° to 75° produced at surface from hydrocarbons which were originally gas or liquid in the reservoir. The term is often loosely applied to any liquid produced at the separator from light volatile oil or gas fluids.[15]

**Conventional Black Oils:** Are the most common reservoir liquids. They have: a viscosity low enough to flow naturally into a well; gravities that are usually between 20° API to 45° API; GORs ranging from 100-2000 scf/stb (20-360 $m^3/m^3$); specific gravity from 0.6 to 1.0; viscosities ranging from below 1cp; and, liquids that are about as thin as water to those that are >100 cp. They are black to green-black in colour.

**Crude Oil (Oil):** Is the common liquid form of petroleum produced from an oil reservoir when the gaseous constituents have been removed or have escaped and ranges from heavy tarry substances to conventional oil. Most petroleum liquid products and crude oils are lighter than water and their weight is often expressed in degrees (º) API.

The higher the number of API degrees, the lighter the oil. An API rating of 46° for a crude would mean that it is super light. Heavy oil would have an API of 18° to 20° degrees. The commercial value of oil varies according to its specific gravity; heavy oil trades at a lower value, i.e. less than 20° API trades at a lower value (US $5-10) to lighter oils, i.e. from 20° API to 45° API. Above 45° API, oil is considered superlight and has a progressively higher value (US $15 or more).

**Gas Condensates:** Condensates that are straw coloured and usually have a specific gravity above 45° API. The distinction between gas condensate, volatile oil fields and gas fields is important in practice as the reservoir may require different production and commercialisation strategies as discussed in *Chapter 11: Refining.*

**Heavy Oil:** Is so viscous that it does not flow easily into a well and has a gravity below 20° API and a viscosity above 20 cp as well as extremely low (negligible) production rates which often include large quantities of loose sand.

**Natural Gas:** Is a mixture of hydrocarbons consisting mainly of methane but also including ethane and minor quantities of NGLs.

**Natural Gas Liquids (NGLs):** Light hydrocarbons consisting mainly of propane and butane, which are liquid under pressure at normal temperature.

**Oil Sands:** Refers to heavy black tar (similar to bitumen) which is frequently mixed with high volumes of sand. They are found principally in Canada and Venezuela. Oil Sands require mineral extraction production akin to mining which is completely different to oil and gas well production.

**Volatile Oils:** Oils that have low specific gravities and viscosities, 45°-70° API and GORs in excess of 360/$m^3$ (2000 scf/stb). They are pale red to brown in colour[16].

Although the above nomenclature for hydrocarbon accumulations is useful, it should be appreciated that reservoirs do not follow strict definitions and have been found to produce hydrocarbons in almost every conceivable ratio. Additionally, variations in pressure and temperature mean that there are no clear divisions between the classes of reservoirs*.

For our purposes, production mainly depends on the physical properties and behaviour of the reservoir fluids which change once production has commenced. Those changes will depend on what is in the reservoir.

## What's In a Reservoir?

Reservoirs have been found to produce almost every conceivable ratio of hydrocarbons. It is this diversity, along with variations in pressure, temperature, depth, thickness, sealing faults and potential links to adjacent reservoirs, that leads to oil and gas accumulations being characterised as uniquely different or heterogeneous structures. Carbonate reservoirs are considered highly heterogeneous. Calcium carbonate is much more

**Figure 5 - GOSP In The Shaybah Field Saudi Arabia (Saudi Aramco)**

chemically active than the silica that constitutes sandstones. It is easily dissolved in water, even more so in acidic water. Mechanical properties are another significant difference. Carbonate rocks tend to be more prone to fractures than sandstones. For all these reasons, carbonates form different rock types with a heterogeneous distribution throughout the reservoir. Moreover, the poor correlation between porosity and permeability, and the presence of caverns and fractures, create very complex paths for fluids making it difficult to accurately model the distribution of permeability in carbonate reservoirs[17].

Consequently, the challenge for the oil company is how best to produce a particular oil and gas accumulation considering all these factors and simulating their interaction over time.

## Reservoir Fluid States

Reservoirs are found at depths varying from 2,000ft+ (610 m) to deeper than 25,000ft+ (7,620 m). As noted in *Chapter 1: The Origin of Oil—Migration*, it is known that heavy oil is usually found in shallow reservoirs while lighter oil is found in deeper reservoirs, with gas alone found in the deepest reservoirs. Pressure and temperature conditions vary between reservoirs. Shallow reservoirs often have near standard conditions (15ºC [59ºF] and 15 psi [1 bar]) while deep reservoirs may have temperatures above 250°C (482°F) and pressures that may exceed 20,000 psi (1378 bar). Reservoir fluid states are held in a complex rock-gas-liquid system and can exist as aqueous and non-aqueous states or multiphase immiscible fluids[18].

We have seen that hydrocarbons occur in unique ratios and diverse states. The same can be said of reservoirs. Reservoir engineers must have a thorough understanding of this heterogeneity, as this plays an important part in understanding how production should best be engineered. Physical properties are needed to accurately describe fluid pressures up to 1,500 bar (22,000 psi), the possibility of high temperatures (up to 250°C) and corrosive fluids (waters that contain more salt than seawater i.e. approximately 35,000 mg/l). Empirical data and laboratory modelling is often applied to field reservoir applications.

Depending on the oil and gas accumulation, and its reservoir pressure and temperature, hydrocarbons underground may be present initially as:

• Liquid only—oil reservoir

• Gas only—gas or gas/condensate reservoir, or

• Gas overlying liquid—oil reservoir with gas cap, or gas reservoir with oil ring.

The comprehension of such complex natural fluids comes from an understanding of simple and ideal systems, which are modelled in the laboratory. The data required includes: density; compressibility; formation volume factors and gas-oil ratios for determination of recovery factors; viscosity and gas-oil ratios for production rates; and interfacial tension for recovery efficiency, as it has a major influence on oil trapping. See *Chapter 1: Origin of Oil—Trapping Mechanisms*.

## The Phase Behaviour of Hydrocarbons

As reservoir pressure drops, the resultant behaviour of the hydrocarbons depends upon the temperature and differential pressure as well as the composition of the hydrocarbons.

As pressure drops, gas expands and liquids tends to vaporise to gas. This is because molecules can move apart through their own kinetic energy breaking the weak bonds that hold them. (See *Chapter 11: Refining—Van der Waals Forces*). Conversely, if pressure is increased, molecules are forced closer together so that gas is compressed and forms a liquid. These changes from gas to liquid and vice versa are known as phase changes and are termed normal behaviour. Understanding this Pressure-Volume-Temperature (PVT) behaviour is essential because it controls the entire oil production process, while the physical parameters are needed to determine the process efficiency and sizing of facilities.

## Multi-Component Mixtures

The behaviour of multi-component hydrocarbons presents greater complexity due to the different volatilities of the components involved. Consequently, vapour and liquid have different compositions when in equilibrium. As the pressure drops, the compositions of both the liquid and gas phases change continuously: the first gas appears at the bubble point and only liquid remains at the dew point. One consequence of this behaviour is that the pressure-temperature plot is no longer a simple curve as for the single component; instead it is an 'envelope'—see Figure 4.

The maximum pressure defined by this envelope is known as the cricondenbar; above it, the liquid and gas phases cannot co-exist. The maximum temperature defined by the envelope (the cricondentherm) is, likewise, one above which the two phases cannot co-exist. The critical point is the point in the envelope at which the properties of the gaseous and liquid phases become identical—it is not related in any simple way to the cricondenbar or the cricondentherm.

| Depth of Reservoir | Initial Pressure | Temperature |
|---|---|---|
| 608m (2000') | 61 bar (900 psia) | 21-32°C / 70-90°F |
| 1520 m (5000') | 153 bar (2250 psia) | 38-65°C / 100-150°F |
| 3952 m (13000') | 408 bar (6000 psia) | 82-149°C / 180-300°F |

**Table 5 - Reservoir Pressure by Depth**

The behaviour of the fluid as it leaves the reservoir (essentially an isothermal environment) and travels through the production tubing and wellbore to the separation facilities requires more complex considerations of the thermodynamic behaviour; however, simple laboratory measurements are sufficient for design calculations[19].

If the reservoir pressure is at the bubble point, the oil is said to be saturated. If the reservoir pressure is above the bubble point, the oil is said to be undersaturated. An oil reservoir which is discovered with a gas cap is at its bubble point and is, therefore, saturated. An oil reservoir that is unsaturated describes hydrocarbons above their bubble point, where the reservoir temperature is substantially below the critical point and surface GORs are low to moderate. On production, as the reservoir pressure drops, gas comes out of the solution (solution gas drive). The first gas liberated is composed principally of the lightest components (methane, ethane and propane) as they possess the highest molecular energy and the lowest molecular attraction for other molecules.

Vaporisation of the lighter components is usually followed by quantities of heavier components until at low pressures only a fraction of the original material remains liquid. Gas has formed due to vaporisation of the light components and, as a result, the remaining liquid is described as having shrunk in volume. For a black oil, the shrinkage is only a small amount (often less than 30%). It increases rapidly, however, through the low pressure range (separator pressures) and through volumetric loss of intermediate and heavy material from the remaining liquid. Shrinkage characteristics in this range of pressures are extremely significant because surface separation of oil from gas occurs under these conditions.

## Condensate Fields

A condensate field is where the reservoir temperature lies between the cricondentherm and the critical temperature. In this case, if the overall reservoir pressure is allowed to drop, liquids condense out in the formation and may be lost because their saturation is so low that no liquid flow toward the well bore occurs (zero permeabil-ity to liquid). In order to prevent this valuable loss by retrograde condensation and to extract the liquids, reservoir pressure is often kept above the dew point by recycling the gas that remains after surface processing. A gas (wet* or dry) field is one in where the reservoir temperature is above the cricondentherm. Once the gas starts to expand up the tubing to the surface, the temperature as well as the pressure falls, and this continues to the final surface conditions. Liquid hydrocarbons may condense out in the tubing and surface lines and are often recoverable. Low-temperature separation increases the yield of these valuable light-end liquids. A dry gas field is one in which the final point (normally the separator) lies to the right of the envelope and no liquids are formed.

## Crude Oil Properties

The PVT characteristics of oilfield liquids are more complicated than for gases and it is usual to distinguish between saturated and unsaturated conditions. In the former, gas starts to separate from the liquid as soon as pressure begins to drop with production. In the latter, the pressure at which gas begins to separate from the liquid is some distance below the initial reservoir pressure at the bubble point, (Pb). The rate of pressure drop in an unsaturated depletion type field can be quite dramatic with a pressure drop of perhaps 1,000 psi for a production of only one or two percent of the oil initially in place. The reservoir fluids have pressure-dependent properties. It is necessary to know how the crude will behave as the reservoir pressure drops, or other reservoir conditions are altered to be able to determine how best to: produce a particular crude-oil accumulation; to forecast attainable production rates and the ultimate cumulative production; and, to develop EOR plans for a reservoir. These properties are measured in the laboratory using samples of crude taken from the field[20].

## PVT Data for Oil

Oil and gas behaviour can be described by using functions of pressure and temperature. Various parameters such as oil and gas interaction, composition and the phase envelope need to be determined for each reservoir. This is often done by laboratory testing of bottom-hole samples or, by using Repeat Formation Testing (RFT) or Modular Formation Dynamics Tester (MDT) tools. Additionally, oil and gas collected at surface may be recombined to represent the reservoir fluid as precisely as possible. This is, however, a difficult task. In many reservoirs, there are variations across the field and also between different reservoirs. Fluid sampling should be carried out as early as possible to ensure reserve calculations, well flow calculations and facilities design are based on representative samples. Great care is needed in conditioning the well to ensure that the fluid sample is representative. Generalised correlations have been developed which give information about the PVT properties for oil and dissolved gas using the available data obtained from a producing well test, e.g. oil gravity, gas gravity, producing GOR and reservoir temperature[21].

Difficulties arise from obtaining representative samples and deciding the correct thermodynamic path the fluids should follow in the laboratory to mimic the path followed by the hydrocarbons as they move through the reservoir to the well, to the surface and finally to the gauges and the stock tanks.

The processes affecting the fluids as they flow from the reservoir to the stock tank vary, but can normally be approximated to the flash or differential process. For instance, flash liberation can simulate the process in the tubing linking the formation to the surface and in the gathering lines from wellhead to separator because the agitation of the flow keeps the two phases in contact with each other. In the surface-gas separator, the pressure on the produced fluids is suddenly dropped and the gas evolved remains, for a time, in contact with the crude, i.e. a flash liberation.

In general, less gas is evolved in differential than in flash liberation, thus a greater proportion of the lighter hydrocarbons remain in liquid form when the pressure reduction follows the differential-liberation path. For black oils, the difference is usually small, but for volatile oils it can be substantial so that two or three stage separation is needed to drop the surface pressure from that at the wellhead to atmospheric (stock-tank pressure) to get maximum liquids (perhaps 8-11% more). Determination of the number of intermediate separators (GOSP) and the pressures at which they should operate depends on oil and gas properties as well as economic considerations[22] (see Figure 5 for Gas Oil Separator Plant).

## Reservoir Pressure and Temperature

In normal conditions, reservoir pressure is about equal to the hydrostatic pressure (pressure due to a column of water) measured from the surface. The hydrostatic gradient is about 0.45 psi per foot (9.6 kPa/m). Temperatures increase with depth by 10°F to 20°F per 1,000 feet (1.8-3.6ºC/100m). The table shows reservoir pressures according to depth.

In overpressured reservoirs, the initial pressure may be considerably higher. If different datum corrected pressures are found in different parts of the field, particularly after some production, it is likely that the field is not totally in communication and that there are sealing faults or isolated sands[23].

**Reservoir Temperature**

Primary recovery methods rely on the assumption that reservoir temperature stays constant. As fluids are produced any change in downhole temperatures due to production is compensated by heat from the cap or base rocks, which are considered to be heat sources of infinite capacity[24].

Average reservoir temperatures are therefore needed for laboratory analyses reflecting reservoir conditions. Reservoir temperatures are used to determine fluid properties such as viscosity, density, formation volume factor and gas in solution. Downhole gauges (during drilling or permanent) are used to measure reservoir temperature.

If a variation in temperature is detected across a reservoir after correcting for depth, an average value can be calculated and used as a constant reservoir temperature. For EOR, involving chemical and miscible processes, changes in temperature affect both the phase behaviour of injected and produced fluids, and therefore will affect recovery. The modelling of such processes must be accompanied by laboratory tests carried out using reservoir temperatures. In EOR processes that employ heat injection, such as steam or in-situ combustion, reservoir temperatures do not remain constant. In these cases, the reservoir temperature needs to be monitored all the time so as to detect the movement of the heat front[25].

## Development of an Oil or Gas Field

Once a discovery has been made, appraisal wells are drilled to determine the extent of the accumulation. The important reservoir calculations from the discovery data are the minimum size of the accumulation and the minimum size needed for commercial production. The appraisal wells are then sited to attempt to answer the question, 'Is this economic?' rather than 'How large is it?' With each appraisal well comes a refinement of the geological model of the accumulation, as represented by maps and cross-sections, and a new economic assessment. If it becomes obvious that the accumulation contains sufficient oil or gas to be considered commercial, development plans will be formulated. The siting of development wells is different from that of the appraisal wells, as now the purpose is to produce the petroleum as efficiently as possible at the lowest unit cost. If the field is complex, with multiple reservoirs and faulting, the most efficient well-spacing may be initially difficult to decide as each fault block may have to be regarded as separate accumulations. Over time production of fluids from the reservoir will change fluid pressure and flow rates. Production engineers will critically examine these factors to ensure that production can maximised over the life of the field.

This was a tough chapter but we now know what is in a reservoir and what actually constitutes a barrel of oil. What we have yet to learn is where these barrels are. Who are the 'oil haves' and 'have-nots'?

Readers note; reservoir and reservoir fluid characteristics are well covered in industry texts. Physical and chemistry texts provide the background to PVT behaviour, single and multi phase fluid flow.

## References


1. Crude oil volumes are still reported in barrels and in some cases in tonnes. However, the number of barrels contained in a tonne varies according to the type and specific gravity of the crude involved. An average number would be around 7.33 barrels per ton. Surface oil is reported at stock-tank (st) conditions, with volumes in cubic metres ($m^3$) or barrels [stb, or (st)bbl].

2. API What a barrel of crude oil makes. API Factsheet.

3. See Petrobras Technology Harts E & P, June 2003 p45 for heavy oil definition below 19ºAPI.

4. TTNRG Nature's Best Wajid Rasheed.

5. Pricing differential is due to higher proportion of heavier and sourer (high sulphur) crudes that relative to light sweet production. More than half the world's produced oil is heavy and sour in quality and this proportion is expected to increase. This depends on the crude oil's molecular structure and sulphur content. The oil will be classified accordingly and priced using reference crudes. Some of the common reference crudes are: West Texas Intermediate (WTI), Brent blend from the East Shetland Basin of the North Sea. Dubai-Oman, used as benchmark for Middle East sour crude oil flowing to the Asia-Pacific region, Tapis (from Malaysia, used as a reference for light Far East oil), Minas (from Indonesia, used as a reference for heavy Far East oil), The OPEC Reference Basket, a weighted average of oil blends from member countries.

6. The compositions of different crudes are measured and published in assays. Refining engineers use assays to decide which crudes will be required to formulate products.

7. API 5 RP 44 Sampling Petroleum Reservoir Fluids Proper management of production from a natural gas or petroleum reservoir can maximize the recovery of the hydrocarbon fluids (gas and oil) originally in the reservoir. Developing proper management strategies requires accurate knowledge of the characteristics of the reservoir fluid. Practices are recommended herein for obtaining samples of the reservoir fluid, from which the pertinent properties can be determined by subsequent laboratory tests.

8. For gas wells, the inverse ratio is sometimes used and the liquid-gas ratio is expressed in barrels per million $m^3$ (or million cubic feet).

9. Formation, Removal, and Inhibition of Inorganic Scale in the Oilfield Environment Author: Wayne W. Frenier and Murtaza Ziauddin ISBN: 978-1-55563-140-6. See also Scale formation RP 45 Analysis of Oilfield Waters 3rd Edition/August 1998.

10. Refining costs Sulphur Corrosion Control Author: Charles Kirkley See also RP 49 Recommended Practice for Drilling and Well Servicing Operations Involving Hydrogen Sulphide Recommendations include well drilling, completion, servicing, workover, downhole maintenance, and plug and abandonment procedures conducted with hydrogen sulphide present in the fluids being handled. 2nd Edition / May 2001. Further cost is added at the refining stage.

11. The Color of Oil Economides et al. Publisher: Round Oak Publishing Company; (March 1, 2000) 220 pages ISBN: 0967724805.

12. EIA BTU fuel content.

13. See also API Manual of Petroleum Measurement Standards. This manual is an ongoing project, as new chapters and revisions of old chapters are released periodically.

14. Condensates Energy supplies are often quoted in barrel of oil equivalent (boe). The energy contained in 6000 scf (170 $sm^3$) of gas is about equivalent to that in one barrel of oil (0.16 $sm^3$), so for an oil with a gas-oil ratio of 1500 scf/bbl (266 $m^3/m^3$), 25% of the energy from the reservoir is contained in the produced gas. Thus for black oils about 10 % of the produced energy is in the gas, whereas for the gas condensate field about 75% of the energy is produced as gas. For

this reason condensate reservoirs are not produced for the sake of the liquids only. A gas field of size 0.6 trillion scf is equivalent to an oil field of around 100 mmbbls.

15. See Advanced Reservoir Engineering Author: Tarek Ahmed and Paul McKinney ISBN: 0-7506-7733-3.

16. Saudi Arabia Oil and Gas Issue 4 The Carbonate Challenge (www.saudiarabioilandgas.com).

17. The behaviour of reservoir fluids is based on the laws of physical chemistry for perfect gases and the phase changes in gas-liquid systems.

18. The Flow of Complex Mixtures in Pipes, 2nd Edition, G.W. Govier and K. Aziz. Thirty-five years after its first publication, remains a fundamental resource, providing a unified approach to all types of complex flow.

19. Lab Crude Samples McCabe, Warren L.; Smith, Julian C.; Harriot, Peter (2005), Unit Operations of Chemical Engineering (seventh ed.), New York: McGraw-Hill, pp. 737-738, ISBN 0-07-284823-5.

20. API 5 RP 44 Sampling Petroleum Reservoir Fluids Proper.

21. SPE 102854 Performance Appraisals of Gas/Oil Separation Plants by S. Kokal, SPE, and A. Al-Ghamdi, SPE, Saudi Aramco.

22. If the field is communication similar datum corrected pressures will be found as average reservoir pressure drops.

23. Fluid Flow & Heat Transfer In Wellbores A.R. Hasan and C.S. Kabir.

24. The properties of crude oil and hydrocarbon gases have been extensively studied over the past several decades and many useful tables and correlations can be found in prior work e.g. charts (Dawe and Bradley 1987, McCain 1990).

25 The compressibility of oil is not entirely pressure dependent. The reported density of the oil is almost always that of the stock-tank oil not the reservoir oil, although reservoir oil density varies with pressure due to the associated effect of the gas in solution, which varies with pressure.

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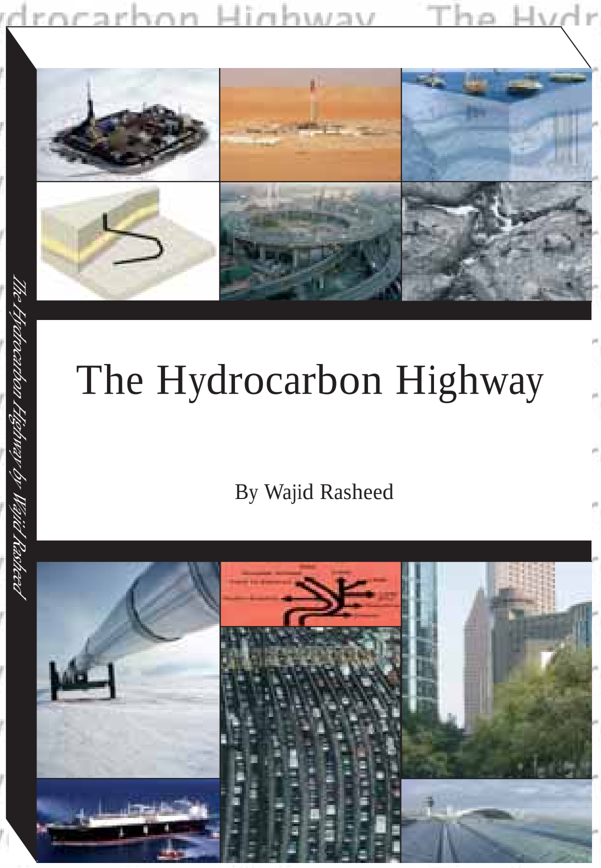


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