NOTES

GEOLOGY OF PETROLEUM: A SIMPLIFIED ACCOUNT*

Petroleum **and** its Generation Process:

Petroleum or Rock-oil is a naturally occurring admixture of various hydrocarbons. These are compounds made primarily of carbon and hydrogen, and range from straight-chain paraffins to ring type cyclo-paraffins (i.e. napthenes) and aromatics. defines are usually not present in the naturally occurring substance. The components present can occur either in simple admixtures or in complex combinations. In molecular size, the individual hydrocarbon constituents can range from the simple methane (CH_4) to highly complex and heavy semi-solids like asphalt and bitumen.

Individually, the lightest hydrocarbons are gases at the surface temperature and pressure, but, in their admixed state, the individual molecules get shared between the liquid and the vapour phase (i.e. gas) according to the equilibrium constant appropriate to the pressure-temperature regime of their occurrence. If the regime undergoes any change, the system tries to stabilise to the new conditions.

Although inorganic reactions, like that of metallic carbides with water, can produce some hydrocarbons, and the earth itself is supposed by some to have had a hydrogen-methane - ammonia atmosphere long before it had its first life forms. The general belief is that most of the commercially produced petroleum was generated by the decay of organic matter from both plant and animal life forms in sedimentary basins under an oxygen deficient environment. The organic matter can be both marine and non-marine. Oxygen deficiency can be produced by basin configuration (e.g. stagnant bottom-water in silled basins), rapid subsidence of the basin floor, flushing out of the pores in the newly laid sediments by the upward moving water (which has been rendered oxygen deficient) from the compacting sediments below, and by a variety of other factors.

The organic materials which produce petroleum can come from many sources, but these tend to accumulate primarily with fine grained sediments. Any material which comes with coarse-grained sediments tend to get winnowed out and destroyed. Some limestone formations can have their own source for the generation of petroleum.

The organic matter thus accumulated, initially forms a dark coloured substance called kerogen. It is highly variable in composition and consists of stacked sheets of aromatic rings in which atoms of nitrogen, sulphur and oxygen also occur. Based on their source materials, 3-types of kerogen are currently recognised (Fig.l). Kerogens are the precursors to petroleum, and their presence in appreciable quantities in fine grained elastics (and limestones) helps to recognise potential petroleum mother - or source rocks. Although, highly variable, each type has a somewhat different originating matter and results in a somewhat different category of the produced petroleum. The Type I kerogen, for example, forms mainly from

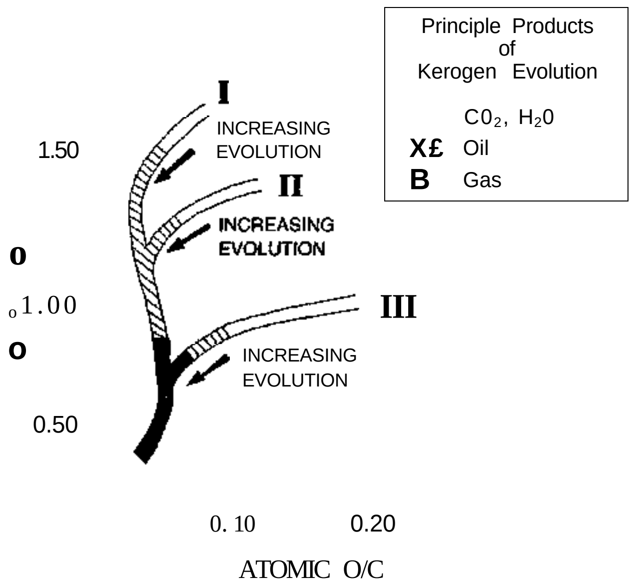

Fig.l. Evolutionary pathways of kerogens (adapted from paper by Tissot et al. in SAAPG, 1974).

lacustrine planktonic debris, intensively reworked by bacteria. Type II forms from marine planktonic debris, sedimented under anoxic conditions. Type III forms from land plant debris sedimented in near-shore marine, lacustrine, deltaic, parallic and flysch-type environments. At the same maturation stage, the capacity to generate more

** This write-up is based on the lecture notes prepared by A.B. Das Gupta for a Refresher Course for University and College teachers, organized by the Calcutta Universit in March, 2002.*

hydrocarbons per unit weight of kerogen, decreases from Type I to II to III.

In the petroleum generation process, not all the organic matter is broken down or reconstituted. Some of the compounds pass through without any major change. These help to trace back the basic type of source material. There are also other aspects of the composition which can be used to fingerprint the oil and thus help to distinguish one crude from the other, even in mixed environments. For example, terrestrial material like land plants and insects generate paraffin waxes with a predominance of such odd numbered hydrocarbons as C_{27}, C_{29}, C_{31}. Marine plants also produce odd numbered hydrocarbons, but in a lower molecular weight range of C_{15}, C_{17}, C_{19}. High wax crudes with paraffins in the C_{27}, C_{29}, C_{31} range would thus be expected to have a terrestrial source. Then there are the carbon isotopes. Lipids from marine planktons tend to have a higher proportion of ^{13}C than those from the terrestrial organic matter.

All these help in tracking down the source rock of the petroleum that has been discovered. Conversely, once a petroleum mother-rock has been found, it also helps assess what type of accumulation can be expected.

In addition, to its conversion to kerogen, the organic matter trapped in sediments initially generates some biogenic methane. With increasing burial, as it reaches an adequate temperature-pressure regime, the kerogen starts to form oil. With further burial and further increase in temperature (and pressure), the hydrocarbons start breaking down into smaller molecules, and the organic matter begins to generate increasing volumes of pyrogenetic gas (primarily methane). The change over from one regime to another is gradual but the major temperature zone within which the main oil formation takes place is around 60° to 165°C. This is popularly known as the *oil window* (Fig.2). Similarly, the geotectonic parts of the basin where any organic accumulations are likely to be so 'cooked' into oil and gas is referred to as the *kitchen.* The pyrolitic gas (methane) generation increases to a maximum rate at around 200°C. With further burial (and consequent rise in temperature), the gas generation slows down abruptly at around 300°C. The residue ultimately left behind can be graphite.The precise depths of burial at which these will happen depends on the geothermal gradient which can vary from basin to basin and from one part of the basin to another.

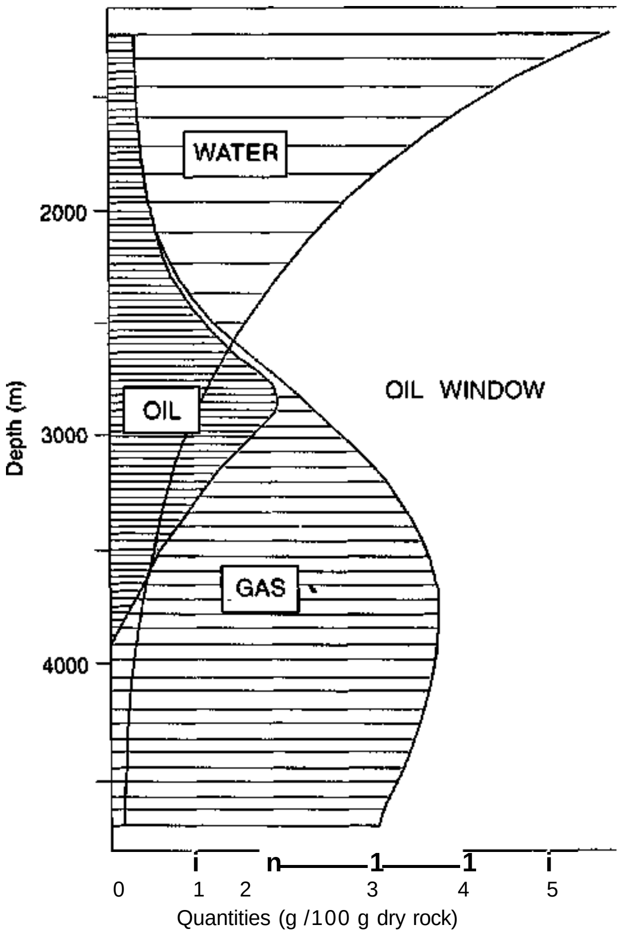

Fig.2. Oil window: compared quantities of water and hydrocarbons in source rocks as a function of burial *(afterTissol,* 1987).

Expulsion, Migration and Accumulation

Petroleum, thus formed, has to be expelled from the mother-rock, transported and trapped at the dead-end of its migrating path to give an accumulation. This calls for availability of expulsion mechanism, migrateable paths and reservoirs in which it can accumulate.Petro-physical properties of the stratigraphical elements involved, differential pressure and gravity play an important role in this process.

Ultimately, in any sedimentary belt, there can be myriads of possible traps and reservoirs, but only a small proportion of these contain commercially exploitable petroleum resources. Very large accumulations of the giant or super-giant class would be fewer still.

It is the task of petroleum exploration groups to sift the "grains from the chaff from whatever observations they can make and locate those that contain these buried exploitable resources. This is naturally a very complex task, and the exploration for petroleum today involves many facets that go far beyond the limits of conventional geology.

At the time of their deposition, fine grained sediments like clays can have upto 90% or more of water. With increasing depth of burial,and its attendant compaction, these sediments begin to lose the absorbed and the adsorbed water. This is the initial stage. Eventually the clays begin to turn into hydro-micas and release large volumes of chemically bound (and now resurgent) water. Compaction of the entire sedimentary column below (and conversion of its clays into hydro-micas) releases additional water- a part of which can also flow through the hydrocarbon mother-rock. The water thus squeezed out carries with it initially the lipids or oily matter of the original organic load, together with biogenetically produced methane and carbon-dioxide. Later, further increase in the depth of burial, leads to the increasing formation of petroleum liquids and gases. By this time, much of the absorbed water has also been squeezed out. Some chemically bound water starts getting released, but its magnitude is variable, as it depends upon the composition of the clays present. The total amount of water still coming out aided by whatever squeezed out additional water is filtering up from the sedimentary succession below, can carry away a part of the generated oil and gas, either in solution or, in micellar and colloidal suspension. Some other mechanism is required to expel the remaining oil and gas. It is believed that the conversion of soild kerogen into liquids (oil) and gases leads to an internal overpressuring and micro-fracturing of the reservoir from time to time. This helps direct release of the major part of the generated oil and gas into the more permeable migration pathways, without necessarily having to go through the solution/micro-emulsion route in water.

After expulsion from the mother-rock, the water carrying the solution/suspended load, as well as the free blobs of oil and gas coming out through the fractures, move along higher porosity and permeability layers of the sediments (and sometimes open fractures and faults) into lower temperature - pressure environments. There the water tends to release its hydrocarbon load which, in its turn, tends to join the free oil/gas stream. At this stage the physico-chemical laws which control the flow of mixed fluids through porous media take over.

Sediments laid under water are primarily water-wet, and water can pass through at rates that the permeability will permit. Oil and gas would however be stopped where the pore sizes in their path are too small to allow their entry under the available pressure differential. An accumulation will then form, in which the gas,oil and water will eventually be gravitationally segregated. The pressure differential is related to the buoyancy of the accumulating oil/gas column. This is usually not of a very high magnitude. If the pressure differential is later increased (either through natural causes or through human intervention) the gas and oil may leak away.

When a clay rock is squeezed, the expressed fluids can move in any direction (up, down, or sideways). Otherwise the primary driving mechanism is gravity. In a stratified system, most of the fluid flow will be updip, and its rate will be proportional to the sine of the angle of dip. Otherwise, it will take the shortest available path, which can be vertical.

If the strata, through which oil and gas is moving, develops an anticlinal form, and the layer concerned has a less permeable cover, we would have the classical anticlinal trap. Many other types of traps are possible, and one can even have a transient accumulation, through the queueing effect, if the slope of the beds decreases appreciably in the up-dip direction, Digboi has similar accumulations in some of its sands at every arrestment of pitch.

How far the oil can travel in this fashion, before it is trapped into an accumulation, has been debated from time to time. There are oil-fields which seem to have formed not far from their oil source. Equally, there are others which have been involved in fairly long distance migration. Apart from the criterion of their distance from the nearest available *kitchen*, there are some subtle indicators which are claimed to be able to give an order of magnitude indication of the distance the oil has travelled.

Non-alkylated benzocarbazoles, which are present in trace quantities in oils (and are not affected by the oil-window level of maturation process), have been suggested as one such indicator. Amongst these, the rod-shaped benzo(a) carbazole molecules seem to get adsorbed on the clay minerals and solid organic matter in their migration path to a greater extent than the sub-spherical benzo(c) carbazoles, with increasing distance of migration. The benzocarbazole ratio (a/a+c) may therefore provide a quasi-quantitative idea of the migration distance. However, at low concentrations, the requirements of analytical precision would be high, and one would need either samples from multiple points or well established parallels to come to any reliable conclusions.

On the whole, the feeling seems to be that both long and short distance migrations are possible. Out of the many oil-fields where various indicators seem to have established a reasonably reliable link with their sources, those containing long distance migrated oil seems to account for over 50% (AAPG Mem. 60, pp. 82-86). Migration distances in excess of 160 Km and possibly upto 500 km are reported to have been observed.The most natural migration path is up-dip from the *kitchen.* An extensive regional cover rock over the migration pathway prevents the oil from getting dissipated Lack of a regional cover permits many points of vertical movement into the nearby reservoirs Petroleum thus needs not only a local cover rock, permeability barrier, or change in the path gradient, to help it to accumulate, but it also needs a regional cover to sweep large areas in its pathway

Geotectonic Framework of Petroliferous Basins

Most sedimentary basins have a Shelf Zone, where the sediments are relatively thin This would be followed by a Hinge Zone, a Slope, and a Basin Deep In compressional basins, the latter would be followed by a faulted and folded Mobile Rim (Figs 3 1, 3 2 and 3 3)

In the Basin Deeps, where the floor subsides *pari pasu* with sedimentation, the sediments have their thickest development The Slope is the zone in which the most rapid change in sediment thickness (including many wedge-outs) takes place Regionally, it is also the zone of the most pronounced upward gradient This flattens rapidly across the hinge zone, into the Shelf There are also wide differences in the lithological facies developed in each of these zones

The Shelves tend to develop cleaner (and more permeable) sands, back lagoon organic rich sediments and limestone reefs The bottoms of the slopes can have turbidites suitable for hosting petroleum The basinal sediments are usually dirty, but these can be rich in organic matter - particularly closer to the shelf and the mobile rim Parts of these are also likely to reach the temperature-pressure regime required for the petroleum kitchens Shelves are seldom absolutely flat These too tend to have their own relatively thick sediment filled depressions, which can also take organic rich sediments down to the oil-window level and generate oil and gas for some of the shelf reservoirs

Interestingly, when Knebel and Rodngues-Eraso were looking into the habitat of oil in 1956, they found that 71% of the oil discovered till then was from the shelf environment, 23% was from the Hinge Zone, 2% from the basin centres and 4% from the mobile rim These possibly relate primarily to basins developed in the zone of compressional tectonics In intra-cratonic basins developed by sagging down of the basement, structures near the basin centre can also have important accumulations Parts of the basin regimes conducive to the generation of petroleum are also those that can develop salt deposits and evapontes Under gravitional pressure, the salt can move up like a plug and carry a lot of oil and gas for filling up the reservoirs in the vicinity

Early History of Petroleum Development

All the factors concerning the generation, migration and accumulation of petroleum were naturally not known at the outset Petroleum residues left behind at the surface by ancient seepages have of course been known and used locally for a variety of purposes in a number of countries tor many centuries but without the people trying to find out much about it From around 200 BC, the Chinese have been producing natural gas in some of their inland provinces like Szechuan for local consumption Their object however was primarily salt They found it much cheaper to produce salt from salt-water springs in their area rather than bring it all the way from the coast Eventually, they developed methods to drill wells for salt-water In the process, they found that they were also producing a combustible gas (methane) Their entire operations from drilling to transportation of gas were conducted with bamboo pipes

In Myanmar, some surface oil seepages in Yenaung-yaung were tracked down to shallow oil sands They developed their own technology for digging deep wells by hand They lifted the oil in buckets and used it as a bullock cart wheel grease and for lighting lamps These were however all small-scale local activities and made no major global impact This came with the Industrial Revolution in the West and the successful drilling of a well close to an oil seepage in USA by Col Drake in 1859 Initially, the Industrial Revolution was fuelled by wood and coal but petroleum took over in time, particularly in the transportation and mobile power sectors The development of internal combustion engines which could operate on a very low weight to generated power ratio revolutionised these sectors and made activities like flying possible The result was a tremendous burst of activity to discover and develop petroleum resources

The Early Modern Era and the Subsequent Evolution of Concepts

In the early stages, the main exploration tool foi finding commercially producible petroleum was to drill oi dig wells close to seepages or residues of petroleum Away from the clogged near-surface zone, the oil tended to be more fluid and could give much larger rates of flow Oil finding was an adventure and a gamble, and many followed their hunch with diverse tools like the Doodle-bug and the Divining Rod Some found commercial fields, many did not Out of these, grew the first concepts that oil accumulations formed at the top of anticlinal (and other) structures m porous reservoir rocks, sealed above by impervious shales or other cover rocks

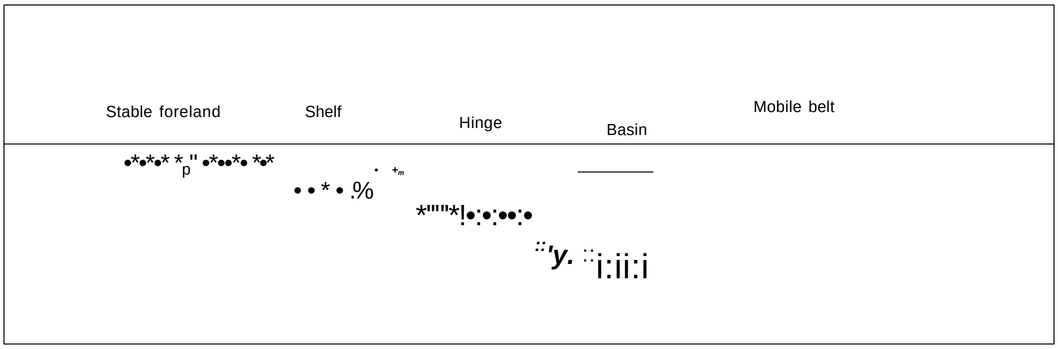

Fig.3.1. Generalised geometry of an asymmetnc sedimentary basin *(after* Tlratsoo, 1973)

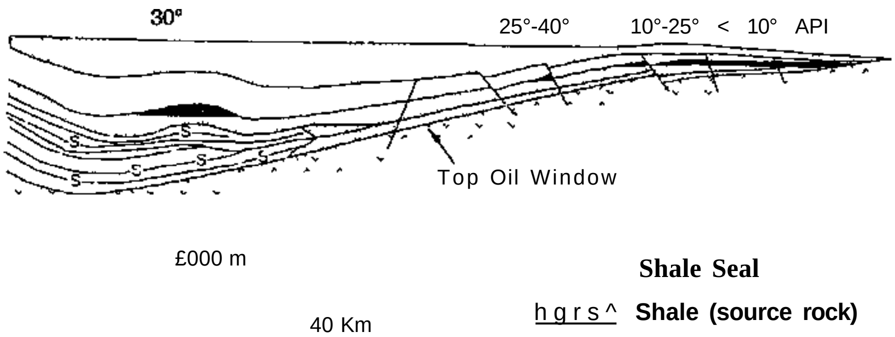

Fig.3.2. Example of a petroleum system, after the eastern Venezuela foreland basin, *(after* Petroleum Systems, 1994)

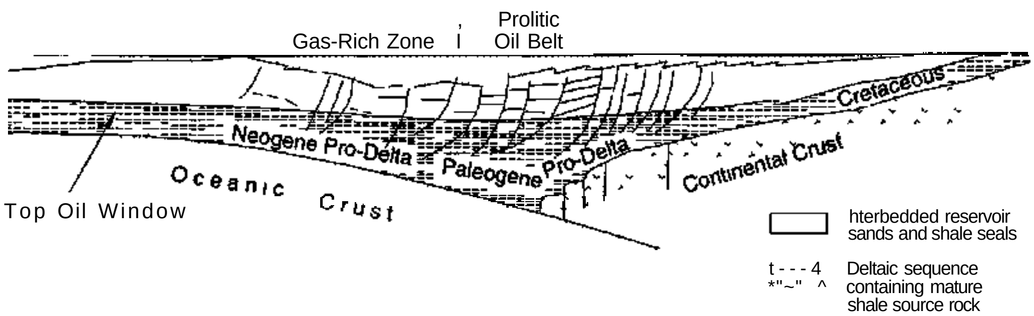

Fig.3.3. Example of a petroleum system, patterned after Niger delta, Nigeria *(after* Petroleum Systems, 1994)

Although the beginnings of this theory were propounded in 1861, by Andrews and enlarged in 1863 by Sterry Hunt, it dtd not get any industry-wise acceptance for many years It had eventually to be revived by IC White in 1896 and to lead to the discovery of Manmngton field before it found acceptance The Digboi Oilfield in NE India was discovered at around this time by drilling close to an oil seepage The party concerned, though eminently successful in other lines of endeavour, did not have any clue to the controlling mechanism of the field and could sustain a small production of less than 200 barrels a day, by drilling at random all around It took another 30 years for the Burmah Oil Company (BOC) to come onto the scene, discover its anticlinal control and eventually to raise its production to the level of around 5000 bis/day In the process they found that not only the anticlinal summit but every arrestment of pitch in the crestal area could also hold accumulations Many could be transient in terms of geological time A clay barrier was not essential to stop the upward movement of oil or gas and even a minor compressional fault in the same sand body could be adequate to hold back the oil or gas and form an accumulation Conversely, the same fault could permit leakage if the pressure difference across was increased They also found that the fold had a pronounced asymmetry in its summit area, and that the culmination of the deeper sand layers there did not he directly below those of the layers above The asymmetry caused a southerly down flank staggering of the deeper culminations, and they had to devise section construction methods which would be able to reasonably predict their positions This helped them to bring in major production from the sands below

Whilst these lessons were being learnt in Digboi, many other important developments were taking place elsewhere in the world During the 1930s, Krumbein, Pettijohn, Sloss and others observed that the sedimentary htho facies were not random in their distribution, they had a distinct relation with the geotectonic regime of the basin in which they were deposited Subsequent investigations on the habitat of oil carried out by Knebel and others showed a parallel association of organic-rich sediments, reservoir rocks, and petroleum accumulations with the geotectonic set up of the sedimentary basins The position of the petroleum *kitchens*, the development of petroleum migration pathways and of the strati graphic cum tectonic associations that trap the oil and gas and form oil/gas fields are all ultimately controlled by the geotectonic fiamework of the basin In fact, even the basin formation itself is a reflection of the overall geotectonic situation

On the micro-scale, of course, there are many local factors which contribute to the development and attributes of all petroleum accumulations The same physicochemical laws which prevent the oil from entering the less permeable strata may also make it bypass the less permeable zones of a heterogeneous but otherwise oil-filled reservoir The oil-water margin normally tends to be horizontal, but if there is any hydro-dynamic movement of the water below, it can develop a tilt in the direction of the flow (Figs 4 and 5) The development of the reservoir, its geometric form, and porosity-permeability pattern, can all be controlled by the immediate mechanism of its sediment transport and deposition. A channel sand can have a long meandering body, cleaner and more permeable below, but more dirty and less permeable towards the top A bar sand can also be linear but, porosity-permeability-wise, just the reverse These are only some stray examples The petroleum accumulation and its geological setting can have a wide diversity based on the local factors

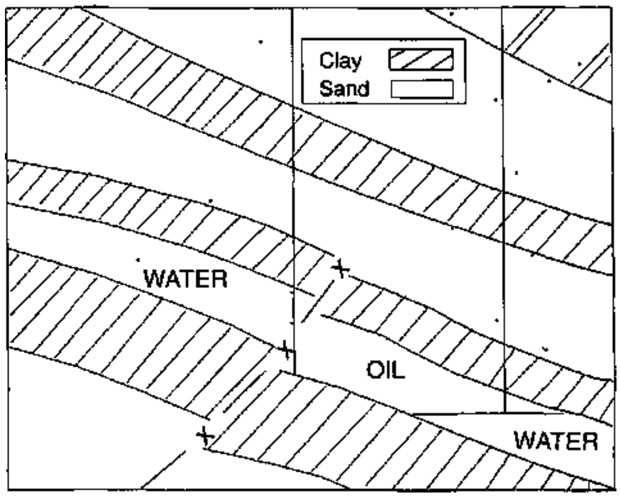

Fig.4. Water overlying oil in the same sand body across a rmnoi reverse fault *(after* Das Gupta, 1969)

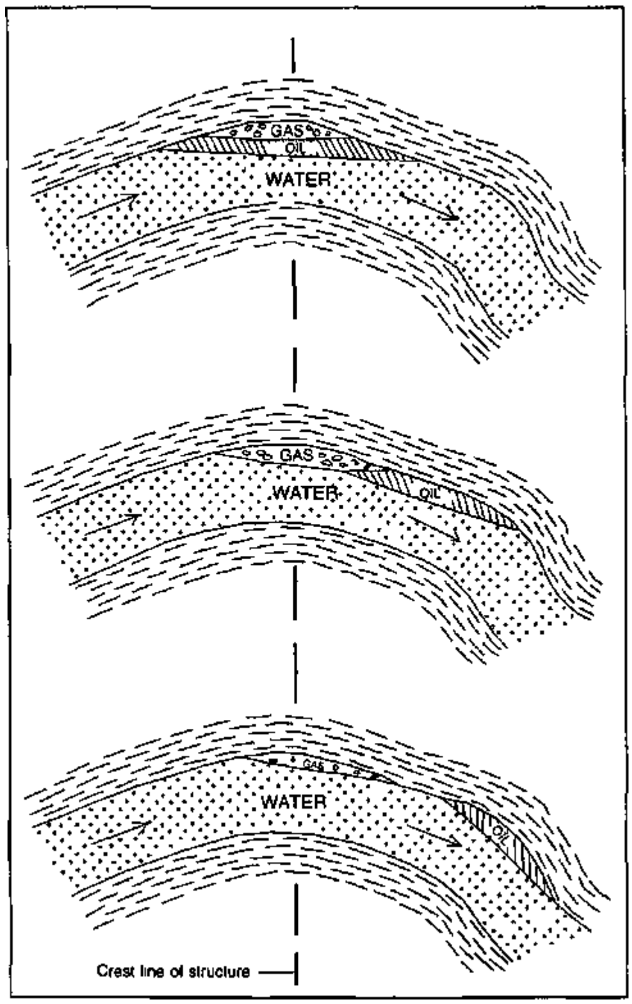

Fig.5. Off centre accumulation of petroleum as a result of formation - water movement *[after* Hubert and ONGC Bull v 6, no 2, Dec 1969)

Exploration Modality, Tools and Philosophy

The problem is how to recognise these in a new area This involves total geology using all possible scientific knowledge and tools that human ingenuity has been able to develop Some of these have grown into highly specialised branches of science and engineering themselves These start with the earth's gravitational, magnetic, electrical, acoustic or seismic and fluid flow properties Exploration teams have to collect the raw data through high precision instruments and process these through elaborate computer systems to generate an overall picture To this has to be added whatever can be gleaned from surface geology, photogeology, remote sensing imageries, palaeontology, palynology, petrology, sub-surface sample studies and reservoir engineering It is a long list but many specialisations are involved and ultimately it takes the form of a very high powered team work

At the end, the various alternative possible pictures produced by this elaborate process have to be analysed, synthesised and decision taken on how to proceed with the next exploratory step This aspect is reasonably covered in a talk I had prepared a few years back on "Exploration Strategy for Petroleum" which was later published in the July 1994 issue of the Journal of the Geological Society of India Extracted below are some of the important points on petroleum generation and accumulation brought out in that note

a) A marine environment is not essential for the formation of petroleum This can take place in widely ranging conditions, from fresh water to marine, and from a fairly wide range of organic materials Most of the paraffinic crude oil, for example, are believed to be derived from terrigenous material
b) The organically rich finer elastics and biologically produced carbonates are regarded as the more common petroleum source rocks Purely inorganic sources are not ruled out
c) To be converted to petroleum hydrocarbon liquids, the organic material entrapped in the above has to be subjected to a range of time cum temperature conditions, often referred to now-a days as the 'oil-window' Maturation and palaeo-temperature studies of organic-rich sediments can sometimes provide a clue to whether, where and when petroleum forming *kitchens* are likely to have been developed
d) In any large basin area, the local depressions which have restricted conditions at the bottom (where little replenishment of oxygen takes place) can be better locations for the generation of hydrocarbons This is not however an essential pre-requisite and with rapid burial, petroleum can also form in basins with otherwise highly oxidising conditions
e) For petroleum accumulations to occur, some of the reservoir rocks available should have had access to areas favourable for petroleum formation at the appropriate geological times concerned, and adequate porosity /permeability must be retained through the subsequent phases of diagenesis and compaction
f) There is a tendency for petroleum accumulations to get concentrated in certain specific types of geotectonic regions (platform areas, hinge belts, central regions of basins within cratons where gravity is the controlling tectonic force, etc)
g) Within a petroliferous basin, the accumulations have often a tendency to occur in progressively younger horizons towards the basin centre Gulf of Mexico and NE-Assam are examples
h) Hydro-dynamics and differential entrapment may be important in the precise location of accumulations
i) Petroleum does not always need an anticline in which to accumulate, even minor changes in the slopes of beds and/or permeability can lead to the formation of accumulation
j) Petroleum accumulations formed through the controlling mechanism of a given set of geological conditions, in any basin often tend to occur in clusters with the individuals ranging in size from large to small With sound geological approach to exploration, the 1 digest accumulation would often be the first or the second to be discovered The subsequent ones would tend to be progressively smaller
k) In any single basin, there may be more than one such cluster, each needing to be discovered separately and each controlled by a different set of conditions In their geographic distribution, the individual clusters may be totally separate or may partially overlap each other
1) Certain classes of heavy crude occur close to land surfaces both past and present Termed by some as 'unconformity oil', their presence can often indicate the existence of better oil away from the unconformity surface or the outcrop concerned
m) Age-wise, petroleum accumulations have been found in sediments ranging from Cambrian to the Pleistocene At times, petroleum formed in a basin has also found reservoir conditions and have accumulated in the metamorphic basements and in igneous sills So far, only minor attention has been

paidtotheProterozoic.but now that evidence of life is well established from formations of this age, these may also need more attention in any search for oil.

n) Maturation of coal beyond the stage where it has 83% carbon, leads to the release of methane which can then either remain there trapped within the coal seam itself, or move to a nearby reservoir rock. Conceptually, it is also possible to have accumulations of inorganically derived methane.

o) Some accumulations can be very unorthodox. In Lake Kivu (Africa), for example, the bottom water has dissolved in it enough methane to provide a theoretical reserve of the order of 57 trillion cubic metres. Together with this, there is also around 190 trillion cubic metres of $C0_2$ and 4 trillion cubic metres of nitrogen.

p) An important matter to remember in any search for oil is that, not all the oil discovered so far has been through well planned exploration. A substantial quantity has been found accidentally by people following at that time no acceptable guidelines whatsoever. In fact, in many instances, the development of concepts on where to look for oil has followed rather than preceded the discoveries concerned. One therefore needs to make an allowance for one's 'ignorance factor' in formulating any scheme for exploration.

As already implied, the above does not constitute an exhaustive list. Many other associations have been noted, but these cannot always be extrapolated and used as exploration guides in other areas. For example, it has been stated that the shear patterns produced by deep-seated wrench faults have influenced the linear distribution of petroleum traps in many areas extending from Alaska, through California to Columbia-Venezuela. A similar association has also been noted from the Gulf of Guinea but it is not clear whether this is a special feature pertaining to some local areas only or it has a much more general application. Likewise, most of the oil-rich belt in Indonesia and its adjoining region, occurs on the inner side of their island arc belt systems, behind the frontal mountain belt of the Indonesian Plate. Whether a similar association can be expected in all places where two plates have collided is not clear. Then again, there is the growth fault controlled roll-over anticline regime which has been found to contain a lot of oil in certain delta environments like the off-shore Nigeria, but we do not seem to be clear about the key combinations that has produced this. May be, a combined geological cum statistical analysis will produce the clues that are required to make these relations more widely useable.

In any case, even the guidelines formulated on the above concepts can only lead to the delimitation of the types of environment where oil has been found so far. In addition, there must be other categories of areas, also favourable, in which no discoveries have been made, and which may continue to remain excluded if guidelines are only sought from the past.

To these, one could add Coal Bed Methane (CBM), Gas (Methane) Hydrates, and Deep Sea Prospects. Coal Bed Methane Prospects depend upon the amount of both biogenic and thermogenic gas absorbed and adsorbed in coal, and on the extent these can be desorbed and produced economically. The quantity theoretically present can be high, but the amount that can be economically extracted may be more modest. The coal constituents with relatively high hydrogen, which form alginites and exinites, generate more gas. Coal seams with a larger internal surface area, through micropores, cleats, joints and fractures, have greater methane adsorption/desorption capability, and are thereby more likely to be commercial.

The natural gas hydrates are crystalline ice-like solids in which the gas molecules (primarily methane) are encased in the interstices of hydrogen bonded water lattice. These are stable only within a narrow range of low temperature and high pressure. Kuldeep Chandra's paper in the Indian Journal of Geology (Dec. 1997) records much useful information on both CBM and Gas Hydrates. The estimated global resources of methane in gas hydrates has been recorded there as 20,000 TCM, which is 70 times that of conventional natural gas. In India, the pressure-temperature constraints keep its potential existence restricted to the deep offshore, where (under favourable conditions of methane supply) it could occur as clogging the pore spaces within a narrow sub-bottom range between 1000 to 3000 metres iso-bath. In this state, it could act as a seal, below which normal gas accumulations may also occur. Very large volumes of hydrates may be present, but the problem lies in developing a technology for controlled production which will not upset the delicate hydrate stability condition.

Ancient basins (faulted, folded or otherwise) forming parts of the present day continents or islands have long been targets of exploration for petroleum. In time, exploration and production activities have extended to the offshore continental shelves and semi-enclosed seas like the Lake Maracaibo, Gulf of Mexico and the North Sea. Over the years, these have extended to the deep seas, adjoining the Continental shelves, wherever these are giving any indications of having thick sediments. The Atlantic Ocean (offshore Brazil) and a number of other places have already proved productive. New to join the hunt are Bay of Bengal and the Arabian Sea. The Bay of Bengal has an enormous sub-marine fan, which is around 5000 m thick at the head of the bay, and around 3000 m thick at the equator. This is not of a uniform thickness. The whole basin has a number of highs and lows, breaking it into a number of components with wide variations in the thickness of sediments,. The younger sediments have been laid by a sub-marine distributary system spreading out from the Swatch of No Ground near the outfall of the Ganga-Brahmaputra drainage system. The major channel carrying this submarine flow is about 180 metres deep and has a width of upto 27 km between the levee crests.

The deep sea accumulations are expected to have largely the same type of geological control as in the on-shore and continental shelf but the reservoir development may have to depend more on the primary and the redistributed turbidites as well as on the mode of development of the submarine fan, and on how the basin floor has responded in terms of horst, graben and sub-basin formation.

Direct Indications of Oil

The above gives a brief outline of how petroleum and its related hydrocarbons form, migrate and where its accumulations are most likely to occur. To help in this search, there are also occassionally some direct indicators. Firstly, there are the micro-seepages of gas which come up vertically from the accumulations below. Normally, the process of molecular diffusion of methane is very slow (about 6.674 years x square of the depth in feet) and there would be little chance of any Tertary oilfields from showing up this way from depths greater than 3000 feet. Water sqeezed out from compacting sediments however can come up much faster and bring up some methane as well in solution. These ought to show up as surface anomalies, but in many areas the dissolved vertically migrating gases can get swept away by the hydro-dynamically moving water in the intervening layers. Buried oilfields can sometimes show up as radioactive and other haloes, but these too may be swept away by the lateral movement of water in the intervening layers.

In an area of low gravity changes, large gas fields may show up as mild features on gravity surveys, but usually these would be masked by stronger changes in the gravity field due to other causes. The presence of low to moderate pressure gas can reduce the seismic veloicity in sediments. This can produce a strong reflection (known as a Flat Spot) at the gas/water contact of a thick gas zone at depths less than 6000 ft. At greater depths the gas is more compressed, the velocity contrast is much reduced, and the contact may not show up. There are a variety of seismic techniques which, under favourable circumstances, can give some idea of the fluid contents of a strong sesimic reflector. Modern time-series, 3-D seismic surveys (i.e. 4-D survey) can bring out changes in the relative fluid contents with time. In marine seismic surveys, in the tropical belt, the presence of gas hydrates may show up through an ocean bottom simulating reflector or BSR. Information from all these naturally have to be ploughed back into the overall synthesis for the evaluation of prospects.

The Ultimate Tasks in Oil Finding

In the search for petroleum, one thus needs to reconstruct the basin geometry, its geotectonic framework, its depositional environment, the likely source rocks, the likely *kitchens*, the likely migration pathways, and where the migrating mass may have accumulated. All these, after taking into account their known favoured associations and any direct indications of gas or oil. The work involves many specialised branches, in the intricacies of which the geologist as such may not know all the details. He would of course be expected to understand the outputs, what they mean, what are the limits of their probability, and what alternatives are possible. Likewise, the other specialists have to imbibe enough geology to understand the basis of what they are trying to measure and display.

Without these, the exploration teams would be unable to arrive at an overall synthesis and recommend the kind of agreed programme on which management can take major investment decisions. Interestingly, as specialisation has grown and massive investments have been made on equipment and interpretational infrastructure, the petroleum majors seem to have been finding it increasingly difficult to make many dicoveries on their own. They seem instead to be finding it cheaper and less risky to buy into properties already discovered by others. In fact, globally there have not been many discoveries of large new oil/gas fields since the 1960s, and most of the rise in proved and probable reserves has been coming from extensions to and reappraisal of old oil/gas fields.

PETROLEUM RESOURCES

Conventional Crude Oils

These are the common types of crude oils which are processed in the refineries to give us the products we commonly use. In order that they can maintain their current economy, as also have a long range perspective, the industry operates on the basis of two types of assessments The current economy (including the ability to raise Bank finance) is ensured by operating on the basis of conservatively estimated proved and probable reserves The long range perspective is taken care of by prognosticating what ultimately discoverable resources one may be dealing with Of this, what is believed to have been discovered (and produced) is only a part

On the basis of the limited directions from which one could hope to make discoveries, the globally prognosticated resources of petroleum were expected to be around 500 billion US bis during the mid-1940s From 1947 to 1958, studies on the Habitat of Oil produced many new ideas and the estimate of prognosticated resources rose sharply to about 2000 billion US bis Thereafter, the more realistic estimates have remained at around 2000±500 billion US bis, equivalent to around 265±65 billion tonnes By 1 1 1996, the Industry had already discovered about 1789 billion US bis or about 245 billion tonnes, and out of the above had been able to produce about 772 billion US bis or roughly about 105 billion tonnes

As on 1st January, 1993, the equivalent figures for Natural Gas were

Prognosticated Resources	11567 5 xlO^{12} eft
Already Produced	1750 2 xlO^{12} eft
Additional Identified Reserves	5136 $OxlO^{12}$ eft
Awaiting Discovery (on Modal Probability Rating)	4681 3 x 10^{12} eft

The corresponding situation in India was

a) Prognosticated Resources of Oil & Oil equivalent Gas at 95% probability (as estimated on 1 1 1992)	13 56 billion tonnes
b) Established Reserves of Oil & Oil equivalent Gas as at 1 1 1994	1 401 billion tonnes
c) Cumulative production of Oil & Oil equivalent Gas to 31 12 1993	0 664 billion tonnes

Globally, the known resources of conventional crude oil and natural gas are not evenly distributed About 65% of the proved reserves of conventional crude oil (as at the end of 1995) occurs in the Middle East The two American continents, which account for 14% comes next Russian Federation, Europe, Africa, Indonesia Malaysia and many other countries also have substantial oil reserves, but these add upto only the balance 21%

In natural gas, the maximum proved reserves are in the Russian Federation (about 1700 trillion cub metres as at the end of 1995) This is about 34 5% of the total The two American continents have another 503 trillion cub metres or 10 2 % The rest is shared by the other countries

In age, the occurrences range from the Teitiaiy down to the Proterozoic By and large, a limited amount of tectonic disturbances help in migration and formation of petroleum accumulations, but excessive disturbances lead to their seeping away Ancient deposits, subject to multiple phases of folding and faulting do not consequently have many large accumulations preserved

Heavy Oil and Tar Sands

Very large deposits of asphaltic heavy oil and sands, impregnated with such oil (i e tar sands) exist in many countries The best known example is perhaps the Athabaska tar sands These are presently in use (either directly or as a fuel or after hydrogenation or after emulsification with water) on a relatively small scale Very large resources exist The total may be of the same order as that of the conventional crude oil The whole future of these resources depends on the extent to which these can be mined and converted into marketable products economically

Oil Shales

Deposits of asphaltic, pyrobituminous shales, otherwise known as oil shales are present in many continents On being heated, in a closed retort, these can produce a distillate resembling crude oil Depending upon the richness of the organic matter, the yield can vary from 4 to 50% of the rock by weight Improved yield and product quality can be obtained if distillation is carried out in a stream of hydrogen

The world production of oil from such shales used to be in the region of 350 million US bis per year in the early 1970s Most of this was from China The present position is not known

It has been estimated that there could be around 2500 billion tons of oil-in-place in known accesible oil-shale deposits, which are capable of yielding 10 to 40% of their weight in oil This is much larger than the ultimately recoverable reserves of conventional crude oil But, how much of this can be availed of would depend upon the extent to which the many attendant environmental, mining and processing problems can be economically overcome

Gas Hydrates

As already mentioned, there is believed to be around 20,000 TCM of methane locked up globally in gas hydrates Their development poses many problems

CONCLUDING REMARKS

Starting from being an important energy source for fuelling the Industrial revolution, petroleum has developed into a vital necessity for all of us Through refining and other chemical processes, it is now routinely converted into special fuels, lubricants and a wide range of petro-chemicals (from textile fibres and artificial leather to structural material) which have become essential to our living Amongst the fuels, the most important are those that can generate a very high level of power from light weight engines In conjunction with electricity, these have revolutionised our transportation cum mobile power sector, and has made activities like flying in heavier than air vehicles possible

The entire subject of petroleum - where and how it forms, and accumulates, how to look for and produce it - is naturally very complex This paper has aimed at presenting a brief outline of the entire spectrum without trying to go into the intricacies of each detail It also deals with the geology of petroleum only up to the stage of its occurrence once discovered Thereafter, it has to be economically recovered from its reservoir This process involves taking maximum advantage of the nature of the reservoir and of the various forces within it, which either support or provide impediment to the flow of fluids present Depending upon the circumstances, and the wisdom with which the situation is met, the recovery attained may range from as low as 10% to as high as 60-80% This takes us to another complex domain- ie that of reservoir engineering and management This aspect has not been covered in the present note Anyone so desirous will find an introduction to this topic in the author's paper on "Improved Oil Recovery" published in the Journal of the Geological Society of India, v 57, no 5, March, 2001

To maintain its focus on the general aspects, the paper has avoided getting involved in too many details The measurement of petroleum fluids is however an area where some details cannot be avoided These have therefore been provided in the Appendix Selected bibliography of reading materials to assist those who may wish to go deeper into the subject has been provided For the rest, one would need to go into text books on geophysical and geochemical surveys, as well as on reservoir engineering

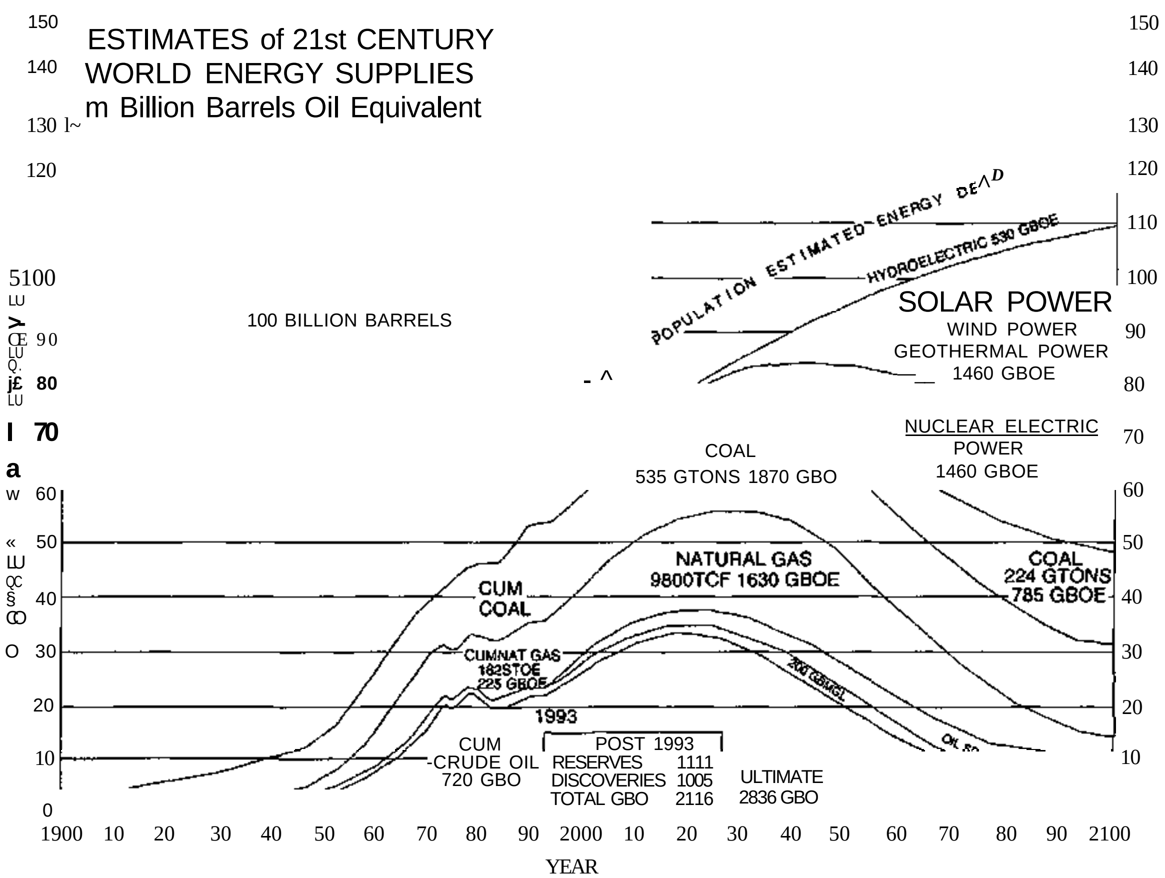

Fig.6. Estimates of 21 st century world energy supplies *(after* J D Edwards, AAPG bulletin, v 81 no 8, August 1997)

There are considerable misgivings amongst the petroleum economists as regards how long the conventional oil/gas supplies will last Many feel that the foreseeable supplies will be unable to support the present growth rate in consumption beyond the 2020s or at best the 2030s The decline in the availability of natural gas is expected to follow a few years later Provided adequate thrust is given, mankind should however be able by then to fall back upon the other non-conventional sources outlined above (Fig 6)

DB6, Salt Lake City,
Kolkata - 700 064

AB DAS GUPTA

Selected Bibliography

CHANDRA, KULDEEP (1997) Non-Conventional Hydrocarbon Resources like Coal Bed Methane and Gas Hydrates Indian Journ Geol, v 69, No 4, Dec 1997, pp 261-281

DAS GUPTA, A B (1969) Some Problems of Petroleum Exploration and Development in India ONGC Bulletin, v 6, no 2, ppl-9

DAS GUPTA, A B (1976) Energy Situation in India and Fossil Fuel Availability QJGMMSI v 48, no 1, pp 1-18

DAS GUPTA, A B (1976) Growth of Technology in the Field of Petroleum Exploration in India Holland Memorial Lecture, MGMI, Feb 1976

DAS GUPTA, A B (1994) Exploration Strategy for Petroleum Jour Geol Soc India, v44, pp 100-109

DAS GUPTA, A B (1995) Competitive Edges in Petroleum Technology Jour Geol Soc India, v 45, pp 497-507

DAS GUPTA, A B (1996) A Historical Perspective of Oil & Gas Exploration in India Bull ONGC, v 33, no 2, pp 1-13

DAS GUPTA, AB (1997) India's Petroleum Reserves Recovery and Evaluation PetroTech - 97, v 1, January, 1997, pp 47-52

DAS GUPTA, A B (1999) Challenges and Opportunities of the Petroleum Industry in India PetroTech-99, pp 307-317, and Indian Journ of Landscape System & Ecological Studies, v 22, no 2, 1999, pp 158-168 and pp 307-317

DAS GUPTA, A B (1999) Estimates of Hydrocarbon Resources and Reserves, and Petroleum Exploration and Production Scenario of India Bull ONGC, v 36, no 2, Dec 1999, pp 29-34

DAS GUPTA, A B (2001) Improved Oil Recovery Jour Geol Soc India, v57, March 2001, pp 283-287

HUNT, J M (1968) How Gas and Oil form and Migrate World Oil, October, 1968, pp 140-150

JOHN D EDWARDS (1997) Crude oil and alternative energy production forecasts for the 21 st century AAPG Bull, v 81, no 8, pp 1292-1305

LARTER, SR and Others (1996) Molecular Indicators of Secondary Oil Migration Distances Nature, v 383, pp 593-597

PETROLEUM SYSTEMS - From Source to Trap (1994) AAPG Memoir 60,1994 (for special note 'Genetic classification of Petroleum Systems using three factors Charge, Migration and Entrapment by G Demaison and B J Huisinga in Chapter 4, pages 73-89)

TLRATSOO, EN (1973) Oil fields of the World Scientific Press Ltd , PO Box 21, Beaconsfield, BUCKS, England, 376p

Appendix

Mensuration

Crude Oil

As crude oil comes up from its underground reservoir to the surface, it releases some gas and shrinks in volume Us density also undergoes a corresponding change (le increase) The magnitude of the change depends upon differences in temperature, pressure and the amount of gas released dunng its movement from the reservoir to the stock tank at the surface The latter is normally used as the standard of reference, and the ratio Reservoir volume/Stock Tank Volume is referred to as the "Formation Volume Factor or FVF

The noimal units of measurement are either Cubic feet or cubic metre or barrels (either Impena! oi US)

1 cu metre	= 1 x 3 2808430 cu ft	= 35 31467 eft
	= 6 289793 US bis	
	= 5 499223 Imp bis	
1 Imp bl	= 6 4217567 eft	= 1 14376 US bis
		= 40 Imp gallons
lUSbl	= 5 6146 eft	= 0 87431 Imp bis
		= 42 US gallons
1 Imp gallon	= 0 160544 eft	= 1 200948 US gallons
1 US gallon	= 0 1336809 eft	= 0 832675 Imp gallons

With widespread international operations, it is now-a days more common to use the US units

Crude oils can be heavy or light depending upon the relative amounts of lighter and heavier hydrocarbons present This is reflected in the crude oil's density or specific gravity The lighter the oil, the lower is its density or SG The industry however, likes to use another term called "API Gravity', which goes up with increase in the lighter hydrocarbon constituents

The relation is "API = 141 5 / SG (at 60/60° F) - 131 5

Thus, a crude oil with a SG of 0 833 will be referred to as 38 37° API, and that with a SG of 0 88 as 29 3° API

Since 1 Imp bl of water weighs 400 lbs, 1 Impblof any crude will weigh 400 xSG/2204 6225 = 0 181437 xSG tonnes

Likewise, each US bl will equal 0 15863 x SG tonnes or 6 304/SG will equal the number of US bis per tonne A 38 37° crude will thus weigh 0 151137 tonnes per Imp bl and 0 1321387 tonnes per US bl under Standard conditions

Gas

Gas is measured in terms of Standard eft and Normal cu metres, but the Standards can differ from user to user In UK and USA, the standard eft is referred to 60° F and 30 inches (762 mm) of mercury under wet conditions, but the normal cubic metre (i e Nm^1) is referred in terms of 0° C and 760 mm of mercury under dry conditions As a result, 1 Nm^3 of gas equals 37 879 Std eft, instead of the conventional (35 31467 eft), if both the standards were to be identical There are, however, operators who do not always observe these distinctions and conversion of their figures from m^3 to eft can be in error by as much as 7 26%

Gas densities are normally described in terms of its specific gravity in relation to air, each eft of which (at 60° F and 1 atmosphere pressure) weighs only 0 7644 lbs The lightest hydrocarbon gas is methane (CH_4) It has a SG in relation to air of 0 554, l e 1 Std eft of Methane weighs 0 7644x0 554 = 0 4235 lbs The next heavier hydrocarbon gas is ethane *(C_3U_6)* It has a SG of 1 038 and weighs 0 79345 lbs/Std eft Propane (C_3H_8) which comes next has a SG of 1 522 and weighs 1 16342 lbs/Std eft Natural hydrocarbon gases are primarily methane with varying amounts of the higher hydrocarbons and would usually have a *SG* range of around 0 56 to 0 8 depending upon its origin and the collection - distribution system, l e , unless some CO, and nitrogen are also present

Hydrocarbon gases do not totally follow the ideal Gas Law in their compression or expansion It is necessary to add a collection factor called "z' or the "Gas Compressibility Factor' to allow for this deviation This converts the gas equation to PV/T = Z nR where n and R are constants Depending upon the gas density and its pressure-temperature regime, "Z" can usually vary from 0 5 to a little over 1 ^

Oil Equivalence of Gas

This is normally done in terms of calorific value 1 Std eft of dry methane has a *gross* calorific value of 1012 BTU The net calorific value, after allowing for the heat absorbed by the products (primarily H.,0) is about 912 BTU The field's gas, normally has some higher hydrocarbons as well, which gives it a net calorific value of around 1000 BTU This would give it an oil equivalence of around 1045 Nm^3 per tonne There are ofcourse some variations and figures of 1000 to 1100 NmVtonne have often been used

Gas/Oil Ratio or GOR

This is an important ratio related to many oil well or oil field s production behaviour It comprises partly of the ratio between the oil and the gas that is coming out from its solution, and partly of the free (and released) gas within the reservoir that is also flowing directly and contnbuting to the gas production It can be either as Vol/Vol or Std eft /bl (Imp or US) or NmVbl

GOR vanes over the life time of oil wells and oil fields To the extent, it can be kept under control, the free gas and the gas freed/released within the reservoir helps to displace more oil into the well and helps improve recovery of the oil The ability to forecast the future pattern of GOR variation also helps in better planning and utilisation of the produced gas