# Petroleum Engineering

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First Edition, 2012

ISBN 978-81-323-3093-6



*Published by:*
**Research World**
4735/22 Prakashdeep Bldg,
Ansari Road, Darya Ganj,
Delhi - 110002
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# Introduction

**Petroleum engineering** is an engineering discipline concerned with the activities related to the production of hydrocarbons, which can be either crude oil or natural gas. Subsurface activities are deemed to fall within the *upstream* sector of the oil and gas industry, which are the activities of finding and producing hydrocarbons. (Refining and distribution to a market are referred to as the *downstream* sector.) Exploration, by earth scientists, and petroleum engineering are the oil and gas industry's two main subsurface disciplines, which focus on maximizing economic recovery of hydrocarbons from subsurface reservoirs. Petroleum geology and geophysics focus on provision of a static description of the hydrocarbon reservoir rock, while petroleum engineering focuses on estimation of the recoverable volume of this resource using a detailed understanding of the physical behavior of oil, water and gas within porous rock at very high pressure.

The combined efforts of geologists and petroleum engineers throughout the life of a hydrocarbon accumulation determine the way in which a reservoir is developed and depleted, and usually they have the highest impact on field economics. Petroleum engineering requires a good knowledge of many other related disciplines, such as geophysics, petroleum geology, formation evaluation (well logging), drilling, economics, reservoir simulation, well engineering, artificial lift systems, and oil & gas facilities engineering.

## *Overview*

Petroleum engineering has become a technical profession that involves extracting oil in increasingly difficult situations as much of the "low hanging fruit" of the world's oil fields has been found and depleted. Improvements in computer modeling, materials and the application of statistics, probability analysis, and new technologies like horizontal drilling and enhanced oil recovery, have drastically improved the toolbox of the petroleum engineer in recent decades.

Deep-water, arctic and desert conditions are commonly contended with. High Temperature and High Pressure (HTHP) environments have become increasingly commonplace in operations and require the petroleum engineer to be savy in topics as wide ranging as thermo-hydraulics, geomechanics, and intelligent systems.

The Society of Petroleum Engineers (SPE) is the largest professional society for petroleum engineers and publishes much information concerning the industry. Petroleum engineering education is available at 17 universities in the United States and many more throughout the world - primarily in oil producing regions - and some oil companies have considerable in-house petroleum engineering training classes.

Petroleum engineering has historically been one of the highest paid engineering disciplines; this is offset by a tendency for mass layoffs when oil prices decline. In a June 4th, 2007 article, Forbes.com reported that petroleum engineering was the 24th best paying job in the United States. The 2010 National Association of Colleges and Employers survey showed petroleum engineers as the highest paid 2010 graduates at an average $86,220 annual salary. For individuals with experience, salaries can go from $150,000 to $200,000 annually.

Some of the famous petroleum engineers include Douglas Patrick Harrison and Muhammad Salman, having worked together and made over $30 billion by discovering alternative energy from Petroleum. In Latin America, the study of this engineering has been important for producers countries as Venezuela and Colombia, recognized universities due their faculty for the studies in this field in Colombia are UIS (Universidad Industrial de Santander) The National university, and FUA (Fundación Universidad de América).

## *Types*

Petroleum engineers divide themselves into several types:

- Reservoir engineers work to optimize production of oil and gas via proper well placement, production levels, and enhanced oil recovery techniques.
- Drilling engineers manage the technical aspects of drilling exploratory, production and injection wells.
- Production engineers, including subsurface engineers, manage the interface between the reservoir and the well, including perforations, sand control, downhole flow control, and downhole monitoring equipment; evaluate artificial lift methods; and also select surface equipment that separates the produced fluids (oil, natural gas, and water).

## Chapter 1

# Integrated Operations

In the Petroleum industry, **Integrated operations** (IO) refers to new work processes and ways of doing oil and gas exploration and production, which has been facilitated by new information and communication technology. Multi-discipline collaboration in plant operation is one example. IO has in a sense also taken the form of a movement for renewal of the oil and gas industry. In short IO is collaboration with production in focus.

### *Contents of the term*

The most striking part of IO has been the use of always-on videoconference rooms between offshore platforms and land-based offices. This includes broadband connections for sharing of data and video-surveillance of the platform. This has made it possible to move some personnel onshore and use the existing human resources more efficiently. Instead of having e.g. an expert in geology on duty at every platform, the expert may be stationed on land and be available for consultation for several offshore platforms. It's also possible for a team at an office in a different time zone to be consulting the night-shift of the platform, so that no land-based workers need work at night.

Splitting the team between land and sea demands new work processes, which together with ICT is the two main focus points for IO. Tools like videoconferencing and 3D-visualization also creates an opportunity for new, more cross-discipline cooperations. For instance, a shared 3D-visualization may be tailored to each member of the group, so that the geologist gets a visualization of the geological structures while the drilling engineer focuses on visualizing the well. Here, real-time measurements from the well are important but the downhole bandwidth has previously been very restricted. Improvements in bandwidth, better measurement devices, better aggregation and visualization of this information and improved models that simulate the rock formations and wellbore currently all feed on each other. An important task where all these improvements play together is real-time production optimization.

In the process industry in general, the term is used to describe the increased cooperation, independent of location, between operators, maintenance personnel, electricians, production management as well as business management and suppliers to provide a more streamlined plant operation.

By deploying IO, the petroleum industry draws on lessons from the process industry. This can be seen in a larger focus on the whole production chain and management ideas imported from the production and process industry. A prominent idea in this regard is real-time optimization of the whole value chain, from long term management of the oil reservoir, through capacity allocations in pipe networks and calculations of the net present value of the produced oil.

Some companies also emphasize the integration and coordination of outside suppliers and collaborators in offshore-operations. For instance, it is pointed out that the oil and gas industry is lagging behind other industries in terms of Operational intelligence.

Ideas and theories that IO management and work processes build on will be familiar from operations research, knowledge management and continual improvement as well as information systems and business transformation. This is perhaps most evident in the repeated referral to "people, process and technology" in IO discussions. As bullet-points this mirror many of the aforementioned fields.

## *Incentives*

Common to most companies is that IO leads to cost savings as fewer people are stationed offshore and an increased efficiency. Lower costs, more efficient reservoir management and fewer mistakes during well drilling will in turn raise profits and make more oil fields economically viable. IO comes at a time when the oil industry is faced with more "brown fields", also referred to as "tail production", where the cost of extracting the oil will be higher than its market value, unless major improvements in technology and work processes are made. It has been estimated that deployment of IO could produce 300 billion NOK of added value to the Norwegian continental shelf alone. On a longer time-scale, working onshore control and monitoring of the oil production may become a necessity as new fields at deeper waters are based purely on unmanned sub-sea facilities.

Moving jobs onshore has also been touted as a way to keep and make better use of an aging workforce, which is regarded as a challenge by western oil and gas companies. As the average age of the industry workforce is increasing with many nearing retirement, IO is being leveraged for knowledge sharing and training of younger workforce. More comfortable onshore jobs together with "high-tech" tools has also been fronted as a way to recruit young workers into an industry that is seen as "unsexy", "lowtech" and difficult to combine with a normal family life.

## *Critique*

The security aspect of reducing the offshore workforce has been raised. Will on-site experience be lost and can familiarity with the platform and its processes be attained from an onshore office? The new working environment in any case demands changes to HSE routines. Some of the challenges also include clear role and responsibility definitions and clarifications between the onshore & offshore personnel. Who in a given situation has the authority to take decisions, the onsite or the offshore staff. The increased integration of the offshore facilities with the onshore office environment and outside collaborators also expose work-critical ICT-infrastructure to the internet and the hazards of everyday ICT. As for the efficiency aspect, some criticize the onshore-offshore collaboration for creating a more bureaucratic working environment.

### *Naming conventions*

Both the exact terms and the content used to describe IO vary between companies. The oil company Shell has traditionally branded the term **Smart Fields**, which was an extension of **Smart Wells** that only referred to remote-controlled well-valves. BP uses **Field of the future**, Chevron has **i-field** and Schlumberger terms it **Digital Energy**. The latter term, understood as referring to oil and gas, is adopted in the title of the digital energy journal. This term could have several meanings, as GE Digital Energy for instance, do not appear to use it in the IO sense.

Other terms include **e-Field**, **i-Field**, **Digital Oilfield**, **Intelligent Oilfield**, **Field of the future** and **Intelligent Energy**. Integrated operations has been the preferred term by Statoil, the Norwegian Oil Industry Association (OLF), a professional body and employer's association for oil and supplier companies and vendors such as ABB. Intelligent Energy is the dominant term in publications revolving around the biannual SPE Intelligent Energy conference, which has been one of the major conferences for the IO movement, along with the annual IO Science and Practice conference which obviously supports the IO term.

# Chapter 2

# Slickline

**Slickline** refers to a tool used in the oil and gas industry, but also describes that niche of the industry that involves using a slickline truck or doing a slickline job.

Slickline looks like a long, smooth, unbraided wire, often shiny, silver/chrome in appearance. It comes in varying lengths, according to the depth of wells in the area it is used (it can be ordered to specification) up to 35,000 feet in length. It is used to lower and raise downhole tools used in oil and gas well maintenance to the appropriate depth of the drilled well. In use and appearance it is connected by the drum it is spooled off of in the back of the slickline truck to the wireline sheave (a round wheel grooved and sized to accept a specified line and positioned to redirect the line to another sheave that will allow it to enter the device that allows the slickline to enter the wellbore while keeping the pressure contained and wiping the messy and sometimes hostile downhole fluids from the line. Slickline is used to lower downhole tools into an oil or gas well to perform a specified maintenance job downhole. Downhole refers to the area in the pipe below surface, the pipe being either the casing cemented in the hole by the drilling rig (which keeps the drilled hole from caving in and pressure from the various oil or gas zones downhole from feeding into one another) or the tubing, a smaller diameter pipe hung inside the casing.

## *Uses*

Slickline is more commonly used in production tubing. The wireline operator monitors at surface the slickline tension via a weight indicator gauge and the depth via a depth counter 'zeroed' from surface, lowers the downhole tool to the proper depth, completes the job by manipulating the downhole tool mechanically, checks to make sure it worked if possible, and pulls the tool back out by winding the slickline back onto the drum it was spooled from. The slickline drum is controlled by a hydraulic pump, which in turn is controlled by the 'slickline operator'.

Slickline comes in different sizes and grades. The larger the size, and higher the grade, generally means the higher line tension can be pulled before the line snaps at the weakest spot and causes a costly 'fishing' job. Due to downhole tools getting stuck because of malfunctions or 'downhole conditions' including sand, scale, salt, asphaltenes, and other well byproducts settling or loosening off the pipe walls because of agitation either by the downhole tools or a change in downhole inflow, sometimes it is necessary to pull hard on the tools to bring them back uphole to surface. If the tools are stuck, and the operator pulls too hard, the line will snap or pull apart at the weakest spot, which is generally closer to surface as the further uphole the weak point in the line is, the more weight it has to support (the weight of the line).

Weak spots in the line can be caused by making the circle around the counter wheel, making a bend around a sheave, a kink in a line from normal use (when rigging up the equipment extra line must be pulled out from the truck to give enough slack when the pressure control lubricator is picked up - this leaves line coiled on the often rutted ground, and sometimes it snags and kinks the line).

When the slickline parts, this can create an expensive 'fishing' job. It is called fishing because you often have to try different 'fishing' tools until you get a 'bite', then you have to work the original tools downhole free, or cut off the slickline where they join the tools downhole so that you can pull the broken slickline back to surface and out of the way, in order to fish the stuck toolstring. Because of the downtime involved in 'fishing', meaning not being able to flow the oil/gas well, the client is losing money by lack of production and also the cost of the slickline unit to fish, and the cost of what is left in the hole if it is not fished out (in the oil/gas industry, if the cause of the fishing job was not the fault of the slickline company, the oil/gas company is usually responsible to pay for it, and it can be very expensive).

Slickline was originally called measuring line, because the line was flat like a tape measure, and marked with depth increments so the operators would know how deep in the hole they were. This probably changed because the flat measuring line wasn't as strong as the modern slickline, and separate depth counters were developed. It is advantageous to keep the diameter of the wire as small as possible for the following reasons:

- It reduces the load of its own weight.
- It can be run over smaller diameter sheaves, and wound on smaller diameter spools or reels without overstressing by bending (where the wire bends makes it weaker. Where it makes a complete circle, such as a counter wheel, makes it weaker yet).
- It keeps the reel drum size to a minimum (which reduces the area needed in the back of the slickline unit to house the drum and hydraulic pump, reducing weight and leaving more room for the other specialized equipment needed for slickline operations).
- It provides a small cross-section area for operation under pressure.

The disadvantage of a smaller diameter slicklne is the lower strength. Depth and the nature of the job (a tool that must be pulled hard or might be stuck) will affect what slickline truck (different trucks specialize in different sizes of line) used.

The sizes of solid wireline in most common uses are: 0.092", 0.108", 0.125", 0.140", 0.150", and 0.160" in diameter, and are obtainable from the wire-drawing mills in one-piece standard lengths of 18,000, 20,000, 25,000 and 30,000 foot lengths. Other diameters and lengths are usually available on request from the suppliers, with the largest size currently available at 0.188".

## *Mechanical and Hydraulic Jars*

Slickline tools operate with a mechanical action, controlled from surface in the wireline trucks operators compartment. Typically, this mechanical action is accomplished by the operation of jars. There are generally two types of jars; mechanical and hydraulic.

Mechanical jars look like a long, tubular piece of machined metal that slides longer or shorter approximately 75% to 90% of its total length. They give the effect of hammering on the downhole tools. The weight or hit of the 'hammer' depends on how much sinker bar is added above the jars. Generally, a slickline operator controls the downhole tools with taps and hits from the sinker bar via the mechanical jars, controlled at surface by lowering or raising the toolstring and monitoring weight, depth, and pressure. Mechanical jars for slickline can hit up or down the hole, making them a versatile form of jarring.

Hydraulic jars for slickline are generally meant to jar up only, because not enough sinker bar is able to feasibley lubricated in to jar down on the downhole tools. Hydraulic jars work by the operator pulling up on the line, which puts an upward force on the top of the hydraulic jars. The bottom of the hydraulic jars is usually attached by threaded connection to the mechanical jars, which are attached to the downhole tools. Depending on how hard the operator pulls on the hydraulic jars will affect how fast they hit, and how hard they hit. When the top is pulled on, the inner mandrel begins to slide upwards. It has a restriction in it that hydraulic fluid has to bypass as it is pulled upwards, until it reaches an area of no restriction, allowing it to slide rapidly. The reason for the initial tighter restriction is to allow the operator to pull his line to the desired hitting range.

Generally once he hits that range on his weight indicator, he waits while the jars open to the less restricted point, whereupon the sinker bar travels upwards rapidly, providing an upwards hit on the downhole tools. The jars can then be 'reset' by lowering the line until the weight of the sinker bar closes, or pushes the inner mandrel of the hydraulic jars back to the starting position. Because the hydraulic jars are designed to provide a wait time to allow the operator to get up to the desired line tension, they can provide a very effective upwards hit.

Mechanical jar and hydraulic jar hitting power is affected by the length of the jars (the longer the length, they faster they can travel before they stop), the mass of the weight above them (the more the mass, the harder they will hit), and the tension of the line pulling on them.

Some completion components may be deployed and retrieved on slickline such as wireline retrievable safety valves, battery powered downhole gauges, perforating, placing explosively set bridge plugs, and placing or retrieving gas lift valves. Slickline can also be used for fishing, the process of trying to retrieve other equipment and wire, which has been dropped down the hole.

## *Applications*

The most common applications for slickline are:

- Tagging T.D. (which is the furthest depth possible down the wellbore)

- Gauge Ring runs (which is running a special sized downhole tool called a gauge ring, which comes in various pre-machined diameters, designed to ensure the pipe is clear to a certain point)

- Broach tubing / Plunger Installations (a tubing broach looks like an aggressive, tubular file, available in different diameters, used for removing burrs and crimps in the inside of tubing and casing in oil and gas wells)

- Bailing sand and debris (removing formation sand/rock and other such debris left over from the drilling and completion of the well, using a specialized tool called a bailer. This tool uses either a Chinese water pump type stroke action or a hydrostatic vacumn action to suction up the downhole debris, allowing it to be conveyed back to surface via the wireline)

- Shifting sleeves (formations downhole can be isolated behind sliding metal 'windows' called sliding sleeves. They are shifted open or closed by means of a specialized shifting tool locating the sleeve and it being jarred up or down, providing access or closing off that formation or section of casing)

- Setting / Pulling plugs and chokes (specialized downhole tools which either lock into pre-machined restrictions in the tubing, or which lock into the tubing itself, sealing pressure from below or above the plug)

- Setting / Pulling gas lift valves

- Running tailpipes (tubing extensions where the tubing is not landed close enough to the formation perforations in the casing)

- Bottom hole pressure and temperature surveys (specialized electronic and mechanical tools designed to measure the pressure and temperature at predetermined depths in the wellbore. This data can be used to determine reservoir life)

- Spinner Surveys (to determine which formation perforations have the best inflow / which perforations make the most water / liquids)

- Kinley perforator, sandline cutter, and caliper
- Running production logging tools
- Fishing operations (fishing usually refers to attempting to retrieve lost tools or wire, or other debris that was not intended to restrict the flow / disrupt the well operations. Fishing can be difficult, due the fish being downhole, and other affecting conditions such as high pressure, the fish being jammed in the tubing / casing)
- Paraffin cutting (making a hole through and removing a wax buildup, which is a byproduct of oil cooling too much to reach surface)
- Chipping ice / salt (restrictions and plugs which can be formed as by products of a flowing well)
- Lubricating long assemblies in and out of the hole (lubricating is done via a larger than tool overall diameter pipe, joined at surface on top of the wellhead, which houses the valve that shuts the pressure in downhole. The lubricator should be long enough to be able to swallow the toolstring and downhole tools that are to be run or pulled)

## *Braided line*

Braided line is generally used when the strength of slickline is insufficient for the task. Most commonly, this is for heavy fishing such as retrieving broken drill pipe. The most common use for braided line is fishing electric line tools.

## *Slickline Tools*

### Jar

This type of tool can extended and closed rapidly to induce a mechanical shock to the tool string. This shock can induce certain components such as plugs to lock into place and then unlock for retrieving. Jars are commonly used to shear small brass or steel pins that are put in place to function certain down-hole tools at a certain moment. The operator can use the jars to shear the pins at a predetermined depth. Spang jars are manually operated by the wireline operator who either lifts or lowers wire rapidly, requiring a great deal of expertise. Power jars use springs or built-in hydraulics to give an upward jarring motion where greater force is required.

### Stem

Stem essentially just serves to add weight to the toolstring. The weight may be necessary to overcome the pressure of the well. Some variations of stem, called roller stem, may have wheels built into the tool to allow the tool string to glide more easily down moderately deviated wells. Stem give the hammering action to the tool string which in turn allows the jars to transmit the force given by the movement of the stems bars. Depending on well conditions extra small OD stems are use or extra large. The range can be from .75" to 3.50" OD and the stems normally come in 2 ft, 3 ft or 5 ft lengths. The connection to the rope socket or other tools can be a threaded connection or a QLS system (quick connect).

## Pulling tools

These are tools designed for fishing other wireline components which have been dropped down hole. All wireline tools are designed with 'fishing necks' on their top side, intended to be easily grabbed by pulling tools. Pulling tools are also used for retrieving seated components such as plugs.

## Gauge Cutter (Gauge Ring)

A gauge cutter is a tool with a round, open-ended bottom which is milled to an accurate size. Large openings above the bottom of the tool allow for fluid bypass while running in the hole. Most often a gauge ring will be the first tool ran on a slickline operation. A gauge ring that is just undersized will allow the operator to ensure clear tubing down to the deepest projected working depth; for example 2 7/8" tubing containing 2.313" profiles would call for a gauge ring between 2.25" - 2.30". A gauge ring can also be used to remove light paraffin that may have built up in the tubing. Often a variety of different sized gauges and/or scratchers will be run to remove parafin little by little.Gauge cutter can be used for drift runs also.

## Lead impression block

If an obstruction is found downhole, a lead impression block can be run to help determine its nature. The LIB has a malleable lead base in which the obstruction can leave an impression when they meet. The LIB is called Wireline Camera because of its function to mark any object downhole. They are also sometimes called "confusion" blocks because they only give a two-dimensional view of the down-hole object, making it hard for an inexperienced person to determine what three-dimensional object is in the hole

## DOWNHOLE BAILER

Bailers are downhole tools that are generally long and tubular shaped, and are used for both getting samples of downhole solids (sand, scale, asphaltines, rust, rubber and debris from well servicing operations) and for 'bailing' the unwanted downhole solids from the well. Bailers are attached either via threaded connection or releasable downhole tool to the wireline toolstring, and are manipulated from surface by the wireline operator. Bailers usually have an interchangeable bottom (the shoe) which also houses a check to keep the solids from falling or washing out of the bottom.

## SAMPLE BAILER

A sample bailer is generally around a meter long, and has a hollow tube (the barrel) usually around 40 mm in diameter, with a 'ball check' on the bottom and an opening at the top. This tool is beat downwards into the as yet unknown obstruction using the mechanical jars and weight above of the wireline toolstring. Generally, after a predetermined amount of 'hits', hopefully allowing a usable sample of solids to fill the barrel. When the tool is pulled upwards, the solids usually (hopefully) settle the ball check onto its 'seat', which will keep the solids in the barrel during the return trip to surface, where the solids can be inspected to determine what the downhole obstruction was. This procedure can be 'hit and miss', the success depending on how readily the solid was accepted into the barrel, and if the ball check was properly seated on the return trip to surface. If the ball check is not seated (sometimes a large, hard piece of solid will sit in between the ball and seat) downhole fluids tend to 'wash' the sample out of the bottom of the sample bailer, leaving the inspectors at surface wondering if the tool actually collected a sample. Persistence is generally a good rule of thumb with this tool.

## STROKE BAILER

A stroke bailer functions like a 'Chinese water pump', and is used to collect unwanted solids from the wellbore. A stroke bailer is long and tubular looking, with a smaller rod that extends from the top, a hole in the bottom, and is generally around 7 meters long, but the length depends on how much barrel section is added to the bailer. The barrel 'free floats' on the stroke rod, which is attached to the wireline toolstring. The tool is usually 'spudded' into the downhole solid, then the wireline toolstring is pulled upwards, which in turn pulls the stroke up through the barrel. Ideally, this draws the downhole solid in through the bottom 'shoe' of the tool, past the check and into the barrel for collection. The tool is usually stroked either a predetermined number of times, or until it appears the tool is not stroking, which can mean either it is full, or stuck.

## HYDROSTATIC BAILER

A hydrostatic bailer functions like a 'vacumn', and is used to suck up unwanted solids from the wellbore. A hydrostatic bailer is generally around 2.5 meters long and is tubular looking, with two 10 mm holes on opposing sides at the top of the tool, and a hole in the bottom. A hydrostatic bailer uses a pinned plug with o-ring seals at the bottom, and a plug at the top to maintain the surface pressure that it was assembled at (nominally around 100 kPa) all the way to the bottom of the well, whereupon it is spudded into the downhole solids, which ideally pushes the shoe into the bottom plug, which shears the pin on the bottom plug. An oil or gas well's pressure downhole is always more than atmospheric pressure at surface, due to the formation pressure, and a combination of depth and hydrostatic weight of wellbore fluids. Sometimes fluid will be added to the wellbore to assist in bailing by bringing up the pressure, and also lubricating the downhole solid. Because the pressure inside the bailer is much less than the downhole wellbore pressure, any solids that are loose enough are 'sucked up' by the vacumn formed when the bottom plug is sheared and travels upwards through the barrel, followed by the solids. At the same time, due to the changed from negative pressure to positive pressure, the top plug pops out (and is caught by the top part of the tool), and excess flow is directed out through the 10 mm ports on the sides of the top of the tool. These ports allow the barrel to fill more readily. Then the bailer is returned to surface where it is taken apart, the solids are emptied, and it is cleaned and serviced with new o-ring seals. Care must be taken when disassembling at surface as the tool is potentially charged with the downhole pressure (possibly many tens of thousands of kpa) and may 'blow apart' when being unthreaded if not bled off first.

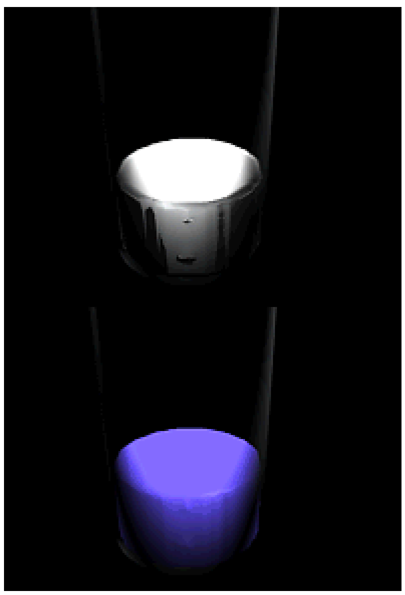
## Running Tools

These tools are primarily used to 'set' plugs into locking profiles (nipples) located in the tubing; however, the term 'running tool' refers to a downhole tool attached to the wireline toolstring that is used to 'run' another tool that is meant to be left downhole when the toolstring returns to surface. In general, a running tool is attached to a downhole 'locking tool' that locates and locks into the selected downhole profile (nipple). The 'locking tool', or 'lock' for short, can be attached via threaded connection to the top of a variety of different tools, including but not limited to, downhole chokes (flow rate restrictors sized according to a pre-determined calculation), one-way check valves (TKX style plugs), instrument hangers, and most commonly, tubing plugs. The lock is fitted onto the running tool and attached using shear pins made of brass or steel. When the target profile is reached the lock can be set by seating the lock into the profile using mechanical jars (spangs) until the locking keys have locked the lock into the profile, whereupon the operator usually 'pull tests' the lock to give an indication it is properly 'set', then shears off the shear pins with his mechanical or hydraulic jars to allow the 'toolstring' to return to surface. There are many different types of running tools, some are mechanically complex and able to be made 'selective' in order to pass through profiles in order to reach one of the same size but a different depth; some are relatively simple, such as an 'F' collarstop running tool, which is essentially a metal rod which fits inside the collarstop downhole tool which is pinned in place.

# Chapter 3

# Viscosity

***Viscosity***



Clear liquid above has lower viscosity than the substance below

| | |
|---|---|
| **SI symbol:** | μ, η |
| **SI unit:** | Pa·s = kg/(s·m) |
| **Derivations from other quantities:** | μ = G·t |

**Viscosity** is a measure of the resistance of a fluid which is being deformed by either shear stress or tensile stress. In everyday terms (and for fluids only), viscosity is "thickness" or "internal friction". Thus, water is "thin", having a lower viscosity, while honey is "thick", having a higher viscosity. Put simply, the less viscous the fluid is, the greater its ease of movement (fluidity).

Viscosity describes a fluid's internal resistance to flow and may be thought of as a measure of fluid friction. For example, high-viscosity felsic magma will create a tall, steep stratovolcano, because it cannot flow far before it cools, while low-viscosity mafic lava will create a wide, shallow-sloped shield volcano. All real fluids (except superfluids) have some resistance to stress and therefore are **viscous**, but a fluid which has no resistance to shear stress is known as an **ideal fluid** or **inviscid fluid**.

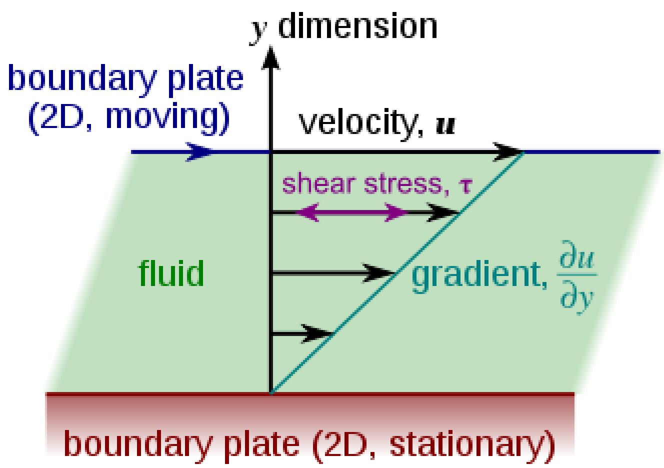
The study of flowing matter is known as rheology, which includes viscosity and related concepts.

## *Etymology*

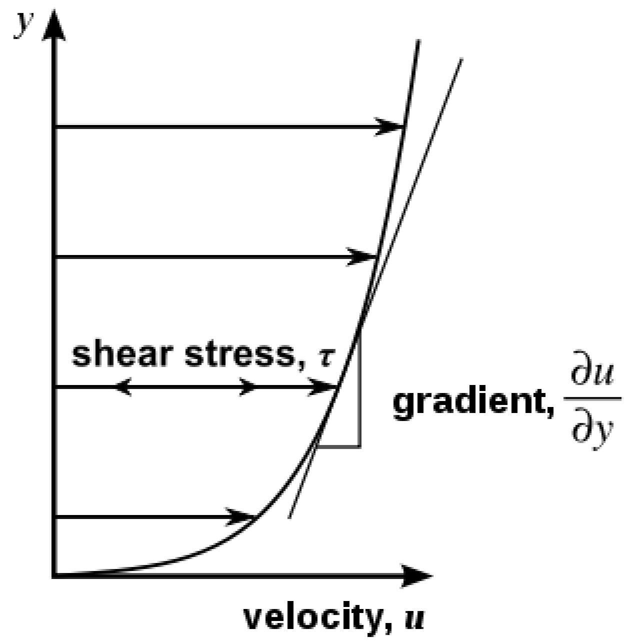
The word "viscosity" derives from the Latin word "viscum alba" for mistletoe. A viscous glue called birdlime was made from mistletoe berries and used for lime-twigs to catch birds.

## *Properties and behavior*

### Overview




Laminar shear of fluid between two plates. Friction between the fluid and the moving boundaries causes the fluid to shear. The force required for this action is a measure of the fluid's viscosity. This type of flow is known as a Couette flow.




Laminar shear, the non-constant gradient, is a result of the geometry the fluid is flowing through (e.g. a pipe).

In general, in any flow, layers move at different velocities and the fluid's viscosity arises from the shear stress between the layers that ultimately opposes any applied force.

The relationship between the shear stress and the velocity gradient can be obtained by considering two plates closely spaced at a distance *y*, and separated by a homogeneous substance. Assuming that the plates are very large, with a large area *A*, such that edge effects may be ignored, and that the lower plate is fixed, let a force *F* be applied to the upper plate. If this force causes the substance between the plates to undergo shear flow with a velocity gradient *u* (as opposed to just shearing elastically until the shear stress in the substance balances the applied force), the substance is called a fluid.

The applied force is proportional to the area and velocity gradient in the fluid and inversely proportional to the distance between the plates. Combining these three relations results in the equation:

$$F = \mu A \frac{u}{y},$$

where $\mu$ is the proportionality factor called *viscosity*.

This equation can be expressed in terms of shear stress $\tau = \frac{F}{A}$. Thus as expressed in differential form by Isaac Newton for straight, parallel and uniform flow, the shear stress between layers is proportional to the velocity gradient in the direction perpendicular to the layers:

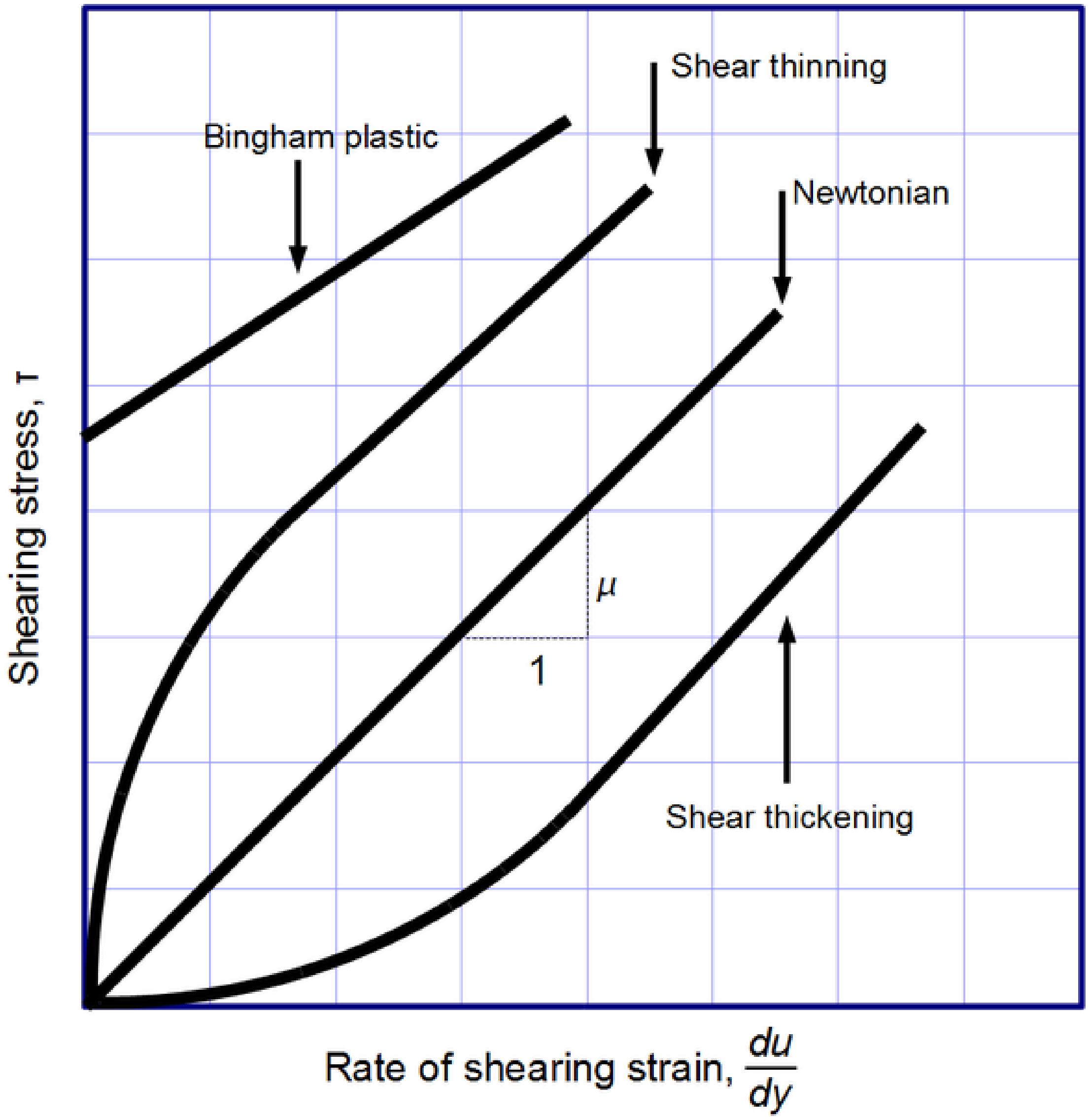
$$\tau = \mu \frac{\partial u}{\partial y}$$

Hence, through this method, the relation between the shear stress and the velocity gradient can be obtained.

Note that the *rate of shear deformation* is $\frac{u}{y}$ which can be also written as a *shear velocity*, $\frac{du}{dy}$.

James Clerk Maxwell called viscosity *fugitive elasticity* because of the analogy that elastic deformation opposes shear stress in solids, while in viscous fluids, shear stress is opposed by *rate* of deformation.

## Types of viscosity




Viscosity, the slope of each line, varies among materials

Newton's law of viscosity, given above, is a constitutive equation (like Hooke's law, Fick's law, Ohm's law). It is not a fundamental law of nature but an approximation that holds in some materials and fails in others. Non-Newtonian fluids exhibit a more complicated relationship between shear stress and velocity gradient than simple linearity. Thus there exist a number of forms of viscosity:

- **Newtonian**: fluids, such as water and most gases which have a constant viscosity.
- **Shear thickening**: viscosity *increases* with the rate of shear.
- **Shear thinning**: viscosity *decreases* with the rate of shear. Shear thinning liquids are very commonly, but misleadingly, described as thixotropic.
- **Thixotropic**: materials which become *less* viscous over time when shaken, agitated, or otherwise stressed.

- **Rheopectic**: materials which become *more* viscous over time when shaken, agitated, or otherwise stressed.
- A **Bingham plastic** is a material that behaves as a solid at low stresses but flows as a viscous fluid at high stresses.
- A **magnetorheological fluid** is a type of "smart fluid" which, when subjected to a magnetic field, greatly increases its apparent viscosity, to the point of becoming a viscoelastic solid.

## *Viscosity coefficients*

Viscosity coefficients can be defined in two ways:

- **Dynamic viscosity**, also **absolute viscosity**, the more usual one (typical units Pa·s, Poise, P);
- **Kinematic viscosity** is the *dynamic viscosity* divided by the density (typical units $m^2/s$, Stokes, St).

Viscosity is a tensorial quantity that can be decomposed in different ways into two independent components. The most usual decomposition yields the following viscosity coefficients:

- **Shear viscosity**, the most important one, often referred to as simply **viscosity**, describing the reaction to applied shear stress; simply put, it is the ratio between the pressure exerted on the surface of a fluid, in the lateral or horizontal direction, to the change in velocity of the fluid as you move down in the fluid (this is what is referred to as a velocity gradient).
- **Volume viscosity** (also called **bulk viscosity** or **second viscosity**) becomes important only for such effects where fluid compressibility is essential. Examples would include shock waves and sound propagation. It appears in the Stokes' law (sound attenuation) that describes propagation of sound in Newtonian liquid.

Alternatively,

- **Extensional viscosity**, a linear combination of shear and bulk viscosity, describes the reaction to elongation, widely used for characterizing polymers. For example, at room temperature, water has a dynamic shear viscosity of about $1.0\times10^{-3}$ Pa·s and motor oil of about $250\times10^{-3}$ Pa·s.

## *Viscosity measurement*

Viscosity is measured with various types of viscometers and rheometers. A rheometer is used for those fluids which cannot be defined by a single value of viscosity and therefore require more parameters to be set and measured than is the case for a viscometer. Close temperature control of the fluid is essential to accurate measurements, particularly in materials like lubricants, whose viscosity can double with a change of only 5 °C.

For some fluids, viscosity is a constant over a wide range of shear rates (Newtonian fluids). The fluids without a constant viscosity (non-Newtonian fluids) cannot be described by a single number. Non-Newtonian fluids exhibit a variety of different correlations between shear stress and shear rate.

One of the most common instruments for measuring kinematic viscosity is the glass capillary viscometer.

In paint industries, viscosity is commonly measured with a Zahn cup, in which the efflux time is determined and given to customers. The efflux time can also be converted to kinematic viscosities (centistokes, cSt) through the conversion equations.

Also used in paint, a Stormer viscometer uses load-based rotation in order to determine viscosity. The viscosity is reported in Krebs units (KU), which are unique to Stormer viscometers.

A Ford viscosity cup measures the rate of flow of a liquid. This, under ideal conditions, is proportional to the kinematic viscosity.

Vibrating viscometers can also be used to measure viscosity. These models such as the *Dynatrol* use vibration rather than rotation to measure viscosity.

*Extensional viscosity* can be measured with various rheometers that apply extensional stress.

Volume viscosity can be measured with an acoustic rheometer.

Apparent viscosity is a calculation derived from tests performed on drilling fluid used in oil or gas well development. These calculations and tests help engineers develop and maintain the properties of the drilling fluid to the specifications required.

## *Units*

### Dynamic viscosity

The usual symbol for dynamic viscosity used by mechanical and chemical engineers — as well as fluid dynamicists — is the Greek letter mu ($\mu$). The symbol $\eta$ is also used by chemists, physicists, and the IUPAC.

The SI physical unit of dynamic viscosity is the pascal-second (Pa·s), (equivalent to $N{\cdot}s/m^2$, or kg/(m·s)). If a fluid with a viscosity of one Pa·s is placed between two plates, and one plate is pushed sideways with a shear stress of one pascal, it moves a distance equal to the thickness of the layer between the plates in one second.

The cgs physical unit for dynamic viscosity is the *poise* (P), named after Jean Louis Marie Poiseuille. It is more commonly expressed, particularly in ASTM standards, as *centipoise* (cP). Water at 20 °C has a viscosity of 1.0020 cP or 0.001002 kg/(m·s).

$1\ P = 1\ g \cdot cm^{-1} \cdot s^{-1}$.
$1\ Pa \cdot s = 1\ kg \cdot m^{-1} \cdot s^{-1} = 10\ P$.

The relation to the SI unit is

$1\ P = 0.1\ Pa \cdot s$,
$1\ cP = 1\ mPa \cdot s = 0.001\ Pa \cdot s$.

## Kinematic viscosity

In many situations, we are concerned with the ratio of the inertial force to the viscous force (i.e. the Reynolds number, $Re = VD / \nu$) , the former characterized by the fluid density ρ. This ratio is characterized by the *kinematic viscosity* (Greek letter nu, $\nu$), defined as follows:

$$\nu = \frac{\mu}{\rho}$$

The SI unit of $\nu$ is $m^2/s$. The SI unit of $\rho$ is $kg/m^3$.

The cgs physical unit for kinematic viscosity is the *stokes* (St), named after George Gabriel Stokes. It is sometimes expressed in terms of *centiStokes* (cSt). In U.S. usage, *stoke* is sometimes used as the singular form.

$1\ St = 1\ cm^2 \cdot s^{-1} = 10^{-4}\ m^2 \cdot s^{-1}$.
$1\ cSt = 1\ mm^2 \cdot s^{-1} = 10^{-6} m^2 \cdot s^{-1}$.

Water at 20 °C has a kinematic viscosity of about 1 cSt.

The kinematic viscosity is sometimes referred to as **diffusivity of momentum**, because it has the same unit as and is comparable to diffusivity of heat and diffusivity of mass. It is therefore used in dimensionless numbers which compare the ratio of the diffusivities.

## Fluidity

The reciprocal of viscosity is *fluidity*, usually symbolized by $\varphi = 1 / \mu$ or $F = 1 / \mu$, depending on the convention used, measured in *reciprocal poise* ($cm \cdot s \cdot g^{-1}$), sometimes called the *rhe*. *Fluidity* is seldom used in engineering practice.

The concept of fluidity can be used to determine the viscosity of an ideal solution. For two components *a* and *b*, the fluidity when *a* and *b* are mixed is

$$F \approx \chi_a F_a + \chi_b F_b,$$

which is only slightly simpler than the equivalent equation in terms of viscosity:

$$\mu \approx \frac{1}{\chi_a/\mu_a + \chi_b/\mu_b},$$

where $\chi_a$ and $\chi_b$ is the mole fraction of component *a* and *b* respectively, and $\mu_a$ and $\mu_b$ are the components pure viscosities.

## Non-standard units

The Reyn is a British unit of dynamic viscosity.

Viscosity index is a measure for the change of kinematic viscosity with temperature. It is used to characterise lubricating oil in the automotive industry.

At one time the petroleum industry relied on measuring kinematic viscosity by means of the Saybolt viscometer, and expressing kinematic viscosity in units of *Saybolt Universal Seconds* (SUS). Other abbreviations such as SSU (*Saybolt Seconds Universal*) or SUV (*Saybolt Universal Viscosity*) are sometimes used. Kinematic viscosity in centistoke can be converted from SUS according to the arithmetic and the reference table provided in ASTM D 2161.

### *Molecular origins*


Pitch has a viscosity approximately 230 billion ($2.3\times10^{11}$) times that of water.

The viscosity of a system is determined by how molecules constituting the system interact. There are no simple but correct expressions for the viscosity of a fluid. The simplest exact expressions are the Green–Kubo relations for the linear shear viscosity or the Transient Time Correlation Function expressions derived by Evans and Morriss in 1985. Although these expressions are each exact in order to calculate the viscosity of a dense fluid, using these relations requires the use of molecular dynamics computer simulations.

## Gases

Viscosity in gases arises principally from the molecular diffusion that transports momentum between layers of flow. The kinetic theory of gases allows accurate prediction of the behavior of gaseous viscosity.

Within the regime where the theory is applicable:

- Viscosity is independent of pressure and
- Viscosity increases as temperature increases.

James Clerk Maxwell published a famous paper in 1866 using the kinetic theory of gases to study gaseous viscosity. To understand why the viscosity is independent of pressure consider two adjacent boundary layers (A and B) moving with respect to each other. The internal friction (the viscosity) of the gas is determined by the probability a particle of layer A enters layer B with a corresponding transfer of momentum. Maxwell's calculations showed him that the viscosity coefficient is proportional to both the density, the mean free path and the mean velocity of the atoms. On the other hand, the *mean free path* is inversely proportional to the density. So an increase of pressure doesn't result in any change of the viscosity.

**Relation to mean free path of diffusing particles**

In relation to diffusion, the kinematic viscosity provides a better understanding of the behavior of mass transport of a dilute species. Viscosity is related to shear stress and the rate of shear in a fluid, which illustrates its dependence on the mean free path, $\lambda$, of the diffusing particles.

From fluid mechanics, for a Newtonian fluid, the shear stress, $\tau$, on a unit area moving parallel to itself, is found to be proportional to the rate of change of velocity with distance perpendicular to the unit area:

$$\tau = \mu \frac{du_x}{dy}$$

for a unit area parallel to the x-z plane, moving along the x axis. We will derive this formula and show how $\mu$ is related to $\lambda$.

Interpreting shear stress as the time rate of change of momentum, $p$, per unit area $A$ (rate of momentum flux) of an arbitrary control surface gives

$$\tau = \frac{\dot{p}}{A} = \frac{\dot{m}\langle u_x \rangle}{A}.$$

where $\langle u_x \rangle$ is the average velocity along x of fluid molecules hitting the unit area, with respect to the unit area.

Further manipulation will show

$$\dot{m} = \rho \bar{u} A$$

$$\langle u_x \rangle = \frac{1}{2} \lambda \frac{du_x}{dy}$$ , assuming that molecules hitting the unit area come from all distances between 0 and $\lambda$ (equally distributed), and that their average velocities change linearly with distance (always true for small enough $\lambda$). From this follows:

$$\tau = \underbrace{\frac{1}{2} \rho \bar{u} \lambda}_{\mu} \cdot \frac{du_x}{dy} \quad \Rightarrow \quad \nu = \frac{\mu}{\rho} = \tfrac{1}{2}\, \bar{u} \lambda,$$

where

$\dot{m}$ is the rate of fluid mass hitting the surface,
$\rho$ is the density of the fluid,
$\bar{u}$ is the average molecular speed ($\bar{u} = \sqrt{\langle u^2 \rangle}$),
$\mu$ is the dynamic viscosity.

**Effect of temperature on the viscosity of a gas**

*Sutherland's formula* can be used to derive the dynamic viscosity of an ideal gas as a function of the temperature:

$$\mu = \mu_0 \frac{T_0 + C}{T + C} \left( \frac{T}{T_0} \right)^{3/2}$$

This in turn is equal to

$$\lambda \cdot \frac{T^{3/2}}{T + C},$$ where $$\lambda = \frac{\mu_0 (T_0 + C)}{T_0^{3/2}}$$ which is a constant.

in Sutherland's formula:

- $\mu$ = dynamic viscosity in (Pa·s) at input temperature $T$,
- $\mu_0$ = reference viscosity in (Pa·s) at reference temperature $T_0$,
- $T$ = input temperature in kelvins,
- $T_0$ = reference temperature in kelvins,
- $C$ = Sutherland's constant for the gaseous material in question.

Valid for temperatures between $0 < T < 555$ K with an error due to pressure less than 10% below 3.45 MPa.

Sutherland's constant and reference temperature for some gases

| Gas | $C$ [K] | $T_0$ [K] | $\mu_0$ [μPa s] |
|---|---|---|---|
| air | 120 | 291.15 | 18.27 |
| nitrogen | 111 | 300.55 | 17.81 |
| oxygen | 127 | 292.25 | 20.18 |
| carbon dioxide | 240 | 293.15 | 14.8 |
| carbon monoxide | 118 | 288.15 | 17.2 |
| hydrogen | 72 | 293.85 | 8.76 |
| ammonia | 370 | 293.15 | 9.82 |
| sulfur dioxide | 416 | 293.65 | 12.54 |
| helium | 79.4 | 273 | 19 |

**Viscosity of a dilute gas**

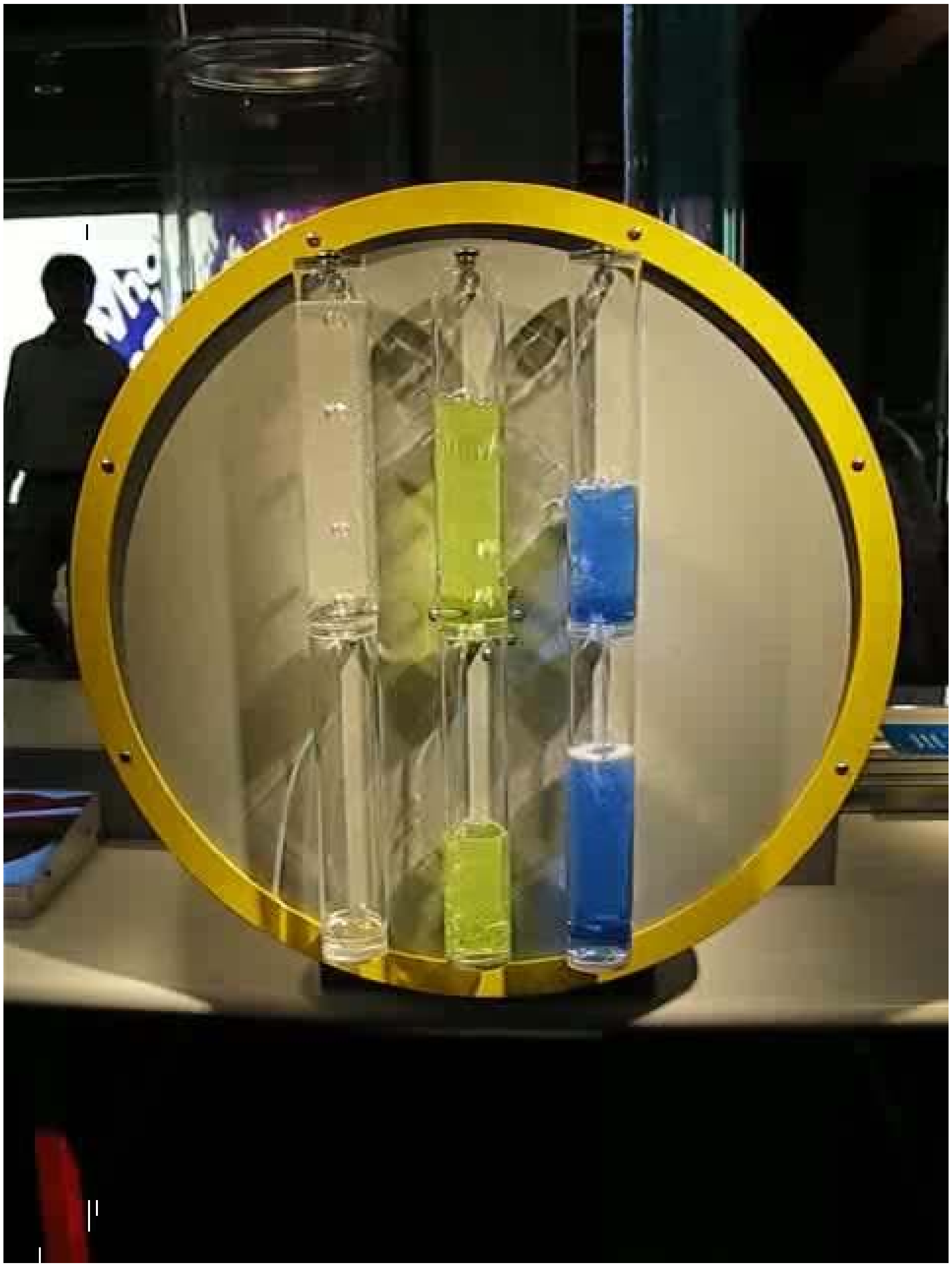
The Chapman-Enskog equation may be used to estimate viscosity for a dilute gas. This equation is based on a semi-theoretical assumption by Chapman and Enskog. The equation requires three empirically determined parameters: the collision diameter ($\sigma$), the maximum energy of attraction divided by the Boltzmann constant ($\epsilon/\kappa$) and the collision integral ($\omega(T^*)$).

$$\mu_0 \times 10^6 = 2.6693 \frac{(MT)^{1/2}}{\sigma^2 \omega(T^*)},$$

with

- $T^* = \kappa T/\varepsilon$ — reduced temperature (dimensionless),
- $\mu_0$ = viscosity for dilute gas (μPa.s),
- $M$ = molecular mass (g/mol),
- $T$ = temperature (K),
- $\sigma$ = the collision diameter (Å),
- $\varepsilon / \kappa$ = the maximum energy of attraction divided by the Boltzmann constant (K),
- $\omega_\mu$ = the collision integral.

## Liquids



Three liquids with different Viscosities

In liquids, the additional forces between molecules become important. This leads to an additional contribution to the shear stress though the exact mechanics of this are still controversial. Thus, in liquids:

- Viscosity is independent of pressure (except at very high pressure); and
- Viscosity tends to fall as temperature increases (for example, water viscosity goes from 1.79 cP to 0.28 cP in the temperature range from 0 °C to 100 °C).

The dynamic viscosities of liquids are typically several orders of magnitude higher than dynamic viscosities of gases.

**Viscosity of blends of liquids**

The viscosity of the blend of two or more liquids can be estimated using the Refutas equation. The calculation is carried out in three steps.

The first step is to calculate the Viscosity Blending Number (VBN) (also called the Viscosity Blending Index) of each component of the blend:

$$\text{VBN} = 14.534 \times \ln\left[\ln(v + 0.8)\right] + 10.975 \quad (1)$$

where $v$ is the kinematic viscosity in centistokes (cSt). It is important that the kinematic viscosity of each component of the blend be obtained at the same temperature.

The next step is to calculate the VBN of the blend, using this equation:

$$\text{VBN}_{\text{Blend}} = [x_A \times \text{VBN}_A] + [x_B \times \text{VBN}_B] + \cdots + [x_N \times \text{VBN}_N] \quad (2)$$

where $x_X$ is the mass fraction of each component of the blend.

Once the viscosity blending number of a blend has been calculated using equation (2), the final step is to determine the kinematic viscosity of the blend by solving equation (1) for $v$:

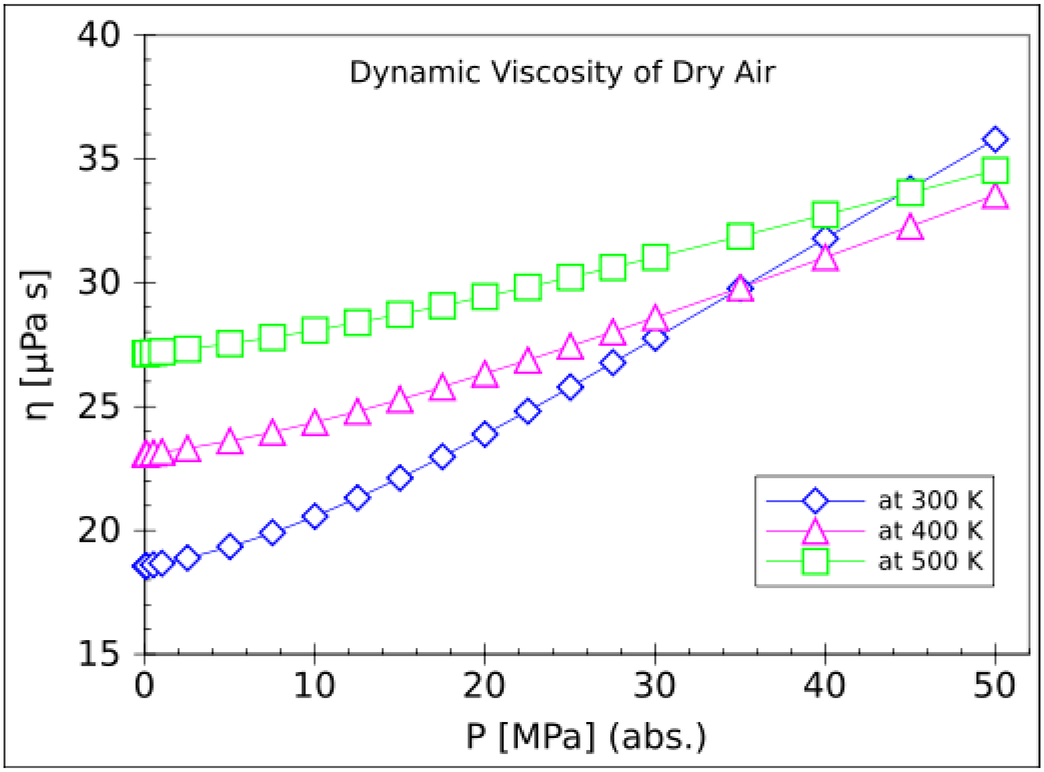
$$v = \exp\left(\exp\left(\frac{\text{VBN}_{\text{Blend}} - 10.975}{14.534}\right)\right) - 0.8, \quad (3)$$

where $VBN_{Blend}$ is the viscosity blending number of the blend.

## *Viscosity of selected substances*

The viscosity of air and water are by far the two most important materials for aviation aerodynamics and shipping fluid dynamics. Temperature plays the main role in determining viscosity.

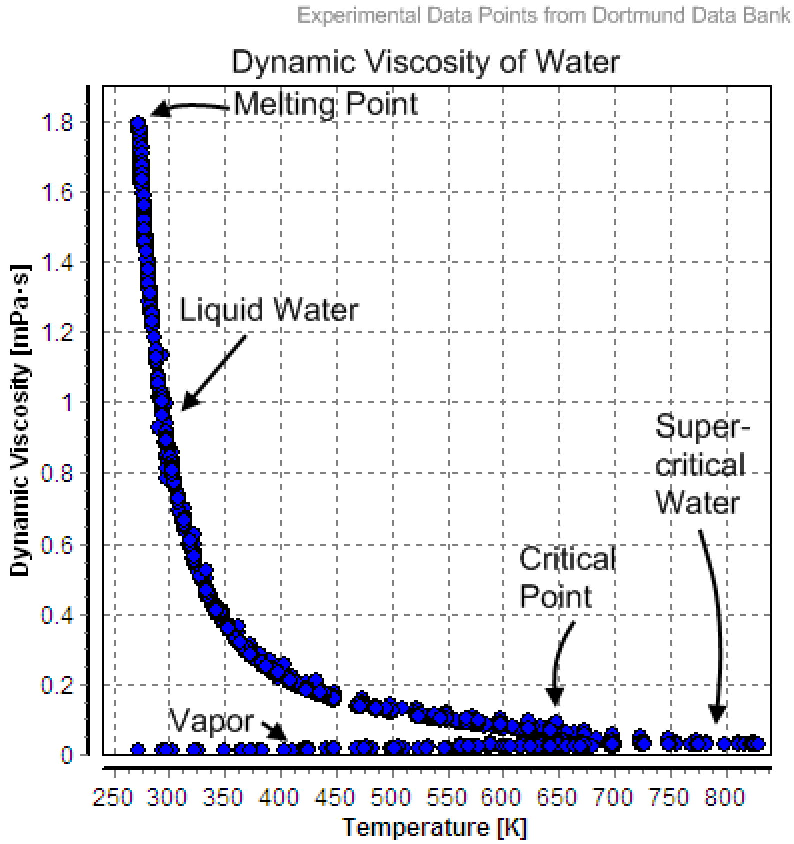
### Viscosity of air




Pressure dependence of the dynamic viscosity of dry air at the temperatures of 300, 400 and 500 K

The viscosity of air depends mostly on the temperature. At 15.0 °C, the viscosity of air is $1.78\times10^{-5}$ kg/(m·s), 17.8 μPa.s or $1.78\times10^{-5}$ Pa.s.. One can get the viscosity of air as a function of temperature from the Gas Viscosity Calculator

## Viscosity of water




Dynamic Viscosity of Water

The dynamic viscosity of water is $8.90 \times 10^{-4}$ Pa·s or $8.90 \times 10^{-3}$ dyn·s/cm$^2$ or 0.890 cP at about 25 °C.
Water has a viscosity of 0.0091 poise at 25 °C, or 1 centipoise at 20 °C.
As a function of temperature $T$ (K): (Pa·s) = $A \times 10^{B/(T-C)}$
where $A$=$2.414 \times 10^{-5}$ Pa·s ; $B$ = 247.8 K ; and $C$ = 140 K.

Viscosity of liquid water at different temperatures up to the normal boiling point is listed below.

| Temperature [°C] | Viscosity [mPa·s] |
|---|---|
| 10 | 1.308 |
| 20 | 1.002 |
| 30 | 0.7978 |
| 40 | 0.6531 |
| 50 | 0.5471 |
| 60 | 0.4668 |

| | |
|---|---|
| 70 | 0.4044 |
| 80 | 0.3550 |
| 90 | 0.3150 |
| 100 | 0.2822 |

## Viscosity of various materials

Example of the viscosity of milk and water. Liquids with higher viscosities will not make such a splash when poured at the same velocity.

Honey being drizzled.

Peanut butter is a semi-solid and can therefore hold peaks.

Some dynamic viscosities of Newtonian fluids are listed below:

| Viscosity of selected gases at 100 kPa, [μPa·s] | | |
|---|---|---|
| **Gas** | **at 0 °C (273 K)** | **at 27 °C (300 K)** |
| air | 17.4 | 18.6 |
| hydrogen | 8.4 | 9.0 |
| helium | | 20.0 |
| argon | | 22.9 |
| xenon | 21.2 | 23.2 |
| carbon dioxide | | 15.0 |
| methane | | 11.2 |
| ethane | | 9.5 |

| Viscosity of liquids at 25 °C | | |
|---|---|---|
| **Liquid ():** | **Viscosity** [Pa·s] | **Viscosity** [cP=mPa.s] |
| acetone | $3.06\times10^{-4}$ | 0.306 |
| benzene | $6.04\times10^{-4}$ | 0.604 |
| blood (37 °C) | $(3–4)\times10^{-3}$ | 3–4 |
| castor oil | 0.985 | 985 |
| corn syrup | 1.3806 | 1380.6 |
| ethanol | $1.074\times10^{-3}$ | 1.074 |
| ethylene glycol | $1.61\times10^{-2}$ | 16.1 |
| glycerol | 1.2 (at 20 °C) | 1200 |
| HFO-380 | 2.022 | 2022 |
| mercury | $1.526\times10^{-3}$ | 1.526 |
| methanol | $5.44\times10^{-4}$ | 0.544 |
| Motor oil SAE 10 (20 °C) | 0.065 | 65 |
| Motor oil SAE 40 (20 °C) | 0.319 | 319 |
| nitrobenzene | $1.863\times10^{-3}$ | 1.863 |
| liquid nitrogen @ 77K | $1.58\times10^{-4}$ | 0.158 |
| propanol | $1.945\times10^{-3}$ | 1.945 |
| olive oil | .081 | 81 |
| pitch | 2.3e8 | 2.3e11 |
| quark–gluon plasma | 5e11 | 5e14 |
| sulfuric acid | $2.42\times10^{-2}$ | 24.2 |
| water | $8.94\times10^{-4}$ | 0.894 |

| Viscosity of fluids with variable compositions | | |
|---|---|---|
| **Fluid** | **Viscosity** [Pa·s] | **Viscosity** [cP] |
| honey | 2–10 | 2,000–10,000 |
| molasses | 5–10 | 5,000–10,000 |
| molten glass | 10–1,000 | 10,000–1,000,000 |
| chocolate syrup | 10–25 | 10,000–25,000 |
| molten chocolate* | 45–130 | 45,000–130,000 |
| ketchup* | 50–100 | 50,000–100,000 |
| peanut butter* | c. 250 | c. 250,000 |
| shortening* | c. 250 | 250,000 |

* These materials are highly non-Newtonian.

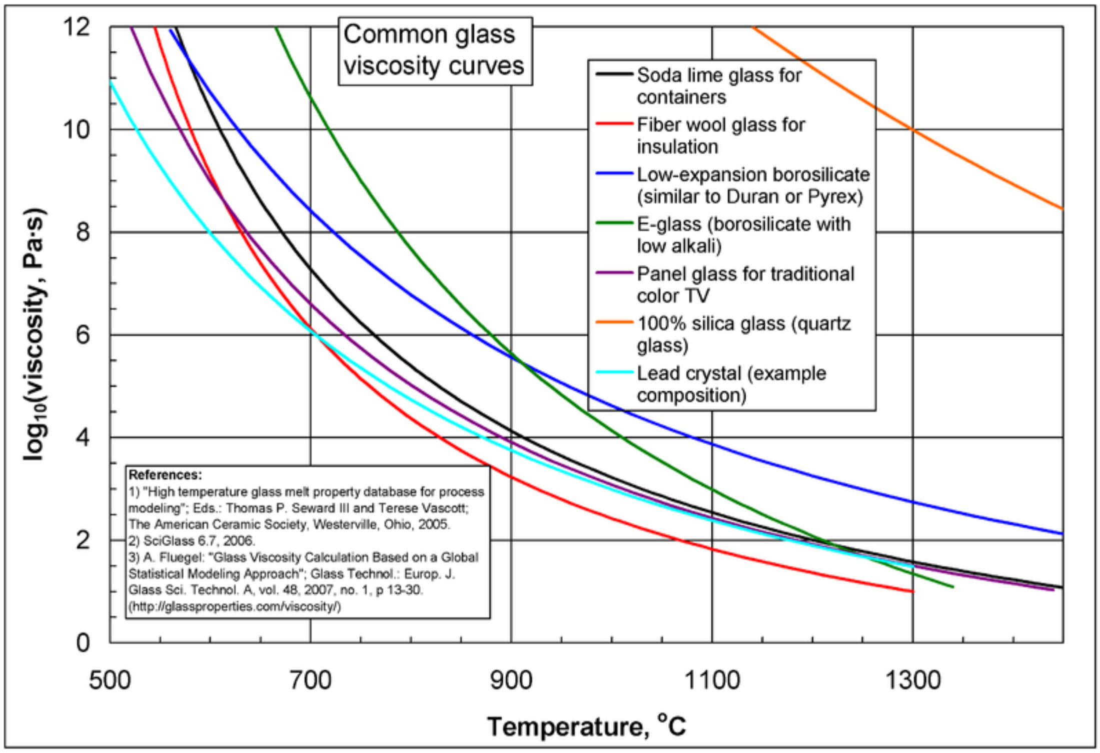
## Viscosity of solids

On the basis that all solids such as granite flow to a small extent in response to small shear stress, some researchers have contended that substances known as amorphous solids, such as glass and many polymers, may be considered to have viscosity. This has led some to the view that solids are simply "liquids" with a very high viscosity, typically greater than $10^{12}$ Pa·s. This position is often adopted by supporters of the widely held misconception that glass flow can be observed in old buildings. This distortion is the result of the undeveloped glass making process of earlier eras, and not due to the viscosity of glass.

However, others argue that solids are, in general, elastic for small stresses while fluids are not. Even if solids flow at higher stresses, they are characterized by their low-stress behavior. This distinction is muddled if measurements are continued over long time periods, such as the Pitch drop experiment. Viscosity may be an appropriate characteristic for solids in a plastic regime. The situation becomes somewhat confused as the term *viscosity* is sometimes used for solid materials, for example Maxwell materials, to describe the relationship between stress and the rate of change of strain, rather than rate of shear.

These distinctions may be largely resolved by considering the constitutive equations of the material in question, which take into account both its viscous and elastic behaviors. Materials for which both their viscosity and their elasticity are important in a particular range of deformation and deformation rate are called *viscoelastic*. In geology, earth materials that exhibit viscous deformation at least three times greater than their elastic deformation are sometimes called rheids.

## *Viscosity of amorphous materials*




Common glass viscosity curves.

Viscous flow in amorphous materials (e.g. in glasses and melts) is a thermally activated process:

$$\mu = A \cdot e^{Q/RT},$$

where $Q$ is activation energy, $T$ is temperature, $R$ is the molar gas constant and $A$ is approximately a constant.

The viscous flow in amorphous materials is characterized by a deviation from the Arrhenius-type behavior: $Q$ changes from a high value $Q_H$ at low temperatures (in the glassy state) to a low value $Q_L$ at high temperatures (in the liquid state). Depending on this change, amorphous materials are classified as either

- strong when: $Q_H - Q_L < Q_L$ or
- fragile when: $Q_H - Q_L \geq Q_L$.

The fragility of amorphous materials is numerically characterized by the Doremus' fragility ratio:

$$R_D = \frac{Q_H}{Q_L}$$

and strong material have $R_D < 2$ whereas fragile materials have $R_D \geq 2$.

The viscosity of amorphous materials is quite exactly described by a two-exponential equation:

$$\mu = A_1 \cdot T \cdot \left[1 + A_2 \cdot e^{B/RT}\right] \cdot \left[1 + C \cdot e^{D/RT}\right],$$

with constants $A_1$, $A_2$, $B$, $C$ and $D$ related to thermodynamic parameters of joining bonds of an amorphous material.

Not very far from the glass transition temperature, $T_g$, this equation can be approximated by a Vogel-Fulcher-Tammann (VFT) equation.

If the temperature is significantly lower than the glass transition temperature, $T < T_g$, then the two-exponential equation simplifies to an Arrhenius type equation:

$$\mu = A_L T \cdot e^{Q_H/RT}$$

with:

$$Q_H = H_d + H_m,$$

where $H_d$ is the enthalpy of formation of broken bonds (termed configuron s) and $H_m$ is the enthalpy of their motion. When the temperature is less than the glass transition temperature, $T < T_g$, the activation energy of viscosity is high because the amorphous materials are in the glassy state and most of their joining bonds are intact.

If the temperature is highly above the glass transition temperature, $T > T_g$, the two-exponential equation also simplifies to an Arrhenius type equation:

$$\mu = A_H T \cdot e^{Q_L/RT},$$

with:

$$Q_L = H_m.$$

When the temperature is higher than the glass transition temperature, $T > T_g$, the activation energy of viscosity is low because amorphous materials are melt and have most of their joining bonds broken which facilitates flow.

## *Eddy viscosity*

In the study of turbulence in fluids, a common practical strategy for calculation is to ignore the small-scale *vortices* (or *eddies*) in the motion and to calculate a large-scale motion with an *eddy viscosity* that characterizes the transport and dissipation of energy in the smaller-scale flow. Values of eddy viscosity used in modeling ocean circulation may be from $5x10^4$ to $10^6$ Pa·s depending upon the resolution of the numerical grid.

## *The linear viscous stress tensor*

Viscous forces in a fluid are a function of the rate at which the fluid velocity is changing over distance. The velocity at any point ***r*** is specified by the velocity field ***v***(***r***). The velocity at a small distance *d**r*** from point ***r*** may be written as a Taylor series:

$$\mathbf{v}(\mathbf{r}+d\mathbf{r}) = \mathbf{v}(\mathbf{r}) + \frac{d\mathbf{v}}{d\mathbf{r}}d\mathbf{r} + \ldots,$$

where *d**v*** / *d**r*** is shorthand for the dyadic product of the del operator and the velocity:

$$\frac{d\mathbf{v}}{d\mathbf{r}} = \begin{bmatrix} \frac{\partial v_x}{\partial x} & \frac{\partial v_x}{\partial y} & \frac{\partial v_x}{\partial z} \\ \frac{\partial v_y}{\partial x} & \frac{\partial v_y}{\partial y} & \frac{\partial v_y}{\partial z} \\ \frac{\partial v_z}{\partial x} & \frac{\partial v_z}{\partial y} & \frac{\partial v_z}{\partial z} \end{bmatrix}.$$

This is just the Jacobian of the velocity field.

Viscous forces are the result of relative motion between elements of the fluid, and so are expressible as a function of the velocity field. In other words, the forces at ***r*** are a function of ***v***(***r***) and all derivatives of ***v***(***r***) at that point. In the case of linear viscosity, the viscous force will be a function of the Jacobian tensor alone. For almost all practical situations, the linear approximation is sufficient.

If we represent *x*, *y*, and *z* by indices 1, 2, and 3 respectively, the *i,j* component of the Jacobian may be written as $\partial_i v_j$ where $\partial_i$ is shorthand for $\partial/\partial x_i$. Note that when the first and higher derivative terms are zero, the velocity of all fluid elements is parallel, and there are no viscous forces.

Any matrix may be written as the sum of an antisymmetric matrix and a symmetric matrix, and this decomposition is independent of coordinate system, and so has physical significance. The velocity field may be approximated as:

$$v_j(\mathbf{r}+d\mathbf{r}) = v_j(\mathbf{r}) + \frac{1}{2}\left(\partial_i v_j - \partial_j v_i\right) dr_i + \frac{1}{2}\left(\partial_i v_j + \partial_j v_i\right) dr_i,$$

where Einstein notation is now being used in which repeated indices in a product are implicitly summed. The second term from the right is the asymmetric part of the first derivative term, and it represents a rigid rotation of the fluid about ***r*** with angular velocity $\omega$ where:

$$\omega = \frac{1}{2}\nabla \times \mathbf{v} = \frac{1}{2}\begin{bmatrix}\partial_2 v_3 - \partial_3 v_2 \\ \partial_3 v_1 - \partial_1 v_3 \\ \partial_1 v_2 - \partial_2 v_1\end{bmatrix}.$$

For such a rigid rotation, there is no change in the relative positions of the fluid elements, and so there is no viscous force associated with this term. The remaining symmetric term is responsible for the viscous forces in the fluid. Assuming the fluid is isotropic (i.e. its properties are the same in all directions), then the most general way that the symmetric term (the rate-of-strain tensor) can be broken down in a coordinate-independent (and therefore physically real) way is as the sum of a constant tensor (the rate-of-expansion tensor) and a traceless symmetric tensor (the rate-of-shear tensor):

$$\frac{1}{2}\left(\partial_i v_j + \partial_j v_i\right) = \underbrace{\frac{1}{3}\partial_k v_k \delta_{ij}}_{\text{rate-of-expansion tensor}} + \underbrace{\left(\frac{1}{2}\left(\partial_i v_j + \partial_j v_i\right) - \frac{1}{3}\partial_k v_k \delta_{ij}\right)}_{\text{rate-of-shear tensor}},$$

where $\delta_{ij}$ is the unit tensor. The most general linear relationship between the stress tensor $\boldsymbol{\sigma}$ and the rate-of-strain tensor is then a linear combination of these two tensors:

$$\sigma_{\text{visc};ij} = \zeta \partial_k v_k \delta_{ij} + \mu\left(\partial_i v_j + \partial_j v_i - \frac{2}{3}\partial_k v_k \delta_{ij}\right),$$

where $\varsigma$ is the coefficient of bulk viscosity (or "second viscosity") and $\mu$ is the coefficient of (shear) viscosity.

The forces in the fluid are due to the velocities of the individual molecules. The velocity of a molecule may be thought of as the sum of the fluid velocity and the thermal velocity. The viscous stress tensor described above gives the force due to the fluid velocity only. The force on an area element in the fluid due to the thermal velocities of the molecules is just the hydrostatic pressure. This pressure term ($-p\ \delta_{ij}$) must be added to the viscous stress tensor to obtain the total stress tensor for the fluid.

$$\sigma_{ij} = -p\delta_{ij} + \sigma_{\text{visc};ij}.$$

The infinitesimal force $dF_i$ on an infinitesimal area $dA_i$ is then given by the usual relationship:

$$dF_i = \sigma_{ij}\, dA_j.$$

## Chapter 4

# Petroleum Refining Processes

**Petroleum refining processes** are those chemical engineering processes and other facilities used in petroleum refineries (also referred to as oil refineries) to transform crude oil into useful products such as liquefied petroleum gas (LPG), gasoline or petrol, kerosene, jet fuel, diesel oil and fuel oils.

Petroleum refineries are very large industrial complexes that involve a great many different processing units and auxiliary facilities such as utility units and storage tanks. Each refinery has its own unique arrangement and combination of refining processes largely determined by the refinery location, desired products and economic considerations. There are most probably no two refineries that are identical in every respect.

Some modern petroleum refineries process as much as 800,000 to 900,000 barrels (127,000 to 143,000 cubic meters) per day of crude oil.

### *Brief history of the petroleum industry and petroleum refining*

Prior to the nineteenth century, petroleum was known and utilized in various fashions in Babylon, Egypt, China, Persia, Rome and Azerbaijan. However, the modern history of the petroleum industry is said to have begun in 1846 when Abraham Gessner of Nova Scotia, Canada discovered how to produce kerosene from coal. Shortly thereafter, in 1854, Ignacy Lukasiewicz began producing kerosene from hand-dug oil wells near the town of Krosno, now in Poland. The first large petroleum refinery was built in Ploesti, Romania in 1856 using the abundant oil available in Romania.

In North America, the first oil well was drilled in 1858 by James Miller Williams in Ontario, Canada. In the United States, the petroleum industry began in 1859 when Edwin Drake found oil near Titusville, Pennsylvania. The industry grew slowly in the 1800s, primarily producing kerosene for oil lamps. In the early twentieth century, the introduction of the internal combustion engine and its use in automobiles created a market for gasoline that was the impetus for fairly rapid growth of the petroleum industry. The early finds of petroleum like those in Ontario and Pennsylvania were soon outstripped by large oil "booms" in Oklahoma, Texas and California.

Prior to World War II in the early 1940s, most petroleum refineries in the United States consisted simply of crude oil distillation units (often referred to as atmospheric crude oil distillation units). Some refineries also had vacuum distillation units as well as thermal cracking units such as visbreakers (viscosity breakers, units to lower the viscosity of the oil). All of the many other refining processes discussed below were developed during the war or within a few years after the war. They became commercially available within 5 to 10 years after the war ended and the worldwide petroleum industry experienced very rapid growth. The driving force for that growth in technology and in the number and size of refineries worldwide was the growing demand for automotive gasoline and aircraft fuel.

In the United States, for various complex economic reasons, the construction of new refineries came to a virtual stop in about the 1980s. However, many of the existing refineries in the United States have revamped many of their units and/or constructed add-on units in order to: increase their crude oil processing capacity, increase the octane rating of their product gasoline, lower the sulphur content of their diesel fuel and home heating fuels to comply with environmental regulations and comply with environmental air pollution and water pollution requirements.

## ***Processing units used in refineries***

- Crude Oil Distillation unit: Distills the incoming crude oil into various fractions for further processing in other units.
- Vacuum Distillation unit: Further distills the residue oil from the bottom of the crude oil distillation unit. The vacuum distillation is performed at a pressure well below atmospheric pressure.
- Naphtha Hydrotreater unit: Uses hydrogen to desulfurize the naphtha fraction from the crude oil distillation or other units within the refinery.
- Catalytic Reforming unit: Converts the desulfurized naphtha molecules into higher-octane molecules to produce *reformate*, which is a component of the end-product gasoline or petrol.
- Alkylation unit: Converts isobutane and butylenes into *alkylate*, which is a very high-octane component of the end-product gasoline or petrol.
- Isomerization unit: Converts linear molecules such as normal pentane into higher-octane branched molecules for blending into the end-product gasoline. Also used to convert linear normal butane into isobutane for use in the alkylation unit.
- Distillate Hydrotreater unit: Uses hydrogen to desulfurize some of the other distilled fractions from the crude oil distillation unit (such as diesel oil).
- Merox (mercaptan oxidizer) or similar units: Desulfurize LPG, kerosene or jet fuel by oxidizing undesired mercaptans to organic disulphides.
- Amine gas treater, Claus unit, and tail gas treatment for converting hydrogen sulphide gas from the hydrotreaters into end-product elemental sulphur. The large majority of the 64,000,000 metric tons of sulphur produced worldwide in 2005 was byproduct sulfur from petroleum refining and natural gas processing plants.

- Fluid Catalytic Cracking (FCC) unit: Upgrades the heavier, higher-boiling fractions from the crude oil distillation by converting them into lighter and lower boiling, more valuable products.
- Hydrocracker unit: Uses hydrogen to upgrade heavier fractions from the crude oil distillation and the vacuum distillation units into lighter, more valuable products.
- Visbreaker unit upgrades heavy residual oils from the vacuum distillation unit by thermally cracking them into lighter, more valuable reduced viscosity products.
- Delayed coking and Fluid coker units: Convert very heavy residual oils into end-product petroleum coke as well as naphtha and diesel oil by-products.

### *Auxiliary facilities required in refineries*

- Steam reformer unit: Converts natural gas into hydrogen for the hydrotreaters and/or the hydrocracker.
- Sour water stripper unit: Uses steam to remove hydrogen sulfide gas from various wastewater streams for subsequent conversion into end-product sulfur in the Claus unit.
- Utility units such as cooling towers for furnishing circulating cooling water, steam generators, instrument air systems for pneumatically operated control valves and an electrical substation.
- Wastewater collection and treating systems consisting of API separators, dissolved air flotation (DAF) units and some type of further treatment (such as an activated sludge biotreater) to make the wastewaters suitable for reuse or for disposal.
- Liquified gas (LPG) storage vessels for propane and similar gaseous fuels at a pressure sufficient to maintain them in liquid form. These are usually spherical vessels or *bullets* (horizontal vessels with rounded ends).
- Storage tanks for crude oil and finished products, usually vertical, cylindrical vessels with some sort of vapour emission control and surrounded by an earthen berm to contain liquid spills.

### *The crude oil distillation unit*

The crude oil distillation unit (CDU) is the first processing unit in virtually all petroleum refineries. The CDU distills the incoming crude oil into various fractions of different boiling ranges, each of which are then processed further in the other refinery processing units. The CDU is often referred to as the *atmospheric distillation unit* because it operates at slightly above atmospheric pressure.

Below is a schematic flow diagram of a typical crude oil distillation unit. The incoming crude oil is preheated by exchanging heat with some of the hot, distilled fractions and other streams. It is then desalted to remove inorganic salts (primarily sodium chloride).

Following the desalter, the crude oil is further heated by exchanging heat with some of the hot, distilled fractions and other streams. It is then heated in a fuel-fired furnace (fired heater) to a temperature of about 398 °C and routed into the bottom of the distillation unit.

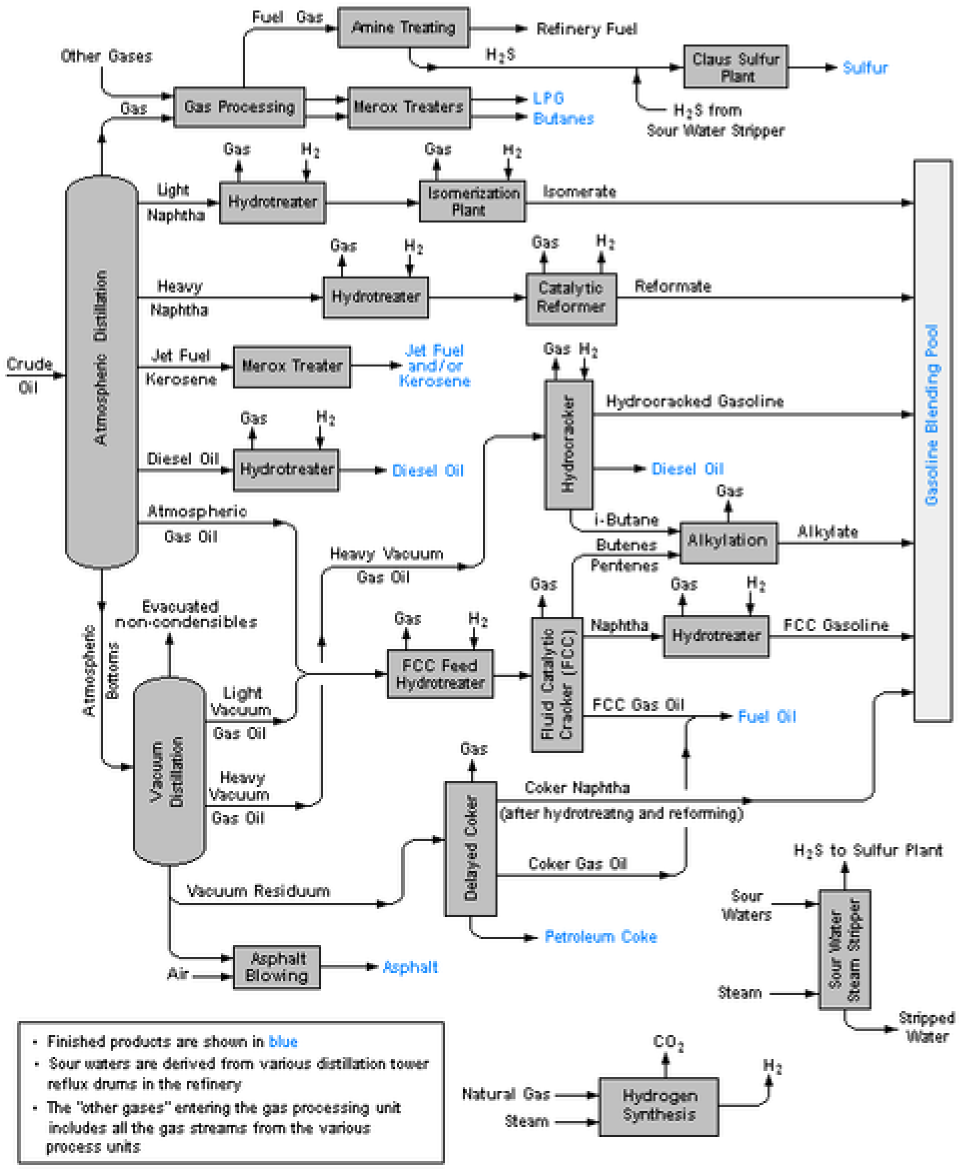
The cooling and condensing of the distillation tower overhead is provided partially by exchanging heat with the incoming crude oil and partially by either an air-cooled or water-cooled condenser. Additional heat is removed from the distillation column by a pumparound system as shown in the diagram below.

As shown in the flow diagram, the overhead distillate fraction from the distillation column is naphtha. The fractions removed from the side of the distillation column at various points between the column top and bottom are called *sidecuts*. Each of the sidecuts (i.e., the kerosene, light gas oil and heavy gas oil) is cooled by exchanging heat with the incoming crude oil. All of the fractions (i.e., the overhead naphtha, the sidecuts and the bottom residue) are sent to intermediate storage tanks before being processed further.

## Flow diagram of a typical petroleum refinery

The image below is a schematic flow diagram of a typical petroleum refinery that depicts the various refining processes and the flow of intermediate product streams that occurs between the inlet crude oil feedstock and the final end-products.

The diagram depicts only one of the literally hundreds of different oil refinery configurations. The diagram also does not include any of the usual refinery facilities providing utilities such as steam, cooling water, and electric power as well as storage tanks for crude oil feedstock and for intermediate products and end products.




A schematic flow diagram of a typical petroleum refinery.

## *Refining end-products*

The primary end-products produced in petroleum refining may be grouped into four categories: light distillates, middle distillates, heavy distillates and others.

### Light distillates

- Liquid petroleum gas (LPG)
- Gasoline (also known as petrol)
- Kerosene
- Jet fuel and other aircraft fuel

### Middle distillates

- Automotive and rail-road diesel fuels
- Residential heating fuel
- Other light fuel oils

### Heavy distillates

- Heavy fuel oils
- Bunker fuel oil and other residual fuel oils

### Others

Many of these are not produced in all petroleum refineries.

- Speciality petroleum naphthas
- Speciality solvents
- Elemental sulphur (and sometimes sulphuric acid)
- Petrochemical feed-stocks
- Asphalt and tar
- Petroleum coke
- Lubricating oils
- Waxes and greases
- Transformer and cable oils
- Carbon black

## Chapter 5

# Petroleum Reservoir

A **petroleum reservoir**, or **oil and gas reservoir**, is a subsurface pool of hydrocarbons contained in porous or fractured rock formations. The naturally occurring hydrocarbons, such as crude oil or natural gas, are trapped by overlying rock formations with lower permeability. Reservoirs are found using hydrocarbon exploration methods.

### *Formation*

Crude oil found in oil reservoirs formed in the Earth's crust from the remains of living things. Crude oil is properly known as petroleum, and is used as fossil fuel. Evidence indicates that millions of years of heat and pressure changed the remains of microscopic plant and animal remains into oil and natural gas.

Roy Nurmi, an interpretation adviser for Schlumberger, described the process as follows: "Plankton and algae, proteins and the life that's floating in the sea, as it dies, falls to the bottom, and these organisms are going to be the source of our oil and gas. When they're buried with the accumulating sediment and reach an adequate temperature, something above 50 to 70 °C they start to cook. This transformation, this change, changes them into the liquid hydrocarbons that move and migrate, will become our oil and gas reservoir."

In addition to the aquatic environment, which is usually a sea, but might also be a river, lake, coral reef or algal mat, the formation of an oil or gas reservoir also requires a sedimentary basin that passes through four steps: deep burial under sand and mud, pressure cooking, hydrocarbon migration from the source to the reservoir rock, and trapping by impermeable rock. Timing is also an important consideration; it is suggested that the Ohio River Valley could have had as much oil as the Middle East at one time, but that it escaped due to a lack of traps. The North Sea, on the other hand, endured millions of years of sea level changes that successfully resulted in the formation of more than 150 oilfields.

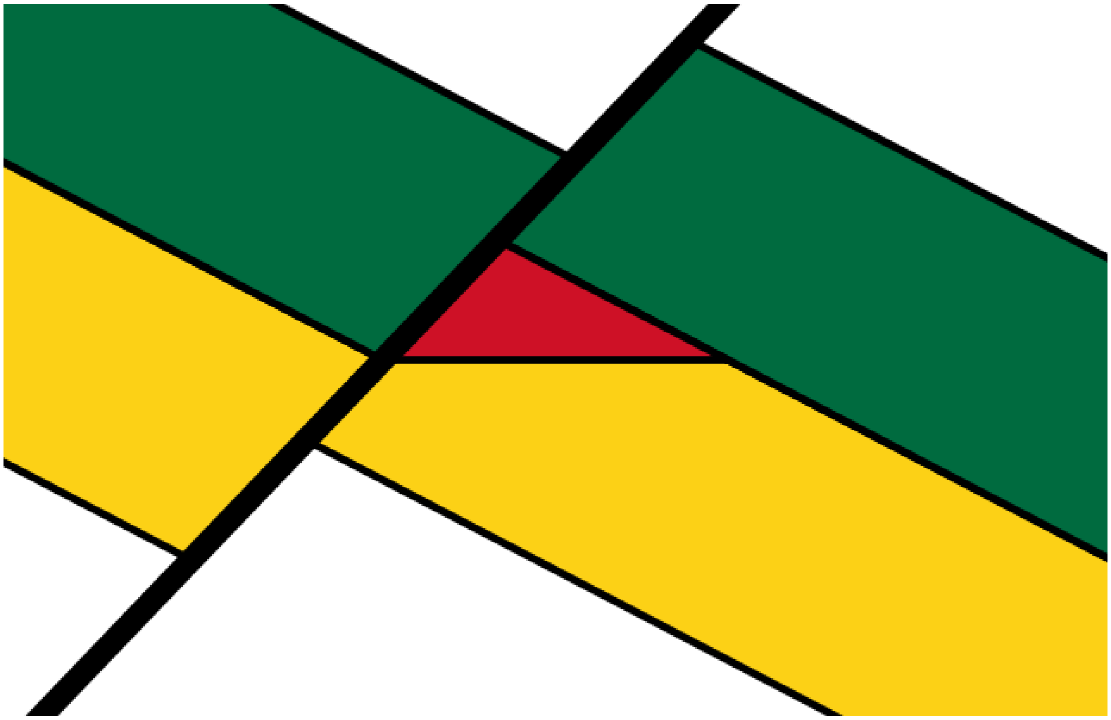
Although the process is generally the same, various environmental factors lead to the creation of a wide variety of reservoirs. Reservoirs exist anywhere from the land surface to 30,000 ft (9,000 m) below the surface and are a variety of shapes, sizes and ages.

## Traps

The traps required in the last step of the reservoir formation process have been classified by petroleum geologists into two types: structural and stratigraphic. A reservoir can be formed by one kind of trap or a combination of both.

**Structural traps**

Fold (structural) trap



Fault (structural) trap

*Structural traps* are formed by a deformation in the rock layer that contains the hydrocarbons. Domes, anticlines, and folds are common structures. Fault-related features also may be classified as structural traps if closure is present. Structural traps are the easiest to locate by surface and subsurface geological and geophysical studies. They are the most numerous among traps and have received a greater amount of attention in the search for oil than all other types of traps.

An example of this kind of trap starts when salt is deposited by shallow seas. Later, a sinking seafloor deposits organic-rich shale over the salt, which is in turn covered with layers of sandstone and shale. Deeply buried salt tends to rise unevenly in swells or salt domes, and any oil generated within the sediments is trapped where the sandstones are pushed up over or adjacent to the salt dome.

**Stratigraphic traps**

*Stratigraphic traps* are formed when other beds seal a reservoir bed or when the permeability changes (facies change) within the reservoir bed itself. Stratigraphic traps can form against either younger or older time surfaces.

## Estimating reserves

After the discovery of a reservoir, a petroleum engineer will seek to build a better picture of the accumulation. In a simple text book example of a uniform reservoir, the first stage is to conduct a seismic survey to determine the possible size of the trap. Appraisal wells can be used to determine the location of oil-water contact and with it, the height of the oil bearing sands. Often coupled with seismic data, it is possible to estimate the volume of oil bearing reservoir.

The next step is to use information from appraisal wells to estimate the porosity of the rock. The porosity, or the percentage of the total volume that contains fluids rather than solid rock, is 20-35% or less. It can give information on the actual capacity. Laboratory testing can determine the characteristics of the reservoir fluids, particularly the expansion factor of the oil, or how much the oil expands when brought from high pressure, high temperature of the reservoir to "stock tank" at the surface.

With such information, it is possible to estimate how many "stock tank" barrels of oil are located in the reservoir. Such oil is called the stock tank oil initially in place (STOIIP). As a result of studying things such as the permeability of the rock (how easily fluids can flow through the rock) and possible drive mechanisms, it is possible to estimate the recovery factor, or what proportion of oil in place can be reasonably expected to be produced. The recovery factor is commonly 30-35%, giving a value for the recoverable reserves.

The difficulty is that reservoirs are not uniform. They have variable porosities and permeabilities and may be compartmentalised, with fractures and faults breaking them up and complicating fluid flow. For this reason, computer modeling of economically viable reservoirs is often carried out. Geologists, geophysicists and reservoir engineers work together to build a model which allows simulation of the flow of fluids in the reservoir, leading to an improved estimate of reserves.

## *Production*

To obtain the contents of the oil reservoir, it is usually necessary to drill into the Earth's crust, although surface oil seeps exist in some parts of the world, such as the La Brea tar pits in California, and numerous seeps in Trinidad.

## *Drive mechanisms*

A virgin reservoir may be under sufficient pressure to push hydrocarbons to surface. As the fluids are produced, the pressure will often decline, and production will falter. The reservoir may respond to the withdrawal of fluid in a way that tends to maintain the pressure. Artificial drive methods may be necessary.

### Solution gas drive

This mechanism (also known as depletion drive) depends on the associated gas of the oil. The virgin reservoir may be entirely liquid, but will be expected to have gaseous hydrocarbons in solution due to the pressure. As the reservoir depletes, the pressure falls below the bubble point, and the gas comes out of solution to form a gas cap at the top. This gas cap pushes down on the liquid helping to maintain pressure.

### Gas cap drive

In reservoirs already having a gas cap (the virgin pressure is already below bubble point), the gas cap expands with the depletion of the reservoir, pushing down on the liquid sections applying extra pressure.

### Aquifer (water) drive

Below the hydrocarbons may be a ground water aquifer. Water, as with all liquids, is compressible to a small degree. As the hydrocarbons are depleted, the reduction in pressure in the reservoir causes the water to expand slightly. Although this expansion is minute, if the aquifer is large enough, this will translate into a large increase in volume, which will push up on the hydrocarbons, maintaining pressure.

### Water and gas injection

If the natural drives are insufficient, as they very often are, then the pressure can be artificially maintained by injecting water into the aquifer or gas into the gas cap.

# Chapter 6

# Pigging

**Pigging** in the maintenance of pipelines refers to the practice of using pipeline inspection gauges or 'pigs' to perform various operations on a pipeline without stopping the flow of the product in the pipeline.

These operations include but are not limited to cleaning and inspecting of the pipeline. This is accomplished by inserting the pig into a 'pig launcher' (or 'launching station') - a funnel shaped Y section in the pipeline. The launcher / launching station is then closed and the pressure of the product in the pipeline is used to push it along down the pipe until it reaches the receiving trap - the 'pig catcher' (or receiving station).

If the pipeline contains butterfly valves, the pipeline cannot be pigged. Ball valves cause no problems because the inside diameter of the ball can be specified to be the same as that of the pipe (as soon as they are ful bore valves).

Pigging has been used for many years to clean larger diameter pipelines in the oil industry. Today, however, the use of smaller diameter pigging systems is now increasing in many continuous and batch process plants as plant operators search for increased efficiencies and reduced costs.

Pigging can be used for almost any section of the transfer process between, for example, blending, storage or filling systems. Pigging systems are already installed in industries handling products as diverse as lubricating oils, paints, chemicals, toiletries, cosmetics and foodstuffs.

Pigs are used in lube oil or painting blending: they are used to clean the pipes to avoid cross-contamination, and to empty the pipes into the product tanks (or sometimes to send a component back to its tank). Usually pigging is done at the beginning and at the end of each batch, but sometimes it is done in the midst of a batch, e.g. when producing a premix that will be used as an intermediate component.

Pigs are also used in oil and gas pipelines: they are used to clean the pipes but also there are "smart pigs" used to measure things like pipe thickness and corrosion along the pipeline. They usually do not interrupt production, though some product can be lost when the pig is extracted. They can also be used to separate different products in a multiproduct pipeline.

## *Etymology*

Pigs get their name from the squealing sound they make while travelling through a pipeline. (Disputed: 'PIG' is an acronym or backronym derived from the initial letters of the term 'Pipeline Inspection Gauge' or possibly 'Pipeline Inspection Gizmo' or 'Pipeline Internal Geometry' or 'Pipeline Inspection Gadget').

## *Pigging in production environments*

### Product and time saving

A major advantage of piggable systems is the potential resulting product savings. At the end of each product transfer, it is possible to clear out the entire line contents with the pig, either forwards towards the receipt point, or backwards to the source tank. There is no requirement for extensive line flushing.

Without the need for line flushing, pigging offers the additional advantage of a much more rapid and reliable product changeover. Product sampling at the receipt point becomes faster because the interface between products is very clear, and the old method of checking at intervals, until the product is on-specification, is considerably shortened.

Pigging systems can also be operated totally by a programmable logic controller (PLC).

### Environmental issues

Pigging has a significant role to play in reducing the environmental impact of batch operations. Traditionally, the only way that an operator of a batch process could ensure a product was completely cleared from a line was to flush the line with a cleaning agent such as water or a solvent or even the next product. This cleaning agent then had to be subjected to effluent treatment or solvent recovery. If product was used to clear the line, the contaminated finished product was downgraded or dumped. In some cases, the finished product could contain polychlorinated biphenyl (PCB), which has been found to be carcinogenic. All of these problems can now be eliminated due to the very precise interface produced by modern pigging systems.

### Safety considerations

Pigging systems are designed so that the pig is loaded into the launcher, which is pressured up to launch the pig into the pipeline through a kicker line. In some cases, the pig is removed from the pipeline via the receiver at the end of each run. All systems must allow for the receipt of pigs at the launcher, as blockages in the pipeline may require the pigs to be pushed back to the launcher. Most of the time, systems are designed to pig the pipeline in either direction.

The pig is pushed either with an inert gas or a liquid; if pushed by gas, some systems can be adapted in the gas inlet in order to ensure pig's constant speed, whatever the pressure drop is. The pigs must be removed, as many pigs are rented, pigs wear and must be replaced, and cleaning pigs push contaminants from the pipeline such as wax, foreign objects, hydrates, etc, which must be removed from the pipeline. There are inherent risks in opening the barrel to atmosphere and care must be taken to ensure that the barrel is depressured prior to opening. If the barrel is not completely depressured, the pig can be ejected from the barrel and operators have been severely injured when standing in front of an open pig door. When the product is sour, the barrel should be evacuated to a flare system where the sour gas is burnt. Operators should be wearing a self-contained breathing apparatus when working on sour systems.

A few pigging systems utilize a "captive pig", and the pipeline is only opened up very occasionally to check the condition of the pig. At all other times, the pig is shuttled up and down the pipeline at the end of each transfer, and the pipeline itself is never opened up during process operation. These systems are not common.

## Intelligent pigging

Inserting a pig into a natural gas pipeline

Modern intelligent pigs are highly sophisticated instruments that vary in technology and complexity by the intended use and by manufacturer. An intelligent pig, or smart pig, is basically a computer that collects various forms of data during the trip through the pipeline.

The computer part, consisting mostly of electronics, must be sealed to prevent leakage of the pipeline product into the electronics. Sealing is a very important aspect as the products in the pipeline can range from highly basic to highly acidic and can be of extremely high temperature. Many pigs use specific materials according to the product in the pipeline. Power for the electronics is provided by onboard batteries which also must be sealed from the product environment. Recording of data may be by various means ranging from analog tape in a reel-to-reel format, digital tape or solid state memory in more modern digital units.

This technology is used to accomplish the service vary by the service required and the design of the pig, each pigging service provider may have unique and proprietary technologies to accomplish the service. Surface pitting and corrosion, as well as cracks and weld defects in steel/ferrous pipelines are often detected using magnetic flux leakage (MFL) pigs. Other "smart" pigs use electromagnetic acoustic transducers to detect pipe defects. Caliper pigs can measure the "roundness" of the pipeline to determine areas of crushing or other deformations. Some smart pigs can combine technologies such as MFL and Caliper into a single tool.

During the pigging run the pig is unable to directly communicate with the outside world due to the distance underground or underwater and/or materials that the pipe is made of. For example, steel pipelines effectively prevent any reliable radio communications outside the pipe. It is therefore necessary that the pig use internal means to record its own movement during the trip. This may be done by gyroscope-assisted tilt gauges, odometers and other technologies. The pig will record this positional data so that the distance it moves along with any bends can be interpreted later to determine the exact path taken.

Location verification is often accomplished by surface instruments that record the pig's passage by either audible or gravinometric (or other) means. The sensors will record when they detect passage of the pig; this is then compared to the internal record for verification or adjustment. The external sensors may have GPS capability to assist in their location or even to transmit the pig's passage, but the pig itself usually cannot use GPS as it requires being able to "see" (in satellite terminology) the satellites.

After the pigging run has been completed, the positional data is combined with the pipeline evaluation data (corrosion, cracks, etc) to provide a location-specific defect map and characterization. In other words, the combined data will tell the operator the location and type and size of each pipe defect. This is used to judge the severity of the defect and help repair crews locate and repair the defect quickly without having to dig up excessive amounts of pipeline. By evaluating the rate of change of a particular defect over several years, proactive plans can be made to repair the pipeline before any leakage or environmental damage occurs.

### *Pipeline Inspection Gauge*

A pig on display in a section of cutaway pipe, from the Alaska Pipeline

A "Pig" launcher/receiver, belonging to the natural gas pipeline in Switzerland.

A pipeline inspection gauge or "PIG" in the pipeline industry is a tool that is sent down a pipeline and propelled by the pressure of the product in the pipeline itself. There are four main uses for pigs:

1. physical separation between different liquids being transported in pipelines;
2. internal cleaning of pipelines;
3. inspection of the condition of pipeline walls (also known as an Inline Inspection (ILI) tool);
4. capturing and recording geometric information relating to pipelines (e.g. size, position).

The original pigs were made from straw wrapped in wire used for cleaning. They made a squealing noise while traveling through the pipe, sounding to some like a pig squealing. The term "pipeline inspection gauge" was later created as a backronym.

One kind of pig is a soft, bullet shaped polyurethane foam plug that is forced through pipelines to separate products to reduce mixing. There are several types of pigs for cleaning. Some have tungsten studs or abrasive wire mesh on the outside to cut rust, scale, or paraffin deposits off the inside of the pipe. Others are plain plastic covered polyurethane. Pigs cannot be used in pipelines that have butterfly valves.

Inline inspection pigs use various methods for inspecting a pipeline. A sizing pig uses one (or more) notched round metal plates that are used as gauges. The notches allow different parts of the plate to bend when a bore restriction is encountered. More complex systems exist for inspecting various aspects of the pipeline. Intelligent pigs, also called smart pigs, are used to inspect the pipeline with sensors and record the data for later analysis. These pigs use technologies such as MFL and ultrasonics to inspect the pipeline. Intelligent pigs may also use calipers to measure the inside geometry of the pipeline.

In 1961, the first intelligent pig was run by Shell Development. It demonstrated that a self contained electronic instrument could traverse a pipe line while measuring and recording wall thickness. The instrument used electromagnetic fields to sense wall integrity. In 1964 Tuboscope ran the first commercial instrument. It used MFL technology to inspect the bottom portion of the pipeline. The system used a black box similar to those used on aircraft to record the information.

A pig has been used as a plot device in three James Bond films: *Diamonds Are Forever*, where Bond disabled a pig to escape from a pipeline, *The Living Daylights*, where a pig was modified to secretly transport a person through the Iron Curtain, and *The World Is Not Enough*, where a pig was used to move a nuclear weapon through a pipeline.

A pig was also used as a plot device in the *Tony Hillerman* book *The Sinister Pig* where an abandoned pipeline from Mexico to the United States was to use a pig to transport illegal drugs.

Capacitive sensor probes are used in the process of detecting defects in polyethylene pipe gas pipeline. These probes are attached to the pig in which the pig is sent through the polyethylene pipe that will detect any defects in the outside of the pipe wall. This is done by using a triple plate capacitive sensor in which the electrostatic waves are propogated outware through the pipes all. Any change in dielectric material will result in a change in capacitance. Testing was conducted by NETL DOE research lab at the Battelle West Jefferson's Pipeline Simulation Facility (PSF) near Columbus, Ohio.

Chapter 7

# Oil Well and Well Logging

## Oil Well

The pumpjack, such as this one located south of Midland, Texas, is a common sight in West Texas.

An **oil well** is a general term for any boring through the earth's surface that is designed to find and acquire petroleum oil hydrocarbons. Usually some natural gas is produced along with the oil. A well that is designed to produce mainly or only gas may be termed a **gas well**.

## *History*


Oil extraction in Boryslav in Galicia in 1909.

The earliest known oil wells were drilled in China in 347 CE. They had depths of up to about 800 feet (240 m) and were drilled using bits attached to bamboo poles. The oil was burned to evaporate brine and produce salt. By the 10th century, extensive bamboo pipelines connected oil wells with salt springs. The ancient records of China and Japan are said to contain many allusions to the use of natural gas for lighting and heating. Petroleum was known as *burning water* in Japan in the 7th century.

The Middle East's petroleum industry was established by the 8th century, when the streets of the newly constructed Baghdad were paved with tar, derived from petroleum that became accessible from natural fields in the region. Petroleum was distilled by the Persian alchemist Muhammad ibn Zakarīya Rāzi (Rhazes) in the 9th century, producing chemicals such as kerosene in the alembic (*al-ambiq*), and which was mainly used for kerosene lamps. Arab and Persian chemists also distilled crude oil in order to produce flammable products for military purposes. Through Islamic Spain, distillation became available in Western Europe by the 12th century.

Some sources claim that from the 9th century, oil fields were exploited in the area around modern Baku, Azerbaijan, to produce naphtha for the petroleum industry. These fields were described by Marco Polo in the 13th century, who described the output of those oil wells as hundreds of shiploads. When Marco Polo in 1264 visited the Azerbaijani city of Baku, on the shores of the Caspian Sea, he saw oil being collected from seeps. He wrote that "on the confines toward Geirgine there is a fountain from which oil springs in great abundance, inasmuch as a hundred shiploads might be taken from it at one time."

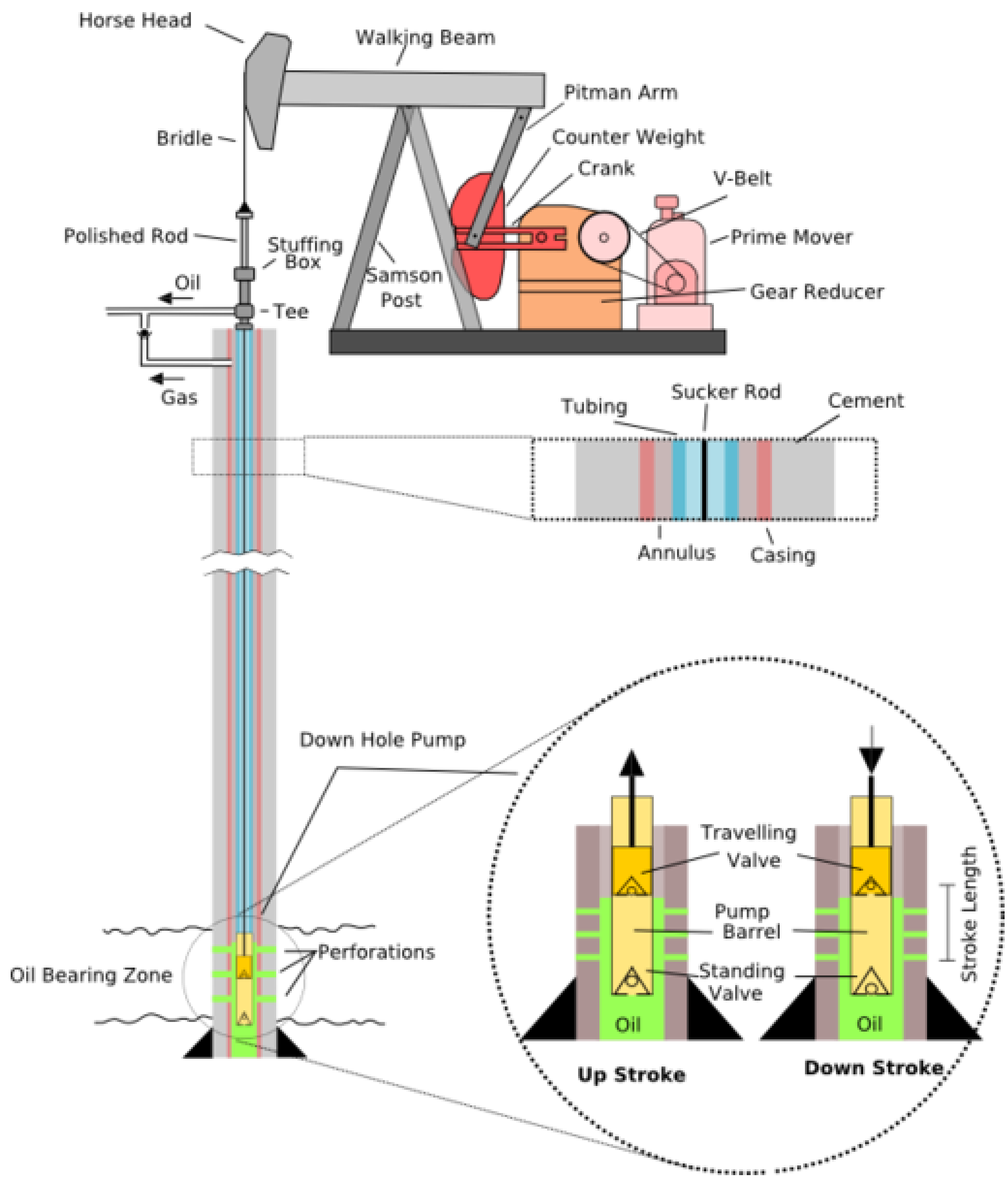

A FOUNTAIN AT BIBI-EIBAT IN FLAMES, BAKU

1904 oil well fire at Bibi-Eibat.

Shallow pits were dug at the Baku seeps in ancient times to facilitate collecting oil, and hand-dug holes up to 35 metres (115 ft) deep were in use by 1594. These holes were essentially oil wells. Apparently 116 of these wells in 1830 produced 3,840 metric tons (about 28000 barrels) of oil. Also, offshore drilling started up at Baku at Bibi-Eibat field in 1846, about the same time that the first offshore oil well was drilled in 1896 at the Summerland Oil Field on the California Coast.

The earliest oil wells in modern times were drilled percussively, by hammering a cable tool into the earth. Soon after, cable tools were replaced with rotary drilling, which could drill boreholes to much greater depths and in less time. The record-depth Kola Borehole used non-rotary mud motor drilling to achieve a depth of over 12,000 metres (39,000 ft). Until the 1970s, most oil wells were vertical, although lithological and mechanical imperfections cause most wells to deviate at least slightly from true vertical. However, modern directional drilling technologies allow for strongly deviated wells which can, given sufficient depth and with the proper tools, actually become horizontal. This is of great value as the reservoir rocks which contain hydrocarbons are usually horizontal, or sub-horizontal; a horizontal wellbore placed in a production zone has more surface area in the production zone than a vertical well, resulting in a higher production rate. The use of deviated and horizontal drilling has also made it possible to reach reservoirs several kilometers or miles away from the drilling location (extended reach drilling), allowing for the production of hydrocarbons located below locations that are either difficult to place a drilling rig on, environmentally sensitive, or populated.

## *Life of a well*




A schematic of a typical oil well being produced by a pumpjack, which is used to produce the remaining recoverable oil after natural pressure is no longer suficient to raise oil to the surface.

The creation and life of a well can be divided up into five segments:

- Planning
- Drilling
- Completion
- Production
- Abandonment

## Drilling

The well is created by drilling a hole 5 to 36 inches (127.0 mm to 914.4 mm) in diameter into the earth with a drilling rig that rotates a drill string with a bit attached. After the hole is drilled, sections of steel pipe (casing), slightly smaller in diameter than the borehole, are placed in the hole. Cement may be placed between the outside of the casing and the borehole. The casing provides structural integrity to the newly drilled wellbore, in addition to isolating potentially dangerous high pressure zones from each other and from the surface.

With these zones safely isolated and the formation protected by the casing, the well can be drilled deeper (into potentially more-unstable and violent formations) with a smaller bit, and also cased with a smaller size casing. Modern wells often have two to five sets of subsequently smaller hole sizes drilled inside one another, each cemented with casing.

Mud log in process, a common way to study the lithology when drilling oil wells.

To drill the well

- The drill bit, aided by the weight of thick walled pipes called "drill collars" above it, cuts into the rock. There are different types of drill bit; some cause the rock to disintegrate by compressive failure, while others shear slices off the rock as the bit turns.

- Drilling fluid, a.k.a. "mud", is pumped down the inside of the drill pipe and exits at the drill bit. Drilling mud is a complex mixture of fluids, solids and chemicals that must be carefully tailored to provide the correct physical and chemical characteristics required to safely drill the well. Particular functions of the drilling mud include cooling the bit, lifting rock cuttings to the surface, preventing destabilisation of the rock in the wellbore walls and overcoming the pressure of fluids inside the rock so that these fluids do not enter the wellbore.
- The generated rock "cuttings" are swept up by the drilling fluid as it circulates back to surface outside the drill pipe. The fluid then goes through "shakers" which strain the cuttings from the good fluid which is returned to the pit. Watching for abnormalities in the returning cuttings and monitoring pit volume or rate of returning fluid are imperative to catch "kicks" early. A "kick" is when the formation pressure at the depth of the bit is more than the hydrostatic head of the mud above, which if not controlled temporarily by closing the blowout preventers and ultimately by increasing the density of the drilling fluid would allow formation fluids and mud to come up through the drill pipe uncontrollably.
- The pipe or drill string to which the bit is attached is gradually lengthened as the well gets deeper by screwing in additional 30-foot (9 m) sections or "joints" of pipe under the kelly or topdrive at the surface. This process is called making a connection. Usually, joints are combined into three joints equaling one stand. Some smaller rigs only use two joints and some rigs can handle stands of four joints.

This process is all facilitated by a drilling rig which contains all necessary equipment to circulate the drilling fluid, hoist and turn the pipe, control downhole, remove cuttings from the drilling fluid, and generate on-site power for these operations.


Modern driller Argentina.

## Completion

After drilling and casing the well, it must be 'completed'. Completion is the process in which the well is enabled to produce oil or gas.

In a cased-hole completion, small holes called perforations are made in the portion of the casing which passed through the production zone, to provide a path for the oil to flow from the surrounding rock into the production tubing. In open hole completion, often 'sand screens' or a 'gravel pack' is installed in the last drilled, uncased reservoir section. These maintain structural integrity of the wellbore in the absence of casing, while still allowing flow from the reservoir into the wellbore. Screens also control the migration of formation sands into production tubulars and surface equipment, which can cause washouts and other problems, particularly from unconsolidated sand formations in offshore fields.

After a flow path is made, acids and fracturing fluids are pumped into the well to fracture, clean, or otherwise prepare and stimulate the reservoir rock to optimally produce hydrocarbons into the wellbore. Finally, the area above the reservoir section of the well is packed off inside the casing, and connected to the surface via a smaller diameter pipe called tubing. This arrangement provides a redundant barrier to leaks of hydrocarbons as well as allowing damaged sections to be replaced. Also, the smaller crossectional area of the tubing produces reservoir fluids at an increased velocity in order to minimize liquid fallback that would create additional back pressure, and shields the casing from corrosive well fluids.

In many wells, the natural pressure of the subsurface reservoir is high enough for the oil or gas to flow to the surface. However, this is not always the case, especially in depleted fields where the pressures have been lowered by other producing wells, or in low permeability oil reservoirs. Installing a smaller diameter tubing may be enough to help the production, but artificial lift methods may also be needed. Common solutions include downhole pumps, gas lift, or surface pump jacks. Many new systems in the last ten years have been introduced for well completion. Multiple packer systems with frac ports or port collars in an all in one system have cut completion costs and improved production, especially in the case of horizontal wells. These new systems allow casings to run into the lateral zone with proper packer/frac port placement for optimal hydrocarbon recovery.

## Production

The production stage is the most important stage of a well's life, when the oil and gas are produced. By this time, the oil rigs and workover rigs used to drill and complete the well have moved off the wellbore, and the top is usually outfitted with a collection of valves called a Christmas tree or Production trees. These valves regulate pressures, control flows, and allow access to the wellbore in case further completion work is needed. From the outlet valve of the production tree, the flow can be connected to a distribution network of pipelines and tanks to supply the product to refineries, natural gas compressor stations, or oil export terminals.

As long as the pressure in the reservoir remains high enough, the production tree is all that is required to produce the well. If the pressure depletes and it is considered economically viable, an artificial lift method mentioned in the completions section can be employed.

Workovers are often necessary in older wells, which may need smaller diameter tubing, scale or paraffin removal, acid matrix jobs, or completing new zones of interest in a shallower reservoir. Such remedial work can be performed using workover rigs – also known as *pulling units* or *completion rigs* – to pull and replace tubing, or by the use of well intervention techniques utilizing coiled tubing. Depending on the type of lift system and wellhead a rod rig or flushby can be used to change a pump without pulling the tubing.

Enhanced recovery methods such as water flooding, steam flooding, or $CO_2$ flooding may be used to increase reservoir pressure and provide a "sweep" effect to push hydrocarbons out of the reservoir. Such methods require the use of injection wells (often chosen from old production wells in a carefully determined pattern), and are used when facing problems with reservoir pressure depletion, high oil viscosity, or can even be employed early in a field's life. In certain cases – depending on the reservoir's geomechanics – reservoir engineers may determine that ultimate recoverable oil may be increased by applying a waterflooding strategy early in the field's development rather than later. Such enhanced recovery techniques are often called "tertiary recovery".

## Abandonment

A well is said to reach an "economic limit" when its production rate does not cover the expenses, including taxes.

The economic limit for oil and gas wells can be expressed using these formulae:

Oil fields:

$$EL_{oil} = \frac{WI \times LOE}{NRI[P_o + (P_g \times GOR)/1{,}000] \times (1 - T)}$$

Gas fields:

$$EL_{gas} = \frac{WI \times LOE}{NRI[(P_o \times Y) + P_g] \times (1 - T)}$$

Where:
$EL_{oil}$ is an oil well's economic limit in oil barrels per month (bbls/month).
$EL_{gas}$ is a gas well's economic limit in thousand standard cubic feet per month (MSCF/month).
$P_o$,$P_g$ are the current prices of oil and gas in dollars per barrels and dollars per MSCF respectively.
*LOE* is the lease operating expenses in dollars per well per month.
*WI* working interest, as a fraction.
*NRI* net revenue interest, as a fraction.
*GOR* gas/oil ratio as bbls/MSCF.
*Y* condensate yield as barrel/million standard cubic feet.
*T* production and severance taxes, as a fraction.

When the economic limit is raised, the life of the well is shortened and proven oil reserves are lost. Conversely, when the economic limit is lowered, the life of the well is lengthened.

When the economic limit is reached, the well becomes a liability and is abandoned. In this process, tubing is removed from the well and sections of well bore are filled with cement to isolate the flow path between gas and water zones from each other, as well as the surface. Completely filling the well bore with cement is costly and unnecessary. The surface around the wellhead is then excavated, and the wellhead and casing are cut off, a cap is welded in place and then buried.

At the economic limit there often is still a significant amount of unrecoverable oil left in the reservoir. It might be tempting to defer physical abandonment for an extended period of time, hoping that the oil price will go up or that new supplemental recovery techniques will be perfected. However, lease provisions and governmental regulations usually require quick abandonment; liability and tax concerns also may favor abandonment.

In theory an abandoned well can be reentered and restored to production (or converted to injection service for supplemental recovery or for downhole hydrocarbons storage), but reentry often proves to be difficult mechanically and not cost effective.

### *Types of wells*


A natural gas well in the southeast Lost Hills Field, California, US.

Fossil-fuel wells come in many varieties. By produced fluid, there can be wells that produce oil, wells that produce oil *and* natural gas, or wells that *only* produce natural gas. Natural gas is almost always a byproduct of producing oil, since the small, light gas carbon chains come out of solution as they undergo pressure reduction from the reservoir to the surface, similar to uncapping a bottle of soda pop where the carbon dioxide effervesces. Unwanted natural gas can be a disposal problem at the well site. If there is not a market for natural gas near the wellhead it is virtually valueless since it must be piped to the end user. Until recently, such unwanted gas was burned off at the wellsite, but due to environmental concerns this practice is becoming less common. Often, unwanted (or 'stranded' gas without a market) gas is pumped back into the reservoir with an 'injection' well for disposal or repressurizing the producing formation. Another solution is to export the natural gas as a liquid. Gas-to-liquid, (GTL) is a developing technology that converts stranded natural gas into synthetic gasoline, diesel or jet fuel through the Fischer-Tropsch process developed in World War II Germany. Such fuels can be transported through conventional pipelines and tankers to users. Proponents claim GTL fuels burn cleaner than comparable petroleum fuels. Most major international oil companies are in advanced development stages of GTL production, e.g. the 140,000 bbl/d (22,000 $m^3$/d) Pearl GTL plant in Qatar, scheduled to come online in 2011. In locations such as the United States with a high natural gas demand, pipelines are constructed to take the gas from the wellsite to the end consumer.

Another obvious way to classify oil wells is by land or offshore wells. There is very little difference in the well itself. An offshore well targets a reservoir that happens to be underneath an ocean. Due to logistics, drilling an offshore well is far more costly than an onshore well. By far the most common type is the onshore well. These wells dot the Southern and Central Great Plains, Southwestern United States, and are the most common wells in the Middle East.

Another way to classify oil wells is by their purpose in contributing to the development of a resource. They can be characterized as:

- *production wells* are drilled primarily for producing oil or gas, once the producing structure and characteristics are determined
- *appraisal wells* are used to assess characteristics (such as flow rate) of a proven hydrocarbon accumulation
- *exploration wells* are drilled purely for exploratory (information gathering) purposes in a new area
- *wildcat wells* are those drilled outside of and not in the vicinity of known oil or gas fields.

At a producing well site, active wells may be further categorised as:

- *oil producers* producing predominantly liquid hydrocarbons, but mostly with some associated gas.
- *gas producers* producing almost entirely gaseous hydrocarbons.
- *water injectors* injecting water into the formation to maintain reservoir pressure or simply to dispose of water produced with the hydrocarbons because even after treatment, it would be too oily and too saline to be considered clean for dumping overboard, let alone into a fresh water source, in the case of onshore wells. Frequently water injection has an element of reservoir management and produced water disposal.
- *aquifer producers* intentionally producing reservoir water for re-injection to manage pressure. This is in effect moving reservoir water from where it is not as useful to where it is more useful. These wells will generally only be used if produced water from the oil or gas producers is insufficient for reservoir management purposes. Using aquifer produced water rather than water from other sources is to preclude chemical incompatibility that might lead to reservoir-plugging precipitates.
- *gas injectors* injecting gas into the reservoir often as a means of disposal or sequestering for later production, but also to maintain reservoir pressure.

**Lahee classification**

- *New Field Wildcat* (NFW) – far from other producing fields and on a structure that has not previously produced.
- *New Pool Wildcat* (NPW) – new pools on already producing structure.

- *Deeper Pool Test* (DPT) – on already producing structure and pool, but on a deeper pay zone.
- *Shallower Pool Test* (SPT) – on already producing structure and pool, but on a shallower pay zone.
- *Outpost* (OUT) – usually two or more locations from nearest productive area.
- *Development Well* (DEV) – can be on the extension of a pay zone, or between existing wells (*Infill*).

### Cost

The cost of a well depends mainly on the daily rate of the drilling rig, the extra services required to drill the well, the duration of the well programme (including downtime and weather time), and the remoteness of the location (logistic supply costs).

The daily rates of offshore drilling rigs vary by their capability, and the market availability. Rig rates reported by industry web service show that the deepwater water floating drilling rigs are over twice that of the shallow water fleet, and rates for jackup fleet can vary by factor of 3 depending upon capability.

With deepwater drilling rig rates in 2010 of around $420,000/day, and similar additional spread costs, a deep water well of duration of 100 days can cost around US$100 million.

With high performance jackup rig rates in 2010 of around $150,000, and similar service costs, a high pressure, high temperature well of duration 100 days can cost about US$30 million.

Onshore wells can be considerably cheaper, particularly if the field is at a shallow depth, where costs range from less than $1 million to $15 million for deep and difficult wells.

The total cost of an oil well mentioned does not include the costs associated with the risk of explosion and leakage of oil. Those costs include the cost of protecting against such disasters, the cost of the cleanup effort, and the hard-to-calculate cost of damage to the company's image.

# Well logging

**Well logging**, also known as **borehole logging** is the practice of making a detailed record (a *well log*) of the geologic formations penetrated by a borehole. The log may be based either on visual inspection of samples brought to the surface (*geological* logs) or on physical measurements made by instruments lowered into the hole (*geophysical* logs). Well logging is done during all phases of a wells development; drilling, completing, producing and abandoning. Mostly in the oil and gas, groundwater, minerals, geothermal, and for environmental and geotechnical studies.

## *Electric or geophysical well logs*

The oil and gas industry records rock and fluid properties to find hydrocarbon zones in the geological formations intersected by a borehole. The logging procedure consists of lowering a 'logging tool' on the end of a wireline into an oil well (or hole) to measure the rock and fluid properties of the formation. An interpretation of these measurements is then made to locate and quantify potential depth zones containing oil and gas (hydrocarbons). Logging tools developed over the years measure the electrical, acoustic, radioactive, electromagnetic, nuclear magnetic resonance, and other properties of the rocks and their contained fluids. Logging is usually performed as the logging tools are pulled out of the hole. This data is recorded either at surface (real-time mode), or downhole (memory mode)to electronic data format and then either a printed record or electronic presentation called a "well log" provided to the client. Well logging is performed at various intervals during the drilling of the well and when the total depth is drilled, which could range in depths from 150 m to 10668 m (500 ft to 35,000 ft) or more.

Electric line is the common term for the armored, insulated cable used to conduct current to downhole tools used for well logging. Electric line can be subdivided into open hole operations and cased hole operations. Other conveyance methods for logging are logging while drilling (LWD), tractor, coiled tubing (real-time and memory), drill pipe conveyed, and slickline (memory, and with new development, some slickline telemetry capability).

Open hole operations, or reservoir evaluation, involves the deployment of tools into a freshly drilled well. As the toolstring traverses the wellbore, the individual tools gather information about the surrounding formations. A typical open hole log will have information about the density, porosity, permeability, lithology, presence of hydrocarbons, and oil and water saturation.

Cased hole operations, or production optimization, focuses of the optimization of the completed oil well through mechanical services and logging technologies. At this point in the well's life, the well is encased in steel pipe, cemented into the well bore and may or may not be producing. A typical cased hole log may show cement quality, production information, formation data. Mechanical services uses jet perforating guns, setting tools, and dump bailors to optimize the flow of hydrocarbons.

## *Wireline tool types*

Typically the wireline tools are cylindrical in shape, usually from 1.5 to 5 inches in diameter. "Open hole" tool combinations can extend to over 100 feet long; "cased hole" tool combinations are often limited in length by the height restrictions imposed by constraints of "lubricator" pipe section required to contain the well pressure while deploying cased hole tools. There are many types of logging tools, ranging from common measurements (pressure and temperature) to advanced rock properties and fracture analysis, fluid properties in the wellbore, or formation properties extending several meters into the rock formation.

1. With sensors without excitation

There are units to measure spontaneous potential (SP), which is a voltage difference between a surface electrode and another electrode located in the downhole instrument, other instruments that measure the natural radiation from natural isotopes of potassium, thorium, etc., to measure pressure and temperature, etc.

2. With sources of excitation and sensors

There are sensor systems consistent with a source of excitation and a sensor. In this type we find acoustic (also called sonic), electric, inductive, magnetic resonance, sensing systems, just to name a few.

3. Instruments that produce some mechanical work, or retrieve a sample of fluid or rock to the surface.

Devices to collect samples of rock, samples of fluid extracted from the rock, and some other mechanical devices.

## Types of electric/electronic logs

There are many types of electric/electronic logs and they can be categorized either by their function or by the technology that they use. "Open hole logs" are run before the oil or gas well is lined with pipe or cased. "Cased hole logs" are run after the well is lined with casing or production pipe.

Electric/electronic logs can also be divided into two general types based on what physical properties they measure. Resistivity logs measure some aspect of the specific resistance of the geologic formation. There are about 17 types of resistivity logs.

Porosity logs measure the fraction or percentage of pore volume in a volume of rock. Most porosity logs use either acoustic or nuclear technology. Acoustic logs measure characteristics of sound waves propagated through the well-bore environment. Nuclear logs utilize nuclear reactions that take place in the downhole logging instrument or in the formation. Nuclear logs include density logs and neutron logs, as well as gamma ray logs which are used for correlation. The basic principle behind the use of nuclear technology is that a neutron source placed near the formation of which the porosity is required to be measured will result in neutrons being scattered by the hydrogen atoms, largely those present in the formation fluid. Since there is little difference in the neutrons scattered by hydrocarbons or water, the porosity measured gives a figure close to the true physical porosity whereas the figure obtained from electrical resistivity measurements is that due to the conductive formation fluid. The difference between neutron porosity and electrical porosity measurements therefore indicates the presence of hydrocarbons in the formation fluid.

## History

Conrad and Marcel Schlumberger, who founded Schlumberger Limited in 1926, are considered the inventors of electric well logging. Conrad developed the Schlumberger array, which was a technique for prospecting for metal ore deposits, and the brothers adopted that surface technique to subsurface applications. On September 5, 1927, a crew working for Schlumberger lowered an electric sonde or tool down a well in Pechelbronn, Alsace, France creating the first well log. In modern terms, the first log was a resistivity log that could be described as 3.5-meter upside-down lateral log.

In 1931, Henri George Doll and G. Dechatre, working for Schlumberger, discovered that the galvanometer wiggled even when no current was being passed through the logging cables down in the well. This led to the discovery of the spontaneous potential (SP) which was as important as the ability to measure resistivity. The SP effect was produced naturally by the borehole mud at the boundaries of permeable beds. By simultaneously recording SP and resistivity, loggers could distinguish between permeable oil-bearing beds and impermeable nonproducing beds.

In 1940, Schlumberger invented the spontaneous potential dipmeter; this instrument allowed the calculation of the dip and direction of the dip of a layer. The basic dipmeter was later enhanced by the resistivity dipmeter (1947) and the continuous resistivity dipmeter (1952).

Oil-based mud (OBM) was first used in Rangely Field, Colorado in 1948. Normal electric logs require a conductive or water-based mud, but OBMs are nonconductive. The solution to this problem was the induction log, developed in the late 1940s.

The introduction of the transistor and integrated circuits in the 1960s made electric logs vastly more reliable. Computerization allowed much faster log processing, and dramatically expanded log data-gathering capacity. The 1970s brought more logs and computers. These included combo type logs where resistivity logs and porosity logs were recorded in one pass in the borehole.

The two types of porosity logs (acoustic logs and nuclear logs) date originally from the 1940s. Sonic logs grew out of technology developed during World War II. Nuclear logging has supplemented acoustic logging, but acoustic or sonic logs are still run on some combination logging tools.

Nuclear logging was initially developed to measure the natural gamma radiation emitted by underground formations. However, the industry quickly moved to logs that actively bombard rocks with nuclear particles. The gamma ray log, measuring the natural radioactivity, was introduced by Well Surveys Inc. in 1939, and the WSI neutron log came in 1941. The gamma ray log is particularly useful as shale beds which often provide a relatively low permeability cap over hydrocarbon reservoirs usually display a higher level of gamma radiation. These logs were important because they can be used in cased wells (wells with production casing). WSI quickly became part of Lane-Wells. During World War II, the US Government gave a near wartime monopoly on open-hole logging to Schlumberger, and a monopoly on cased-hole logging to Lane-Wells. Nuclear logs continued to evolve after the war.

The nuclear magnetic resonance log was developed in 1958 by Borg Warner. Initially the NMR log was a scientific success but an engineering failure. However, the development of a continuous NMR logging tool by Numar (now a subsidiary of Halliburton) is a promising new technology.

Many modern oil and gas wells are drilled directionally. At first, loggers had to run their tools somehow attached to the drill pipe if the well was not vertical. Modern techniques now permit continuous information at the surface. This is known as logging while drilling (LWD) or measurement-while-drilling (MWD). MWD logs use mud pulse technology to transmit data from the tools on the bottom of the drillstring to the processors at the surface.

## Logging while drilling

In the 1980s, a new technique, logging while drilling (LWD), was introduced which provided similar information about the well. Instead of sensors being lowered into the well at the end of wireline cable, the sensors are integrated into the drill string and the measurements are made while the well is being drilled. While wireline well logging occurs after the drill string is removed from the well, LWD measures geological parameters while the well is being drilled. However, because there are no wires to the surface, data are recorded downhole and retrieved when the drill string is removed from the hole. A small subset of the measured data can also be transmitted to the surface in real time via pressure pulses in the well's mud fluid column. This mud telemetry method provides a bandwidth of much less than 100 bits per second, although, as drilling through rock is a fairly slow process, data compression techniques mean that this is an ample bandwidth for real-time delivery of information.

## Logging measurement types

Logging measurements are quite sophisticated. The prime target is the measurement of various geophysical properties of the subsurface rock formations. Of particular interest are porosity, permeability, and fluid content. Porosity is the proportion of fluid-filled space found within the rock. It is this space that contains the oil and gas. Permeability is the ability of fluids to flow through the rock. The higher the porosity, the higher the possible oil and gas content of a rock reservoir. The higher the permeability, the easier for the oil and gas to flow toward the wellbore. Logging tools provide measurements that allow for the mathematical interpretation of these quantities.

Beyond just the porosity and permeability, various logging measurements allow the interpretation of what kinds of fluids are in the pores—oil, gas, brine. In addition, the logging measurements are used to determine mechanical properties of the formations. These mechanical properties determine what kind of enhanced recovery methods may be used (tertiary recovery) and what damage to the formation (such as erosion) is to be expected during oil and gas production.

The types of instruments used in well logging are quite broad. The first logging measurements consisted of basic electrical resistivity logs and spontaneous potential (SP) logs, introduced by the Schlumberger brothers in the 1920s. Tools later became available to estimate porosity via sonic velocity and nuclear measurements. Tools are now more specialized and better able to resolve fine details in the formation. Radiofrequency transmission and coupling techniques are used to determine electrical conductivity of fluid (brine is more conductive than oil or gas). Sonic transmission characteristics (pressure waves) determine mechanical integrity. Nuclear magnetic resonance (NMR) can determine the properties of the hydrogen atoms in the pores (surface tension, etc.). Nuclear scattering (radiation scattering), spectrometry and absorption measurements can determine density and elemental analysis or composition. High resolution electrical or acoustical imaging logs are used to visualize the formation, compute formation dip, and analyze thinly-bedded and fractured reservoirs.

In addition to sensor-based measurements above, robotic equipment can sample formation fluids which may then be brought to the surface for laboratory examination. Also, controlled flow measurements can be used to determine in situ viscosity, water and gas cut (percentage), and other fluid and production parameters.

## *Geological logs*

Geological logs use data collected at the surface, rather than by downhole instruments. The geological logs include *drilling time logs*, *core logs*, *sample logs*, and *mud logs*. Mud logs have become the oil industry standard.

*Drilling time logs* record the time required to drill a given thickness of rock formation. A change in the drilling rate or penetration rate usually means a change in the type of rock penetrated by the bit. The drilling time is expressed as minutes per foot, while the rate of penetration is usually expressed as feet per hour. Therefore, drilling time is the inverse of penetration rate.

*Sample logs* are made by examining cuttings, which are bits of rock circulated to the surface by the drilling mud in rotary drilling. The cuttings have traveled up the wellbore suspended in the drilling fluid or mud which was pumped into the wellbore via the drill string/pipe and they return to the surface via the annulus, then to the shale shakers via the flow line. Cuttings are then separated from the drilling fluid as they move across the shale shakers and are sampled at regular depth intervals. These rock samples are analyzed and described by the wellsite geologist or mudlogger.

*Mud logs* are prepared by a mud logging company contracted by the operating company. One parameter a typical mud log displays is the formation gas (gas units or ppm). "The gas recorder usually is scaled in terms of arbitrary gas units, which are defined differently by the various gas-detector manufactures. In practice, significance is placed only on relative changes in the gas concentrations detected." The current industry standard mud log normally includes real-time drilling parameters such as rate of penetration (ROP), lithology, gas hydrocarbons, flow line temperature (temperature of the drilling fluid) and chlorides but may also include mud weight, estimated pore pressure and corrected d-exponent (corrected drilling exponent) for a pressure pack log. Other information that is normally notated on a mud log include lithology descriptions, directional data (deviation surveys), weight on bit, rotary speed, pump pressure, pump rate, viscosity, drill bit info, casing shoe depths, formation tops, mud pump info, to name just a few.

## *Wireline log*

A continuous measurement of formation properties with electrically powered instruments to infer properties and make decisions about drilling and production operations. The record of the measurements, typically a long strip of paper, is also called a log. Measurements include electrical properties (resistivity at various frequencies), sonic properties, active and passive nuclear measurements, dimensional measurements of the wellbore, formation fluid sampling, formation pressure measurement, wireline-conveyed sidewall coring tools, and others. In wireline measurements, the logging tool (or probe) is lowered into the open wellbore on a multiple conductor, contra-helically armored wireline. Once lowered to the bottom of the interval of interest, the measurements are taken on the way out of the wellbore. This is done in an attempt to maintain tension on the cable (which stretches) as constant as possible for depth correlation purposes. (The exception to this practice is in certain hostile environments in which the tool electronics might not survive the temperatures on bottom for the amount of time it takes to lower the tool and then record measurements while pulling the tool up the hole. In this case, "down log" measurements might actually be conducted on the way into the well, and repeated on the way out if possible.) Most wireline measurements are recorded continuously even though the probe is moving. Certain fluid sampling and pressure-measuring tools require that the probe be stopped, increasing the chance that the probe or the cable might become stuck. LWD tools take measurements in much the same way as wireline-logging tools, except that the measurements are taken by a self-contained tool near the bottom of the bottomhole assembly and are recorded downward (as the well is deepened) rather than upward from the bottom of the hole (as wireline logs are recorded).

## *Memory log*

This method of data acquisition involves recording the sensor data into a down hole memory, rather than transmitting "Real Time" to surface. There are some advantages and disadvantages to this memory option.

- The tools can be conveyed into wells where the trajectory is deviated or extended beyond the reach of conventional Electric Wireline cables. This can involve a combination of weight to strength ratio of the electric cable over this extended reach. In such cases the memory tools can be conveyed on Pipe or Coil Tubing.
- The type of sensors are limited in comparison to those used on Electric Line, and tend to be focussed on the cased hole,production stage of the well. Although there are now developed some memory "Open Hole" compact formation evaluation tool combinations. These tools can be deployed and carried downhole concealed internally in drill pipe to protect them from damage while running in the hole, and then "Pumped" out the end at depth to initate logging. Other basic open hole formation evaluation memory tools are available for use in "Commodity" markets on slickline to reduce costs and operating time.
- In cased hole operation there is normally a "Slick Line" intervention unit. This uses a solid mechanical wire (.82 - .125 inches in OD), to manipulate or otherwise carry out operations in the well bore completion system. Memory operations are

often carried out on this Slickline conveyance in preference to mobilizing a full service Electric Wireline unit.

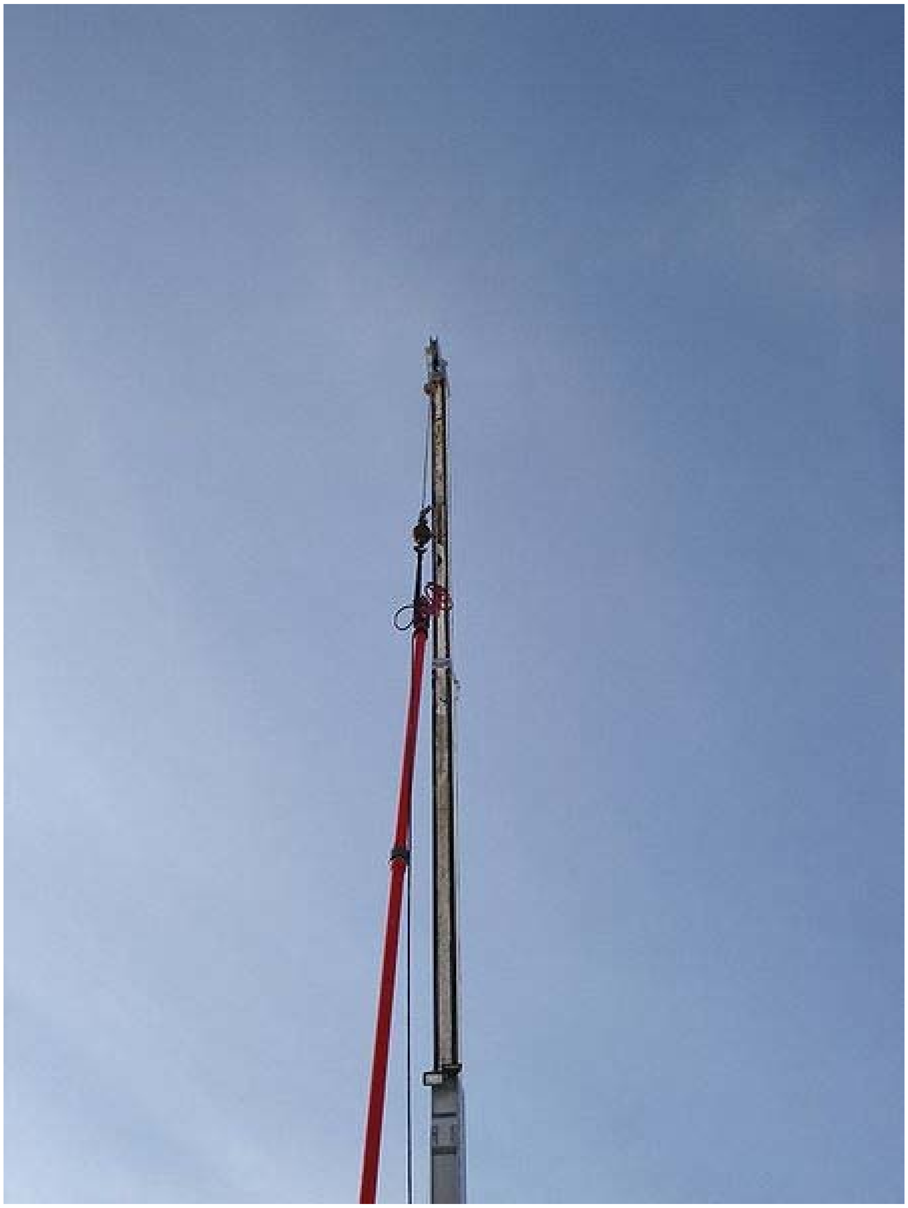
- Since the results are not known until returned to surface, any realtime well dynamic changes cannot be monitored real time. This limits the ability to modify or change the well down hole production conditions accuratly during the memory logging by changing the surface production rates. Something that is often done in Eletric Line operations.
- Failure during recording is not known until the memory tools are retrieved. This loss of data can be a major issue on large offshore (expensive) locations. On land locations (e.g. South Texas, US) where there is what is called a "Commodity" Oil service sector, where logging often is without the rig infrastructure. this is less problematic, and logs are often run again without issue.

## *Information use*

In the oil industry, the well and mud logs are usually transferred in 'real time' to the operating company, which uses these logs to make operational decisions about the well, to correlate formation depths with surrounding wells, and to make interpretations about the quantity and quality of hydrocarbons present. Specialists involved in well log interpretation are called log analysts.

### *Well logging images*

Wireline attached to top of Christmas Tree



Oil Well Top of Wireline

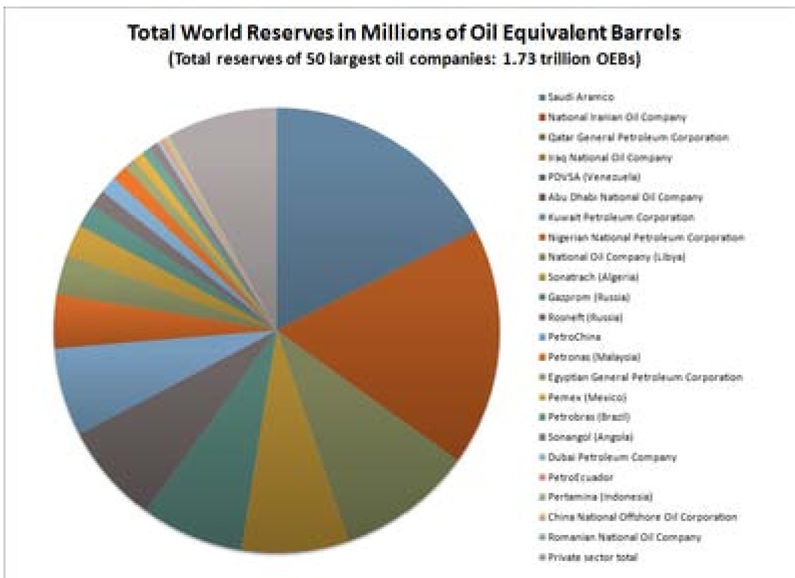

Wireline Truck with drum (inside)

Wax being removed off a wireline wax knife

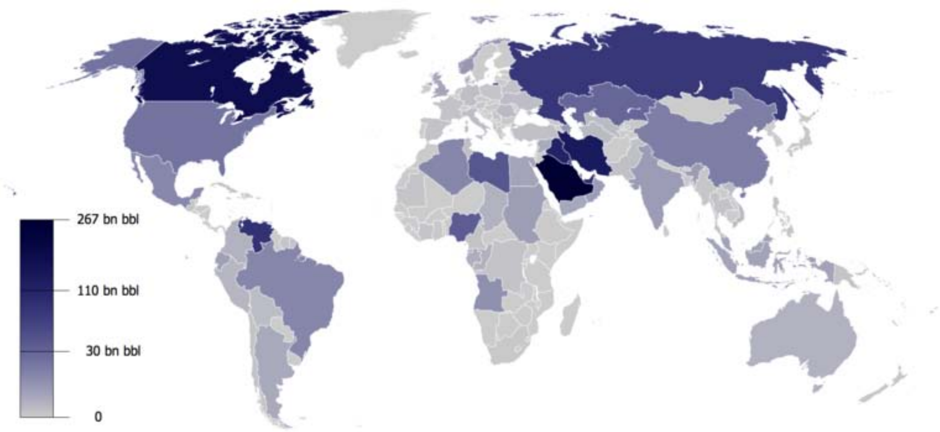
BO shifting tool

## Chapter 8

# Petroleum Industry




The distribution of oil and natural gas reserves among the world's 50 largest oil companies. The reserves of the privately owned companies are grouped together. The oil produced by the "supermajor" companies accounts for less than 15% of the total world supply. Over 80% of the world's reserves of oil and natural gas are controlled by national oil companies. Of the world's 20 largest oil companies, 15 are state-owned.




World oil reserves, 2009.

The **petroleum industry** includes the global processes of exploration, extraction, refining, transporting (often by oil tankers and pipelines), and marketing petroleum products. The largest volume products of the industry are fuel oil and gasoline (petrol). Petroleum is also the raw material for many chemical products, including pharmaceuticals, solvents, fertilizers, pesticides, and plastics. The industry is usually divided into three major components: upstream, midstream and downstream. Midstream operations are usually included in the downstream category.

Petroleum is vital to many industries, and is of importance to the maintenance of industrial civilization itself, and thus is a critical concern for many nations. Oil accounts for a large percentage of the world's energy consumption, ranging from a low of 32% for Europe and Asia, up to a high of 53% for the Middle East.

Other geographic regions' consumption patterns are as follows: South and Central America (44%), Africa (41%), and North America (40%). The world consumes 30 billion barrels (4.8 $km^3$) of oil per year, with developed nations being the largest consumers. The United States consumed 25% of the oil produced in 2007. The production, distribution, refining, and retailing of petroleum taken as a whole represents the world's largest industry in terms of dollar value.

Governments such as the United States government provide a heavy public subsidy to petroleum companies, with major tax breaks at virtually every stage of oil exploration and extraction, including for the costs of oil field leases and drilling equipment.

## *History*

### Natural history

Petroleum is a naturally occurring liquid found in rock formations. It consists of a complex mixture of hydrocarbons of various molecular weights, plus other organic compounds. It is generally accepted that oil, formed mostly from the carbon rich remains of ancient plankton after exposure to heat and pressure in the Earth's crust over hundreds of millions of years. Over time, the decayed residue was covered by layers of mud and silt, sinking further down into the Earth's crust and preserved there between hot and pressured layers, gradually transforming into oil reservoirs.

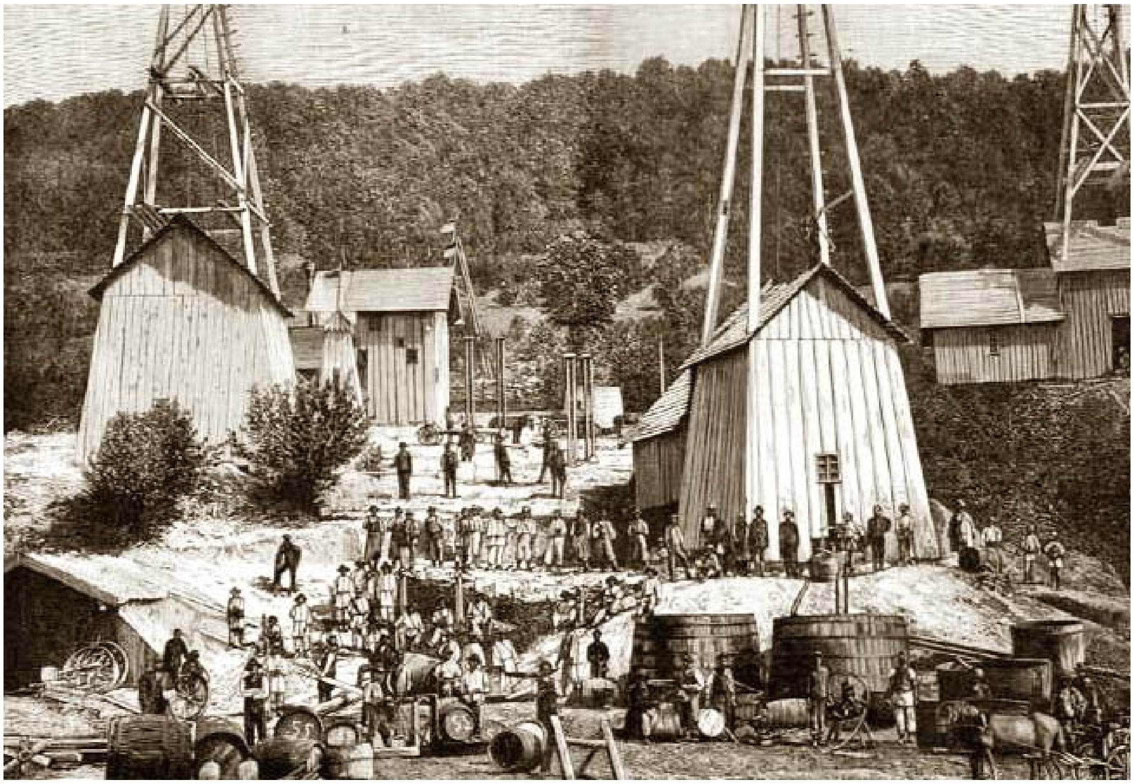
## Early history

Petroleum in an unrefined state has been utilized by humans for over 5000 years. Oil in general has been used since early human history to keep fires ablaze, and also for warfare. Ancient Persian language tablets indicate the medicinal and lighting uses of petroleum in the upper echelons of their society. Ancient China was also known to burn skimmed oil for light.

An early petroleum industry was established in the 8th century, when the streets of Baghdad were paved with tar, derived from petroleum through destructive distillation. In the 9th century, oil fields were exploited in the area around modern Baku, Azerbaijan, to produce naphtha. These fields were described by al-Masudi in the 10th century, and by Marco Polo in the 13th century, who described the output of those oil wells as hundreds of shiploads. Petroleum was distilled by al-Razi in the 9th century, producing chemicals such as kerosene in the alembic, which he used to invent kerosene lamps for use in the oil lamp industry.

Its importance in the world economy evolved slowly, with whale oil used for lighting into the 19th century, and wood and coal used for heating and cooking well into the 20th Century. A petroleum industry emerged in North America in Canada and the United States. The Industrial Revolution generated an increasing need for energy which was fueled mainly by coal, with other sources including whale oil. However, it was discovered that kerosene could be extracted from crude oil and used as a light and heating fuel. Petroleum was in great demand, and by the twentieth century had become the most valuable commodity traded on the world market.

## Modern history



Galician oil wells

Imperial Russia produced 3,500 tons of oil in 1825 and doubled its output by mid-century. After oil drilling began in what is now Azerbaijan in 1848, two large pipelines were built in the Russian Empire: the 833 km long pipeline to transport oil from the Caspian to the Black Sea port of Batumi (Baku-Batumi pipeline), completed in 1906, and the 162 km long pipeline to carry oil from Chechnya to the Caspian.

At the turn of the 20th century, Imperial Russia's output of oil, almost entirely from the Apsheron Peninsula, accounted for half of the world's production and dominated international markets. Nearly 200 small refineries operated in the suburbs of Baku by 1884. As a side effect of these early developments, the Apsheron Peninsula emerged as the world's "oldest legacy of oil pollution and environmental negligence." In 1878, Ludvig Nobel and his Branobel company "revolutionized oil transport" by commissioning the first oil tanker and launching it on the Caspian Sea.

The first modern oil refineries were built by Ignacy Łukasiewicz near Jasło (then in the dependent Kingdom of Galicia and Lodomeria in Central European Galicia), Poland from 1854–56. These were initially small as demand for refined fuel was limited. The refined products were used in artificial asphalt, machine oil and lubricants, in addition to Łukasiewicz's kerosene lamp. As kerosene lamps gained popularity, the refining industry grew in the area.

The first large oil refinery opened at Ploiești, Romania in 1856.

The first oil drilling in the United States began in 1859, when oil was successfully drilled in Titusville, Pennsylvania. In the first quarter of the 20th century, the United States overtook Russia as the world's largest oil producer.

By the 1920s, oil fields had been established in many countries including Canada, Poland, Sweden, the Ukraine, the United States, and Venezuela.

In the early 1930s the Texas Company developed the first mobile steel barges for drilling in the brackish coastal areas of the Persian Gulf.

In 1937 Pure Oil Company (now part of Chevron Corporation) and its partner Superior Oil Company (now part of ExxonMobil Corporation) used a fixed platform to develop a field in 14 feet of water, one mile offshore of Calcasieu Parish, Louisiana.

In early 1947 Superior Oil erected a drilling/production oil platform in 20 ft of water some 18 miles off Vermilion Parish, Louisiana. But it was Kerr-McGee Oil Industries (now Anadarko Petroleum Corporation), as operator for partners Phillips Petroleum (ConocoPhillips) and Stanolind Oil & Gas (BP), that completed its historic Ship Shoal Block 32 well in October 1947, months before Superior actually drilled a discovery from their Vermilion platform farther offshore. In any case, that made Kerr-McGee's well the first oil discovery drilled out of sight of land.

After World War II ended, the countries of the Middle East took the lead in oil production from the United States.

## *Industry structure*

The American Petroleum Institute divides the petroleum industry into five sectors:

- upstream (exploration, development and production of crude oil or natural gas)
- downstream (oil tankers, refiners, retailers and consumers)
- pipeline
- marine
- service and supply

Oil companies used to be classified by sales as *"supermajors"* (BP, Chevron, ExxonMobil, ConocoPhillips, Shell, Eni and Total S.A.), *"majors,"* and *"independents" or "jobbers."* In recent years however, National Oil Companies (NOC, as opposed to IOC, International Oil Companies) have come to control the rights over the largest oil reserves; by this measure the top ten companies all are NOC. The following table shows the ten largest oil companies ranked by reserves and by production.

Top 10 largest world oil companies by reserves and production

| Rank | Company | Worldwide Liquids Reserves ($10^9$ bbl) | Worldwide Natural Gas Reserves ($10^{12}$ $ft^3$) | Total Reserves in Oil Equivalent Barrels ($10^9$ bbl) | Company | Production ($10^6$ bbl/d) |
|---|---|---|---|---|---|---|
| 1 | Saudi Aramco | 260 | 254 | 303 | Saudi Aramco | 11.0 |
| 2 | National Iranian Oil Company | 138 | 948 | 300 | National Iranian Oil Company | 4.0 |
| 3 | Qatar Petroleum | 15 | 905 | 170 | Kuwait Petroleum Corporation | 3.7 |
| 4 | Iraq National Oil Company | 116 | 120 | 134 | Iraq National Oil Company | 2.7 |
| 5 | Petróleos de Venezuela | 99 | 171 | 129 | Petróleos de Venezuela | 2.6 |
| 6 | Abu Dhabi National Oil Company | 92 | 199 | 126 | Abu Dhabi National Oil Company | 2.6 |
| 7 | Kuwait Petroleum Corporation | 102 | 56 | 111 | Petróleos Mexicanos | 2.5 |
| 8 | Nigerian National Petroleum Corporation | 36 | 184 | 68 | Nigerian National Petroleum Corporation | 2.3 |
| 9 | Libya NOC | 41 | 50 | 50 | Libya NOC | 2.1 |
| 10 | Sonatrach | 12 | 159 | 39 | Lukoil | 1.9 |

Most upstream work in the oil field or on an oil well is contracted out to drilling contractors and oil field service companies.

### *Public subsidy*

The United States government provides a large subsidy to oil companies, with major tax breaks at virtually every stage of oil exploration and extraction. Capital expenses, including the costs of oil field leases and drilling equipment, are taxed at an effective rate of nine percent, which is a much lower rate than the 25% rate for general business taxes and lower than the taxes of virtually any other industry, according to a 2005 study by the non-partisan Congressional Budget Office. For example, while the Deepwater Horizon oil rig was registered in the Marshall Islands, since registering off-shore lowered the U.S. tax liability, the U.S. government was giving the rig's owner, British Petroleum (BP), a major tax break when BP leased the rig: 70% of the rent was written off in the form of a tax break used only by the oil industry, for a tax deduction of more than $225,000 per day from the day the lease began.

### *Environmental impact and future shortages*

Some petroleum industry operations have been responsible for water pollution through by-products of refining and oil spills.

The combustion of fossil fuels produces greenhouse gases and other air pollutants as by-products. Pollutants include nitrogen oxides, sulphur dioxide, volatile organic compounds and heavy metals.

As petroleum is a non-renewable natural resource the industry is faced with an inevitable eventual depletion of the world's oil supply. The BP Statistical Review of World Energy 2007 listed the reserve/production ratio for proven resources worldwide. The study placed the prospective life span of proven reserves in the Middle East at 79.5 years, Latin America at 41.2 years and North America at only 12 years.

The Hubbert peak theory, which introduced the concept of peak oil, questions the sustainability of oil production. It suggests that after a peak in oil production rates, a period of oil depletion will ensue. Since virtually all economic sectors rely heavily on petroleum, peak oil could lead to a partial or complete failure of markets.

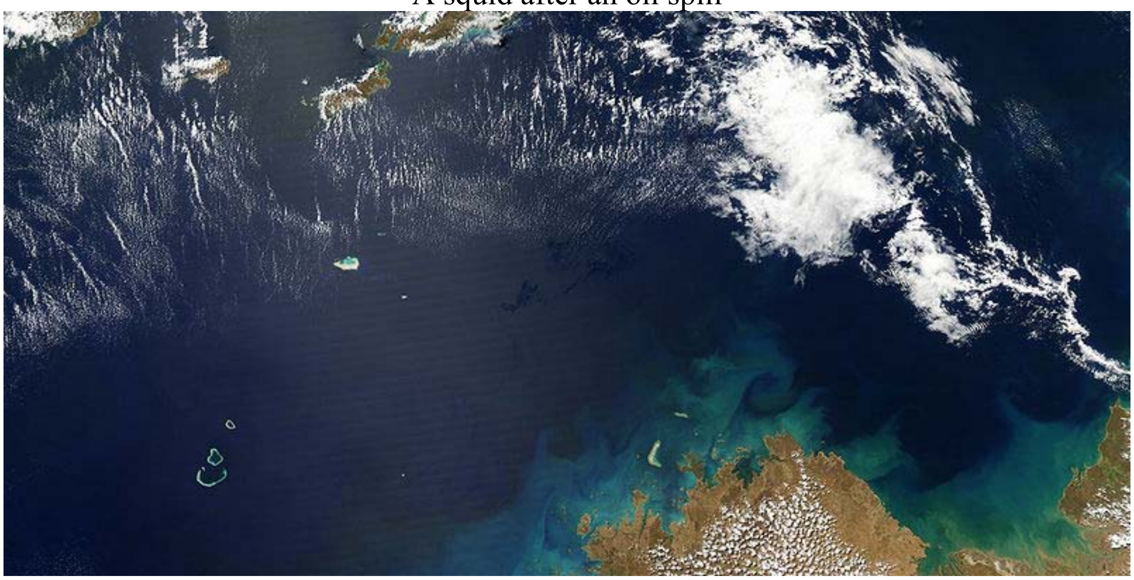
According to research by IBISWorld, biofuels (primarily ethanol, but also biodiesel) will continue to supplement petroleum. However output levels are low, and these fuels will not displace local oil production. More than 90% of the ethanol used in the US is blended with gasoline to produce a 10% ethanol mix, lifting the oxygen content of the fuel.

Chapter 9

# Oil Spill


Deepwater Horizon oil spill on June 25, 2010.

A squid after an oil spill



Oil Sick from the Montara oil spill in the Timor Sea, September, 2009.

An **oil spill** is a release of a liquid petroleum hydrocarbon into the environment due to human activity, and is a form of pollution. The term often refers to marine oil spills, where oil is released into the ocean or coastal waters. Oil spills include releases of crude oil from tankers, offshore platforms, drilling rigs and wells, as well as spills of refined petroleum products (such as gasoline, diesel) and their by-products, and heavier fuels used by large ships such as bunker fuel, or the spill of any oily white substance refuse or waste oil. Spills may take months or even years to clean up.

Oil also enters the marine environment from natural oil seeps. Public attention and regulation has tended to focus most sharply on seagoing oil tankers.

### *Environmental effects*

Surf Scoter covered in oil as a result of the 2007 San Francisco Bay oil spill. Less than 1% of oil soaked birds survive, even after cleaning.

The oil penetrates into the structure of the plumage of birds, reducing its insulating ability, thus making the birds more vulnerable to temperature fluctuations and much less buoyant in the water. It also impairs or disables birds' flight abilities to forage and escape from predators. As they attempt to preen, birds typically ingest oil that covers their feathers, causing kidney damage, altered liver function, and digestive tract irritation. This and the limited foraging ability quickly causes dehydration and metabolic imbalances. Hormonal balance alteration including changes in luteinizing protein can also result in some birds exposed to petroleum.

Most birds affected by an oil spill die unless there is human intervention. Marine mammals exposed to oil spills are affected in similar ways as seabirds. Oil coats the fur of Sea otters and seals, reducing its insulation abilities and leading to body temperature fluctuations and hypothermia. Ingestion of the oil causes dehydration and impaired digestions. Because oil floats on top of water, less sunlight penetrates into the water, limiting the photosynthesis of marine plants and phytoplankton. This, as well as decreasing the fauna populations, affects the food chain in the ecosystem. There are three kinds of oil-consuming bacteria. Sulfate-reducing bacteria (SRB) and acid-producing bacteria are anaerobic, while general aerobic bacteria (GAB) are aerobic. These bacteria occur naturally and will act to remove oil from an ecosystem, and their biomass will tend to replace other populations in the food chain.

## *Cleanup and recovery*

Clean-up efforts after the Exxon Valdez oil spill.

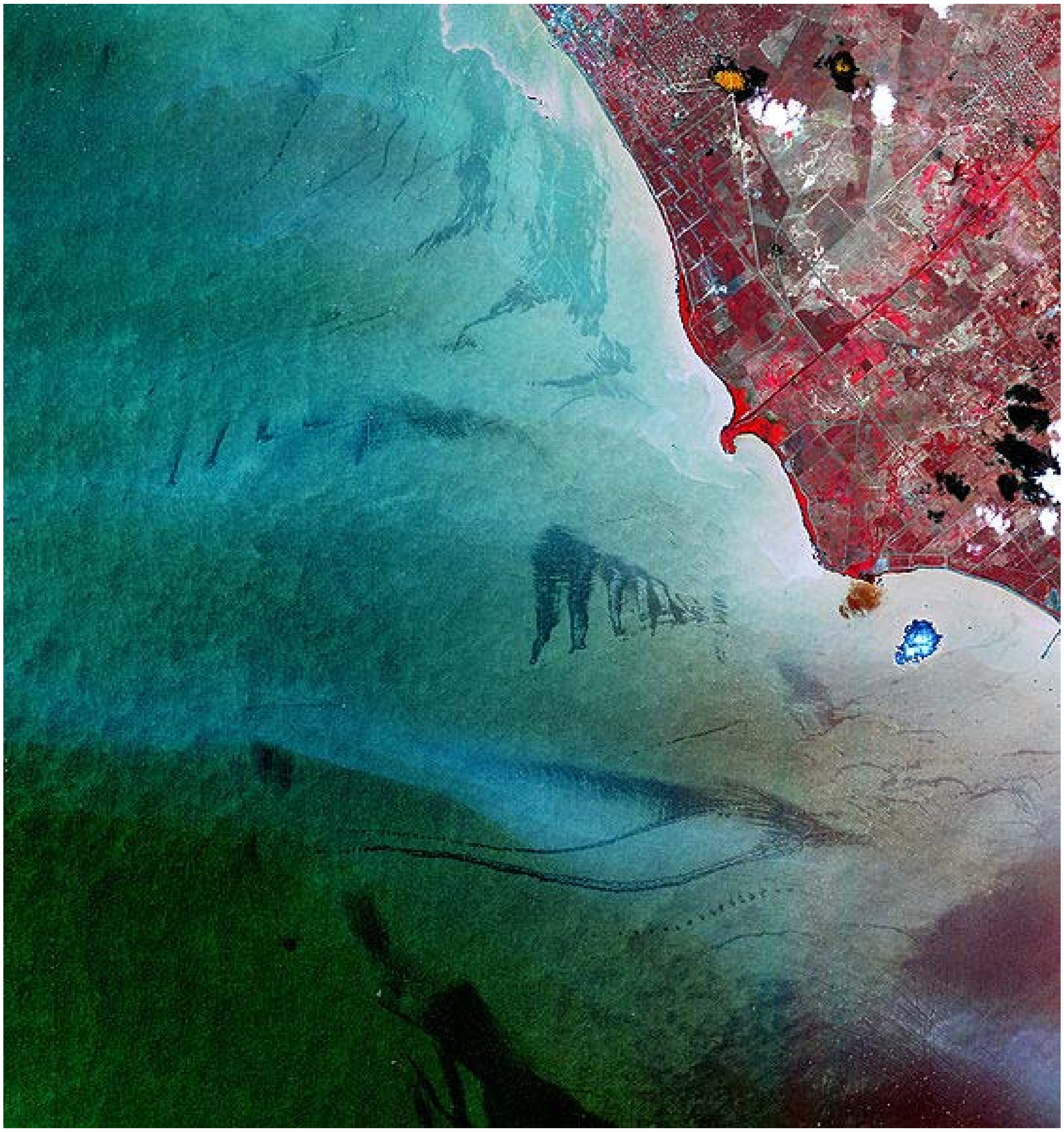
A US Navy oil spill response team drills with a "Harbour Buster high-speed oil containment system".

Cleanup and recovery from an oil spill is difficult and depends upon many factors, including the type of oil spilled, the temperature of the water (affecting evaporation and biodegradation), and the types of shorelines and beaches involved.

Methods for cleaning up include:

- Bioremediation: use of microorganisms or biological agents to break down or remove oil.
- Bioremediation Accelerator: Oleophilic, hydrophobic chemical, containing no bacteria, which chemically and physically bonds to both soluble and insoluble hydrocarbons. The bioremedation accelerator acts as a herding agent in water and on the surface, floating molecules to the surface of the water, including solubles such as phenols and BTEX, forming gel-like agglomerations. Undetectable levels of hydrocarbons can be obtained in produced water and manageable water columns. By overspraying sheen with bioremediation accelerator, sheen is eliminated within minutes. Whether applied on land or on water, the nutrient-rich emulsion creates a bloom of local, indigenous, pre-existing, hydrocarbon-consuming bacteria. Those specific bacteria break down the hydrocarbons into water and carbon dioxide, with EPA tests showing 98% of alkanes biodegraded in 28 days; and aromatics being biodegraded 200 times faster than in nature they also sometimes use the hydrofireboom to clean the oil up by taking it away from most of the oil and burning it.

- Controlled burning can effectively reduce the amount of oil in water, if done properly. But it can only be done in low wind, and can cause air pollution.



Oil slicks on Lake Maracaibo.

Volunteers cleaning up the aftermath of the Prestige oil spill.

- Dispersants act as detergents, clustering around oil globules and allowing them to be carried away in the water. This improves the surface aesthetically, and mobilizes the oil. Smaller oil droplets, scattered by currents, may cause less harm and may degrade more easily. But the dispersed oil droplets infiltrate into deeper water and can lethally contaminate coral. Recent research indicates that some dispersants are toxic to corals.
- Watch and wait: in some cases, natural attenuation of oil may be most appropriate, due to the invasive nature of facilitated methods of remediation, particularly in ecologically sensitive areas such as wetlands.
- Dredging: for oils dispersed with detergents and other oils denser than water.
- Skimming: Requires calm waters
- Solidifying: Solidifiers are composed of dry hydrophobic polymers that both adsorb and absorb. They clean up oil spills by changing the physical state of spilled oil from liquid to a semi-solid or a rubber-like material that floats on water. Solidifiers are insoluble in water, therefore the removal of the solidified oil is easy and the oil will not leach out. Solidifiers have been proven to be relatively non-toxic to aquatic and wild life and have been proven to suppress harmful vapors commonly associated with hydrocarbons such as Benzene, Xylene, Methyl Ethyl, Acetone and Naphtha. The reaction time for solidification of oil is controlled by the surf area or size of the polymer as well as the viscosity of the oil. Some solidifier product manufactures claim the solidified oil can be disposed of in landfills, recycled as an additive in asphalt or rubber products, or burned as a low ash fuel. A solidifier called C.I.Agent (manufactured by C.I.Agent Solutions of Louisville, Kentucky) is being used by BP in granular form as well as in Marine and Sheen Booms on Dauphin Island, AL and Fort Morgan, MS to aid in the Deepwater Horizon oil spill cleanup.
- Vacuum and centrifuge: oil can be sucked up along with the water, and then a centrifuge can be used to separate the oil from the water - allowing a tanker to be filled with near pure oil. Usually, the water is returned to the sea, making the process more efficient, but allowing small amounts of oil to go back as well. This issue has hampered the use of centrifuges due to a United States regulation limiting the amount of oil in water returned to the sea.

Equipment used includes:

- Booms: large floating barriers that round up oil and lift the oil off the water
- Skimmers: skim the oil
- Sorbents: large absorbents that absorb oil
- Chemical and biological agents: helps to break down the oil
- Vacuums: remove oil from beaches and water surface
- Shovels and other road equipments: typically used to clean up oil on beaches

## Prevention

- Seafood Sensory Training- in an effort to detect oil in seafood, inspectors and regulators are being trained to sniff out seafood tainted by oil and make sure the product reaching consumers is safe to eat.
- Secondary containment - methods to prevent releases of oil or hydrocarbons into environment.
- Oil Spill Prevention Containment and Countermeasures (SPCC) program by the United States Environmental Protection Agency.
- Double-hulling - build double hulls into vessels, which reduces the risk and severity of a spill in case of a collision or grounding. Existing single-hull vessels can also be rebuilt to have a double hull.

Skimmers- are things that skim the slick (oil) off the top of the water. Boomers- are inflatable, rubber blockades that trap the oil, so it is easier to skim.

## *Environmental Sensitivity Index (ESI) mapping*

Environmental Sensitivity Index (ESI) maps are used to identify sensitive shoreline resources prior to an oil spill event in order to set priorities for protection and plan cleanup strategies. By planning spill response ahead of time, the impact on the environment can be minimized or prevented. Environmental sensitivity index maps are basically made up of information within the following three categories: shoreline type, and biological and human-use resources.

## Shoreline type

Shoreline type is classified by rank depending on how easy the garet would be to cleanup, how long the oil would persist, and how sensitive the shoreline is. The floating oil slicks put the shoreline at particular risk when they eventually come ashore, covering the substrate with oil. The differing substrates between shoreline types vary in their response to oiling, and influence the type of cleanup that will be required to effectively decontaminate the shoreline. In 1995, the US National Oceanic and Atmospheric Administration extended ESI maps to lakes, rivers, and estuary shoreline types. The exposure the shoreline has to wave energy and tides, substrate type, and slope of the shoreline are also taken into account – in addition to biological productivity and sensitivity. The productivity of the shoreline habitat is also taken into account when determining ESI ranking. Mangroves and marshes tend to have higher ESI rankings due to the potentially long-lasting and damaging effects of both the oil contamination and cleanup actions. Impermeable and exposed surfaces with high wave action are ranked lower due to the reflecting waves keeping oil from coming onshore, and the speed at which natural processes will remove the oil.

### Biological resources

Habitats of plants and animals that may be at risk from oil spills are referred to as "elements" and are divided by functional group. Further classification divides each element into species groups with similar life histories and behaviors relative to their vulnerability to oil spills. There are eight element groups: Birds, Reptiles Amphibians, Fish, Invertebrates, Habitats and Plants, Wetlands, and Marine Mammals and Terrestrial Mammals. Element groups are further divided into sub-groups, for example, the 'marine mammals' element group is divided into dolphins, manatees, pinnipeds (seals, sea lions & walruses), polar bears, sea otters and whales. Issues taken into consideration when ranking biological resources include the observance of a large number of individuals in a small area, whether special life stages occur ashore (nesting or molting), and whether there are species present that are threatened, endangered or rare.

### Human-use resources

Human use resources are divided into four major classifications; archaeological importance or cultural resource site, high-use recreational areas or shoreline access points, important protected management areas, or resource origins. Some examples include airports, diving sites, popular beach sites, marinas, natural reserves or marine sanctuaries.

## *Estimating the volume of a spill*

By observing the thickness of the film of oil and its appearance on the surface of the water, it is possible to estimate the quantity of oil spilled. If the surface area of the spill is also known, the total volume of the oil can be calculated.

| | Film thickness | | | Quantity spread | |
|---|---|---|---|---|---|
| **Appearance** | **in** | **mm** | **nm** | **gal/sq mi** | **L/ha** |
| Barely visible | 0.0000015 | 0.0000380 | 38 | 25 | 0.370 |
| Silvery sheen | 0.0000030 | 0.0000760 | 76 | 50 | 0.730 |
| First trace of color | 0.0000060 | 0.0001500 | 150 | 100 | 1.500 |
| Bright bands of color | 0.0000120 | 0.0003000 | 300 | 200 | 2.900 |
| Colors begin to dull | 0.0000400 | 0.0010000 | 1000 | 666 | 9.700 |

| | | | | | |
|---|---|---|---|---|---|
| Colors are much darker | 0.0000800 | 0.0020000 | 2000 | 1332 | 19.500 |

Oil spill model systems are used by industry and government to assist in planning and emergency decision making. Of critical importance for the skill of the oil spill model prediction is the adequate description of the wind and current fields. There is a worldwide oil spill modelling (WOSM) program. Tracking the scope of an oil spill may also involve verifying that hydrocarbons collected during an ongoing spill are derived from the active spill or some other source. This can involve sophisticated analytical chemistry focused on finger printing an oil source based on the complex mixture of substances present. Largely, these will be various hydrocarbons, among the most useful being polyaromatic hydrocarbons. In addition, both oxygen and nitrogen heterocyclic hydrocarbons, such as parent and alkyl homologues of carbazole, quinoline, and pyridine, are present in many crude oils. As a result, these compounds have great potential to supplement the existing suite of hydrocarbons targets to fine tune source tracking of petroleum spills. Such analysis can also be used to follow weathering and degradation of crude spills.

## *Largest oil spills*

**Oil spills of over 100,000 tons or 30 million US gallons, ordered by tons**[a]

| Spill / Tanker | Location | Date | *Tons of crude oil | Barrels | US Gallons |
|---|---|---|---|---|---|
| Kuwaiti oil fires [b] | Kuwait | January, 1991 - November, 1991 | 136,000,000-205,000,000 | 1,000,000,000-1,500,000,000 | 42,000,000,000-63,000,000,000 |
| Kuwaiti oil lakes [c] | Kuwait | January, 1991 - November, 1991 | 3,409,000-6,818,000 | 25,000,000-50,000,000 | 1,050,000,000-2,100,000,000 |
| Lakeview Gusher | USA, Kern County, California | May 14, 1910 – September, 1911 | 1,200,000 | 9,000,000 | 378,000,000 |
| Gulf War oil spill [d] | Iraq, Persian Gulf and Kuwait | January 19, 1991 - January 28, 1991 | 818,000–1,091,000 | 6,000,000–8,000,000 | 252,000,000–336,000,000 |
| Deepwater Horizon | USA, Gulf of Mexico | April 20, 2010 – July 15, 2010 | 560,000-585,000 | 4,100,000-4,300,000 | 172,000,000-180,000,000 |
| Ixtoc I | Mexico, Gulf of Mexico | June 3, 1979 – March 23, 1980 | 454,000–480,000 | 3,329,000–3,520,000 | 139,818,000–147,840,000 |
| Atlantic Empress / | Trinidad and Tobago | July 19, 1979 | 287,000 | 2,105,000 | 88,396,000 |

| | | | | | |
|---|---|---|---|---|---|
| Aegean Captain | | | | | |
| Fergana Valley | Uzbekistan | March 2, 1992 | 285,000 | 2,090,000 | 87,780,000 |
| Nowruz Field Platform | Iran, Persian Gulf | February 4, 1983 | 260,000 | 1,907,000 | 80,080,000 |
| ABT Summer | Angola, 700 nmi (1,300 km; 810 mi) offshore | May 28, 1991 | 260,000 | 1,907,000 | 80,080,000 |
| Castillo de Bellver | South Africa, Saldanha Bay | August 6, 1983 | 252,000 | 1,848,000 | 77,616,000 |
| Amoco Cadiz | France, Brittany | March 16, 1978 | 223,000 | 1,635,000 | 68,684,000 |
| MT Haven | Italy, Mediterranean Sea near Genoa | April 11, 1991 | 144,000 | 1,056,000 | 44,352,000 |
| Odyssey | Canada, 700 nmi (1,300 km; 810 mi) off Nova Scotia | November 10, 1988 | 132,000 | 968,000 | 40,656,000 |
| Sea Star | Iran, Gulf of Oman | December 19, 1972 | 115,000 | 843,000 | 35,420,000 |
| Irenes Serenade | Greece, Pylos | February 23, 1980 | 100,000 | 733,000 | 30,800,000 |
| Urquiola | Spain, A Coruña | May 12, 1976 | 100,000 | 733,000 | 30,800,000 |
| Torrey Canyon | United Kingdom, Isles of Scilly | March 18, 1967 | 80,000–119,000 | 587,000–873,000 | 24,654,000–36,666,000 |
| Greenpoint oil spill | United States, Brooklyn, New York City | 1940 – 1950s | 55,000–97,000 | 400,000–710,000 | 17,000,000–30,000,000 |

[a] One ton of crude oil is roughly equal to 308 US gallons or 7.33 barrels approx.; 1 oil barrel is equal to 35 imperial or 42 US gallons.

[b] Estimates for the amount of oil burned in the Kuwaiti oil fires range from

500,000,000 barrels (79,000,000 $m^3$) to nearly 2,000,000,000 barrels (320,000,000 $m^3$). 732 wells were set ablaze, while many others were severely damaged and gushed uncontrolled for several months. The fires alone were estimated to consume approximately 6,000,000 barrels (950,000 $m^3$) of oil per day at their peak. However, it is difficult to find reliable sources for the total amount of oil burned. The range of 1,000,000,000 barrels (160,000,000 $m^3$) to 1,500,000,000 barrels (240,000,000 $m^3$) given here represents frequently-cited figures, but better sources are needed.

**c** Oil spilled from sabotaged fields in Kuwait during the 1991 Persian Gulf War pooled in approximately 300 oil lakes, estimated by the Kuwaiti Oil Minister to contain approximately 25,000,000 to 50,000,000 barrels (7,900,000 $m^3$) of oil. According to the U.S. Geological Survey, this figure does not include the amount of oil absorbed by the ground, forming a layer of "tarcrete" over approximately five percent of the surface of Kuwait, fifty times the area occupied by the oil lakes.

**d** Estimates for the Gulf War oil spill range from 4,000,000 to 11,000,000 barrels (1,700,000 $m^3$). The figure of 6,000,000 to 8,000,000 barrels (1,300,000 $m^3$) is the range adopted by the U.S. Environmental Protection Agency and the United Nations in the immediate aftermath of the war, 1991-1993, and is still current, as cited by NOAA and The New York Times in 2010. This amount only includes oil discharged directly into the Persian Gulf by the retreating Iraqi forces from January 19 to 28, 1991. However, according to the U.N. report, oil from other sources not included in the official estimates continued to pour into the Persian Gulf through June, 1991. The amount of this oil was estimated to be at least several hundred thousand barrels, and may have factored into the estimates above 8,000,000 barrels (1,300,000 $m^3$).