Guide to the different ways in which rocks are fractured in Oil and Gas field operations – A Briefing Paper

By Dr John Pucknell
School of Engineering
University of Portsmouth
Anglesea Building
Anglesea Road
Portsmouth PO1 3DJ

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Abstract

This note describes occasions when the reservoir rocks of oil and gas fields are fractured. These include:

- Natural fractures, created over geologic time;
- Fractures creased by Propellants;
- Hydraulic fractures created by the pressure of water or some other fluid;
- Propped fractures, in which fractures created hydraulically are held open by sand or a similar artificial material;
- Acid fracturing;
- Fractures associated with waterflooding;
- Various other types of fracturing.

A brief description of the fluids used in fracturing, and the factors controlling the orientation and size of fractures, are given. Typical shale gas treatments are described.

Background

In the effort to encourage production from oil and gas wells many techniques have been used over the years. In early wells, as long ago as 1890, nitro-glycerine or similar products were used to create explosions at the bottom of oil wells to fracture the rock. Nowadays we have moved to a variety of less dramatic treatments.

Recently, propped, hydraulic fracturing treatments used in Shale gas development have attracted attention, called “fracking” by various groups. However there are many occasions when rocks may be fractured, this note tries to explain some of the different techniques used in oil & gas operations.

Fracturing a rock

Oil and Gas is found in rocks, in microscopic holes called pores between grains of sand, silt or clay, or in similar pores or cavities in limestones and chalks. In some rocks oil and gas flows easily into a well, in which case the rock is said to have a high **permeability**[1]. In other cases, permeabilities are low and flow has to be encouraged by "**stimulating**" production. Stimulation may also be needed if the act of the drilling the well has reduced the permeability close to the borehole in an otherwise permeable rock.

Natural fractures

Some rocks maintain high production rates even though the permeabilities are low. This can happen because the rock is **naturally fractured**. Oil or gas flows from the rock into a network of the natural fractures which then act as "highways" so that oil or gas can reach the well more quickly. Natural fractures can be created in a variety of ways; for example, earth movements over millions of years, that have created mountain ranges can also cause more brittle rocks to fracture as continents are pushed against each other. More plastic rocks, such as those rich in clays, can deform in a more ductile manner without fracturing in the same circumstances.

Making fractures with explosives and propellants

In the absence of natural fractures, to enhance production, engineers have for many years tried to create fractures artificially. Nitro-glycerine is no longer in use, however, devices made from rocket propellants (called Stimguns or similar trade names) are available. These devices are lowered into the well, and when ignited create a pulse of gas, very quickly, but not quite as fast as an explosion. The gas creates a network of fractures close to the well and can provide a modest increase in production. Fractures do not extend beyond a few tens of feet[2].

Perforating charges are another type of explosive used in oil and gas wells. These punch holes through the steel casing cemented into a well to allow oil or gas to flow from the formation. Perforating charges are shaped charges developed in the Second World War to penetrate steel armour. The holes created are about half an inch wide and a foot or so long; small fractures, a few inches long may extend from their tip.

Hydraulic Fracturing

As more science was applied to understanding petroleum production in the 1930's and 1940's, it was realised that explosive charges were not necessary to fracture the rock, instead a fracture could be created by simply pumping water (or some other fluid such as oil) into a well. At low injection rates, the water simply flows into the rock, but as the pumping rate is increased, a point is reached when the permeability of the rock is too low to accept all the water being pumped. At this point the pressure of the water against the sides of the wellbore, trying to escape from the well into the rock, causes the rock to fracture. Unlike explosives or propellants, a single fracture rather than multiple

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[1] Technical terms are shown in bold. Various glossaries of oilfield terms exist such as http://www.glossary.oilfield.slb.com/

[2] http://stimgun-products.com/documents/File8_General_Interest.pdf

fractures tend to be created. The name **hydraulic fracturing** means water or some other liquid at pressure is being used to create the fracture.

Unpropped fractures

Having fractured the rock by pumping in water (or oil), it was observed that there was often an increase in production rate when the well was subsequently placed on production. Such an increase occurred as the fracture was acting as a conduit for oil to flow into the well. This increase was generally not sustained, as the fractures tend to close due to the pressure of surrounding rock at depth, there being nothing in the fractures to prop them open.

Propped fractures

In 1947 this problem was solved by pumping not just water or oil to create a fracture, but also adding sand[3]. Then, when the fracture closed, it closed on the sand, and the sand held the fracture open. To do this they had to find a way to keep the sand suspended in the liquid while it was pumped. They did this by pumping diesel mixed with a gelling agent to create a viscous fluid, called a gel that would stop the sand settling before it could be pumped down the fracture.

The success of propped fracturing rapidly displaced the earlier practice of "shooting" wells with Nitro-glycerine, and led to many variations of the original technique.

Gels and cross-linked gels

Although diesel was used in the very first propped fracture treatment, and oil based treatments are still in use, most fracture treatments use a water based fluid to fracture the formation, due to lower cost and to avoid any fire risk. Water is mixed with a **gelling agent** to create the viscosity needed to keep the sand suspended. The most common gelling agents are based on Guar gum. Guar beans are used as cattle food in India and Guar gum is added to low fat deserts to give "creaminess" without adding fat. A variety of other gelling agents are also in use, most of which are also found in household products. Products like Guar gum are long chain polymers, long linear molecules, and so the gels are sometimes called linear gels. It was found that their viscosity in water could be greatly increased by linking the long chains together with **a cross linking agent**[4]. By using cross-linked gels, very high concentrations of sand can be held in suspension and pumped into the fracture to keep a wide fracture open.

Other chemicals are added, such as a **bactericide** to prevent deterioration of the gel through bacterial action. Once the fracture has been created, the gel in the formation would impede the flow of oil or gas, so a "**breaker**" may be

[3] "Hydraulic Fracturing" by G.C.Howard & C.R.Fast, SPE, 1970
[4] You can make your own cross linked gel with materials from sites such as http://www.miniscience.com/projects/slime/GuarGumSlime.html

added to turn the gel into a low viscosity fluid. A **friction reducer** may also be added to reduce the required pumping pressure.

It is commonly noted that not all the water injected as part of a fracture treatment is returned when the well is placed on production. One of the reasons for this is that rocks, especially clays, like to hang on to water[5]. This adsorbed water can interfere with oil or gas production by blocking small pores in the rock, so **surfactants** or other "cleaning" agents can be added to the fracturing fluid to aid recovery of the water injected, when the well is placed on production.

Proppant

Although sand is the cheapest material to prop open a fracture, it can be crushed by the rock forces trying to close the fracture, especially in deeper wells. For this reasons stronger **proppants** made of bauxite, or various ceramic materials can be used.

Slickwater treatments

As an alternative to pumping high concentrations of proppant in highly viscosified fluids, another approach is to use low proppant concentrations in water, and to pump at high rates to get it into the fracture before it drops to the bottom of the well due to gravity. To pump at high rates, friction reducer is added to these **slickwater** treatments to reduce the pressure drop, no other chemicals may be needed.

Other variants

There are many other variants on the basic propped fracturing procedure. At the cheaper end, produced crude oil, which is often quite viscous, is a useful fracturing fluid. At the other extreme, liquid carbon dioxide can be used where the operator is concerned that water or oil may damage the permeability of the formation.

Other variants include Polymulsion fracturing fluid in which viscosity is created by emulsifying oil and water. Methanol based fluids have been used on formations believed to be vulnerable to permeability damage by water. Foams can be used as a fracturing fluid and are helpful in areas where the reservoir pressure may otherwise be too low to push the fracturing fluid into the well. Nitrogen, butane and propane have also been used.

Fracture orientation and growth

The fracture created by hydraulic fracturing is normally vertical, like a vertical sheet, extending out from each side of the well. A horizontal fracture would have to lift the whole weight of the rock above it, maybe several thousand feet

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[5] Clay's affinity for water is why clays make good mud pies, or with a little less water, can be moulded into pottery.

of rock, whereas a vertical fracture just has to push the rock aside, squashing it a little. Only at shallow depths, less than 2000ft, when the weight of the rock above is smaller, can horizontal, “pancake like”, fractures develop.

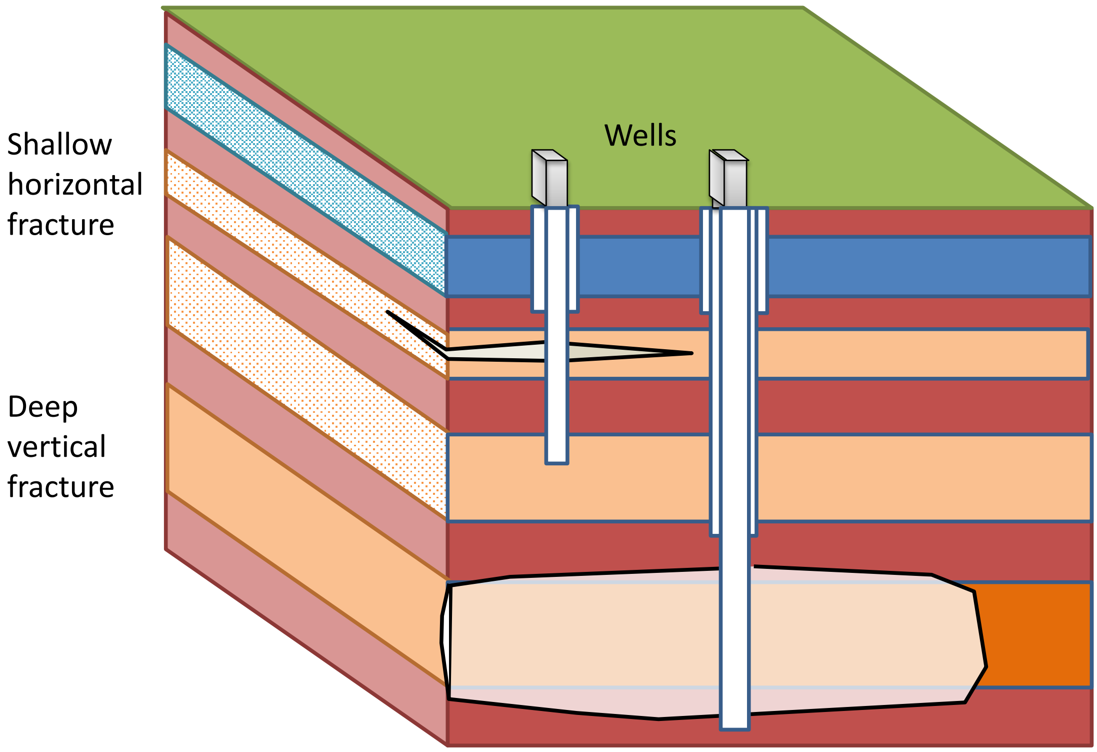

Figure 1 Illustration of vertical and horizontal hydraulic fractures. Horizontal fractures can normally only form at shallow depths.

The ideal fracture would grow outwards from the well through the oil or gas bearing formation. Upward or downward growth into the layers above and below the productive formation is a waste of proppant and fracturing fluid. When fracturing sandstones and limestones, surrounded by shale or mudstone, fractures tend to be **contained** in these more brittle formations. Rocks with a lot of clay such as shale are more “squashy”; when the weight of the rocks above presses down on them, they tend to push sideways, horizontally, tending to prevent the growth of fractures.

If fracturing shales, the layers of rock to prevent upward and downward growth of vertical fractures may be less obvious, although even shales are a mixture of more brittle and less brittle layers. Where there is no clay rich confining layers, “penny” shaped fractures are created. For a penny the height and width are the same.

Fracture size

The size of a hydraulic fracture is increased when the rate at which fluid is pumped into the fracture exceeds the rate at which it flows out into the formation through the sides of the fracture. As the fracture becomes larger, the area of the fracture faces increases and so the rate at which fracturing fluid is lost to the formation also increases. This makes it difficult to create very large fractures. To ensure the fracture grows, fluid is either pumped in really fast, and / or the fluid is viscosified as viscous fluids seeps into the rock more slowly. This is a second reason for gelling fracturing fluids (in addition to increasing the ability to keep proppant suspended). Occasionally **fluid loss additives** are added to the fracturing fluid to reduce the amount of fluid that is lost to the formation.

An efficient fracturing fluid needs to have low fluid loss, so that the size of the fracture will increase with the amount of fluid pumped. Conversely, a fluid which easily flows into the rock formation can never create a large fracture. The magnitude of the formation permeability is also important. If the permeability is high, a lot of fluid will flow out of the fracture making it difficult to create a large fracture. Conversely, if the permeability is very low, as in shales, a large fracture is possible even with just slick water.

Treatment sizes

In a small, propped fracture treatment maybe a few tons of proppant will be pumped, in a larger treatment it could be well over 100 tons. The amount of fracture fluid pumped may vary from 10,000 to over a million gallons.

Mini fracs or Data fracs

To determine the pressure needed for a fracture to form (the **fracture pressure**) and evaluate the amount of fluid loss into the formation that may be expected (from which the eventual fracture size can be calculated), the formation may be fractured with a suitable fluid prior to the main treatment. A variety of protocols may be used such as a **breakdown test**, in which the fracture is initiated and pumping is then stopped to monitor the pressure fall off. In a **step rate test**, the rate is gradually increased until the formation fractures, at which point it accepts fluid much more easily.

Very low permeability reservoirs, shale gas and oil

As older fields are depleted, attention has turned to reservoirs with progressively lower permeability. These include very low permeability or “**tight**” sands and shales. To obtain production from such reservoirs two techniques were initially used, propped hydraulic fracturing and horizontal drilling. Horizontal drilling enhances production by increasing the length of formation in contact with the well. The two techniques were then combined such that multiple hydraulic fracture treatments were created from the same horizontal well. This is achieved by fracturing the far end of the well, then isolating it, then fracturing the next section of well, then isolating it and continuing until several fractures had been created in one well.

The creation of multiple fractures from one horizontal well was a concept developed in the late 1980’s for chalk wells in the North Sea (and much earlier for multiple fractures in vertical wells), however the breakthrough in the development of shale gas was more a conceptual one. Shale had previously been considered an impermeable rock, which could not be produced directly except in rare cases where it was extensively naturally fractured. Efforts by George Mitchell in the Barnett Shale in Texas in the 1990's proved this wrong and initiated the boom in shale gas drilling. As this has brought down the price of gas in the US, drilling activity has increasingly moved onto shale gas which is also rich in oil, and shale oil, in formations such as the Bakken shale. Although many of the shale oil formations commonly have significant carbonate or siltstone layers.

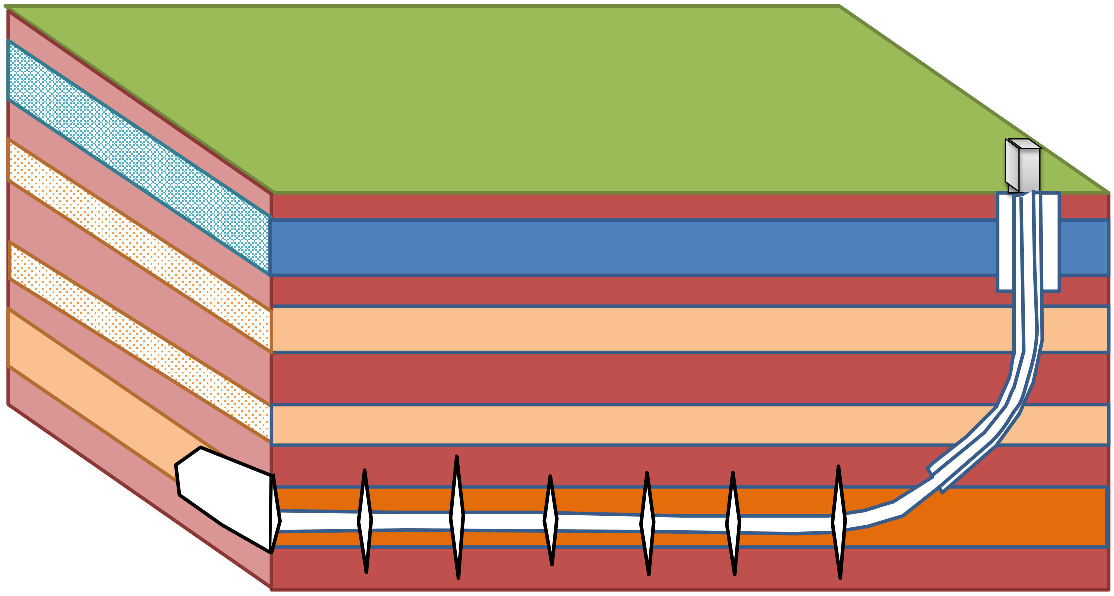

Figure 2 Horizontal well with multiple hydraulic fractures as used in Shale Gas developments

Typical Shale Gas treatments

The length of the horizontal section through the producing formation varies from 2500 to 5000ft in newer Shale Gas wells[6]. Over this length 8 to 20 separate fracture treatments may be performed. Slickwater treatments are the dominant type of treatment, often outperforming gelled fracturing. Evidence suggests this is because the water penetrates natural fractures, opening them up for the flow of hydrocarbons. As the permeability of the shale itself is extremely low, the presence of natural fractures is extremely important to gaining commercial production rates. The success of fracture treatments is due in part to connecting the well to these natural fracture systems.

Each fracture treatment may involve 36 to 140 tons of proppant, and 300 to 600 thousand gallons of water. To reduce the pressure needed to initiate the fracture a small amount of Hydrochloric acid may be pumped ahead of the fracture treatment.

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[6] Details of typical treatments are taken from "Thirty Years of Gas Shale Fracturing: What Have We Learned" by George King, 2010, Society of Petroleum Engineers Paper 133456

Acidisation

Hydraulic fracturing is not the only means of stimulating oil or gas production. Acid has been used to stimulate oil and gas wells since at least the 1930's, and this has widest use in carbonate rocks such as limestone, chalk and dolomite, as these rocks readily dissolve in acid. The most widely used acid is hydrochloric acid, at strengths of 15% and 28%, although acetic and formic acids are also used on carbonate formations.

There are several types of acid treatment. In an **acid wash**, the acid is just circulated past the formation, some enters the formation but the aim is for a gentle treatment, typically designed to remove or bypass areas where the permeability has been reduced by the action of drilling or scale deposition close to the well. The acid simply dissolves a small amount of rock allowing the free flow of oil or gas.

For a more deeply penetrating treatment acid is pumped or "**squeezed**" into the formation. For removal of permeability damage close to the well, a **matrix acid** job will be performed in which pumping pressure is kept below the fracture pressure. In low permeability formations there is also the option to perform an **acid fracture** treatment, in which the pumping pressure exceeds the fracture pressure. In acid fracturing the acid rapidly reacts with the sides of the fracture. This is helpful as it etches channels, which continue to allow a fast passage for oil and gas even after the fracture closes. Acid reaction with the sides of the fracture also increases permeability, which means that the acid rapidly leaks off. This makes it difficult to create fractures of significant size with acid fracture treatments unless the permeability is very low.

Acid fracture treatments may have gelling agents similar to hydraulic fracture treatments. Although no proppant is pumped, these gelling agents are added to reduce fluid leak-off and in an attempt to create fractures in more than one place in the well. Unlike most propped fracturing fluids, acid fracture treatments also have two other important additives, a **corrosion inhibitor** to stop the acid attacking the tubing and casing in the well, and **an iron sequestering or reducing agent**, which is to prevent precipitation of iron products that can occur when the acid spends.

The acid injected into carbonate rocks is soon used up and the hydrochloric acid turns into calcium chloride. Acid treatments are not confined to the oil industry but are normal for example in potable water wells sunk in chalk aquifers.

The amount of acid injected ranges from 25 to 250 gals for each foot of formation, so up to 25,000 gals may be used for a 100ft formation. The amount of rock this will dissolve is relatively small, about 270 cubic foot[7].

[7] This is about the volume of my airing cupboard

Although carbonate reservoirs are the main target of acid treatments, sandstones may also be treated with acid, often using “mud acid”, a mixture of hydrofluoric and hydrochloric acid that can dissolve clays. However in sandstone and shale reservoirs acid is not normally injected above fracture pressure, as the amount of quartz these formations contain mean that the fracture faces cannot be etched by the acid, and no fracture conductivity remains after the fracture closes.

Water Flooding

Water is often injected into oilfields using wells designated as water injection wells, in order to push oil into the production wells, a process known as **waterflooding**. As this maximises oil recovery, and so tax revenue for the people of a country, waterflooding is generally also encouraged by governments as good production practice. It is also a means of returning water produced from oil wells, back into the formation from which it came, without the environmental damage that could occur from disposal at surface. Such produced water is supplemented by another source of water (such as the sea) so that each barrel of oil or water produced is replaced by one barrel of water injected. This ensures that pressure in the reservoir is maintained. Such **pressure maintenance** stops gas bubbles coming out of solution in the reservoir and impeding oil flow; it keeps production steady and where formations are compressible, ensures that the ground above the oil field does not subside.

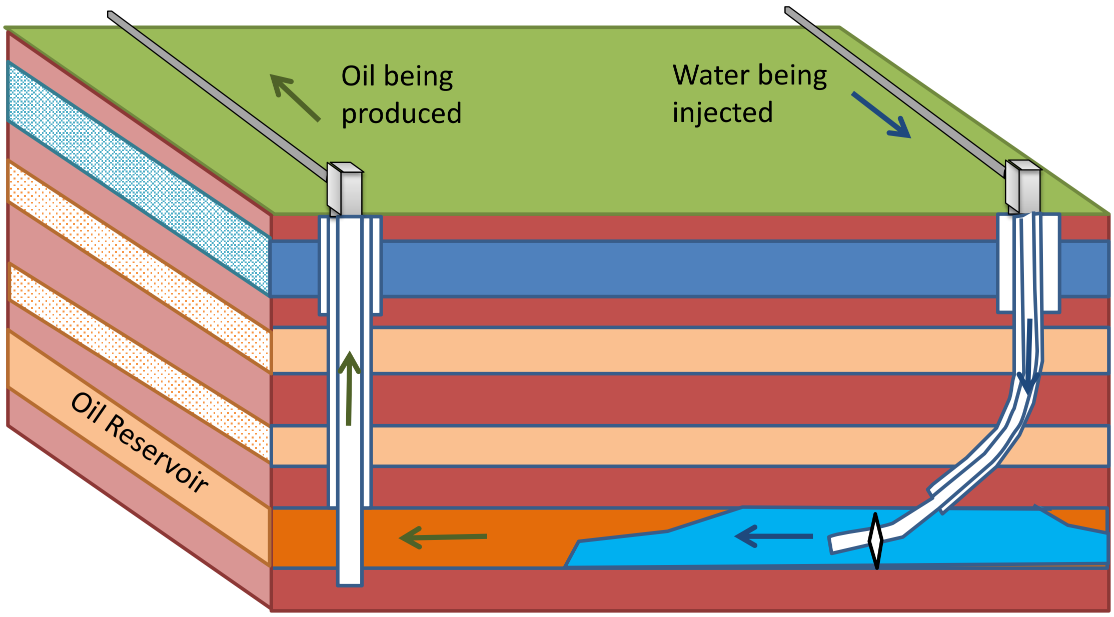

Figure 3 Illustration of a waterflood, in which water is injected to push oil out of the reservoir

As the injection water is cooler than the rock into which it is being injected, the rock formation is cooled down. Rock, like most other materials, contracts when it is cooled. Contraction causes the rock to fracture more easily. So the injection of cooler water creates a fracture by a process known as **Thermal Fracturing**. Most water in waterfloods is injected into fractures created by a combination of pressure and temperature. If fractures were not created the amount of water that could be injected would be greatly limited and the injection wells would be vulnerable to plugging by small amounts of solids. These fractures are not large as the injected water has a low viscosity so rapidly leaks off into the permeable rock formation, so the fracture never grows beyond a certain size no matter how much water is injected. Thermal fracturing only occurs in permeable zones as the cooler water cannot penetrate into impermeable zones and cause them to contract. In consequence thermal fractures are confined to the zone of injection.

Other sorts of Fracturing

Fractures may be created in other oilfield operations. For example, when a section of rock needs to be isolated (e.g. when it has started to produce water), a **cement squeeze** may be performed, in which cement may be pumped into a section of rock above fracture pressure. Of course the resulting fracture is filled with cement.

When wells are drilled they create cuttings, small pieces of rock chipped away by the drill bit. One way of disposing of these without adding to landfill sites is to pump them back into the subsurface formations. As the cuttings will not penetrate the small pores of the rock, **cuttings re-injection** takes place above fracture pressure, and the cuttings are permanently left in that fracture.

More serious fracturing occurs during **external blowouts**. As a will is drilled shallower formations are isolated by running steel casing and cementing it in place. If the casing is set too shallow, and a well blows out from a deeper formation due to some major drilling problem, even if the blowout preventers are closed at the surface, the pressure of the oil or gas from the deeper formation can fracture the formation at the base of the casing. This can result in the escape of oil or gas to shallow formations or even the surface. The risks are well understood so after setting a casing and cementing it in place a very small fracture may be created by pumping mud into the well, known as a **Leak off test**. This tells the drilling engineer how much pressure can be contained by the well in the event of a blowout and dictates where the next casing is set. In some cases fracture pressure will not be reached and the formation will be tested to some lower pressure by a **Formation Integrity test**.

Endpiece

As shown above, fracturing of rock formations takes place in many operations in oil and gas fields, and has done for many years. While the development of Shale gas has only been possible by the use of multiple hydraulic fractures from horizontal wells, the real breakthrough was perhaps more a change in mindset. Whereas before shales were generally written off as a source of oil or gas production without any testing, it has now been demonstrated that, at least in the United States, commercial production can be achieved from shale.