Oil and natural gas are found in the pore spaces of certain underground rock formations. In some oil-bearing or gas-bearing formations, the pore spaces are thoroughly interconnected. When a well is drilled into such a formation, oil or gas can flow through the rock and to the well by traveling from one pore space to the next through the interconnections between pores. But if the pore spaces are not thoroughly interconnected—as is the case with the shales and tight sandstones that contain much of the oil and gas that remain in the United States—oil or gas generally cannot move easily through the formation. In such cases, oil or gas might not flow to the well at a sufficient rate to justify drilling.

Fracturing is the process of creating fractures in the rock so that the fractures can serve as pathways for the flow of oil or gas. Fracturing is sometimes called well stimulation, and it has been used to stimulate wells almost since the start of the modern oil and gas industry. "Colonel" Edwin Drake drilled the first oil well in the United States near Titusville, Pennsylvania in 1859,1 and by the 1860s, well owners had begun using a practice called explosive fracturing.2 Over time, the oil and gas industry has used two major types of fracturing: explosive fracturing and hydraulic fracturing. This chapter discusses these two major types of fracturing, as well as some of the different techniques used in hydraulic fracturing, including the slick water technique that has become common relatively recently for use in shale formations.

I. Explosive Fracturing

In explosive fracturing, an operator lowers an explosive into a well and detonates it, thereby fracturing the target formation. The first explosive that was used for this purpose was black powder, but nitroglycerin soon became the explosive of choice.3 To per-

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2See Norman J. Hyne, Nontechnical Guide to Petroleum Geology, Exploration, Drilling, and Production, 422 (2d ed. 2001); see also Roberts v. Dickey, 20 F. Cas. 880, 884–85 (W.D. Pa. 1871) (discussing a patent granted in 1866 for an invention relating to explosive fracturing); People’s Gas Co. v. Tyner, 31 N.E. 59, 59–60 (Ind. 1892) (nuisance action in which plaintiffs complained about use of explosive fracturing in urban area).
form explosive fracturing, a person would fill a metal container called a “torpedo” with nitroglycerin, lower it into the well, and then detonate it. The fracturing caused by the explosion often would dramatically increase the well’s rate of oil production. Handling nitroglycerin was dangerous and could cause a nuisance if used near neighboring properties, but explosive fracturing using nitroglycerin was effective, and the process, which sometimes was called “shooting a well,” continued to be commonly used for several decades into the 1900s.

But explosive fracturing also can be performed using explosives other than nitroglycerin. Indeed, the United States and Soviet Union each conducted several tests in which they performed explosive fracturing using a type of explosive device that was substantially more powerful than a metal container filled with nitroglycerin. In the late 1960s and early 1970s, the U.S. Atomic Energy Commission (AEC) experimented with using underground nuclear explosions to fracture low permeability formations. The AEC conducted the experiments at two locations in Colorado and one in New Mexico. The experiments were part of the AEC’s Plowshare program, in which the AEC sought to develop peaceful uses for nuclear energy. The Soviet Union also experimented with using nuclear explosions to stimulate oil and gas production. Both the U.S. and the Soviet experiments succeeded in substantially boosting the rate of natural gas production from the formations where the tests were conducted, but the gas that was produced contained radiation. For this reason, and perhaps others, attempts to use nuclear devices to conduct explosive fracturing were abandoned. Other factors that could have contributed to the abandonment of efforts to use nuclear devices for this purpose include the same environmental, national security, and political concerns that led to the abandonment of other efforts to use nuclear explosives for non-military purposes. Explosive fracturing is seldom used today because the process has largely been superseded by hydraulic fracturing.
II. Hydraulic Fracturing

In the late 1940s, the process known as “hydraulic fracturing” was commercially developed. The nature of hydraulic fracturing is reviewed here to give context to this chapter’s discussion of the various types of fracturing and hydraulic fracturing methods.

Hydraulic fracturing is the process of using hydraulic pressure to create fractures, taking advantage of the fact that rocks generally will fracture if exposed to sufficiently high pressure. Before using hydraulic fracturing, an operator drills a well. Then, the operator uses special tools to create perforations in the portion of the well’s piping that is within the subsurface formation from which oil or gas will be produced. After the well has been “perfed,” the operator uses high-pressure pumps to push a fracturing fluid down the well and out through the perforations into the formation to be fractured. The fluid then moves into the formation, where it imposes pressure sufficient to create fractures in the rock. The fluid then moves into the fractures and helps propagate the fractures.

In most hydraulic fracturing operations, the fracturing fluid is a mixture of base fluid, proppants, and various additives. The base fluid is usually water in most contemporary hydraulic fracturing operations. The base fluid serves two purposes. First, it is used to impose the hydraulic pressure that causes the subsurface formation to fracture. Second, the base fluid carries the proppant into the newly created fractures. The proppant is composed of small granular particles (most often sand). The purpose of these particles is to prop the fractures open, preventing the newly created fractures from closing after the fracturing operation is complete. The additives are a variety of substances that adjust properties of the base fluid (e.g., to retard corrosion and bacterial growth, reduce friction, and “thicken” the base fluid in order to help it carry proppant).

After the formation has been fractured, the operator turns off the high-pressure pumps and allows the pressure of the formation to push the fracturing fluid back through the well and up to the surface, where this “flowback” fluid is recovered. The fraction of the base fluid that is recovered depends on the formation and the type of fracturing fluid. This process is used to increase the productivity of a well by creating fractures in the formation through which the oil or gas can flow more freely. The process can also be used to stimulate production from existing wells by increasing the permeability of the rock.

Additives are used to improve the flowback characteristics of the fracturing fluid, including biocides, corrosion inhibitors, friction reducers, and viscosifiers. Biocides are used to prevent bacterial growth in the fracturing fluid, which can lead to plugging of the fractures. Corrosion inhibitors are used to prevent corrosion of the wellbore and casing. Friction reducers are used to reduce friction in the wellbore, which can help maintain higher flow rates during treatment.

Proppants are used to keep the fractures open after the fracturing fluid has been removed. The most common proppant is sand, but other substances, such as ceramic spheres and sintered bauxite, are also used. Proppants are typically injected into the fractures at a high rate and volume, and they remain in the fractures to maintain an open flow path for the produced fluids.

The fracturing fluid additives are critical to the success of hydraulic fracturing operations. They help to maintain the integrity of the fractures, reduce damage to the formation, and improve the oil and gas production from the well.

References:
3. Id.
4. See id. at ES-4; Hyne, supra note 2, at 423.
5. Shale Gas Primer, supra note 17, at 62.
6. Proppants are small granular particles. During hydraulic fracturing, the fracturing fluid carries the proppants into the newly created fractures. When the fracturing fluid is removed from the well, the proppants remain behind, propping open the fractures, which usually would close after the fracturing fluid is removed. Kurth et al., supra note 16, at 279, 283. The most common proppant is sand, though other substances, such as small ceramic spheres and sintered bauxite are sometimes used. See Robin Beckwith, Proppants: Where in the World, J. Petroleum Tech. 36-40 (Apr. 2011), http://www.spe.org/jpt/print/archives/2011/04/11ProppantShortage.pdf.
7. Shale Gas Primer, supra note 17, at 63 (stating that additives include biocides, corrosion inhibitors, friction reducers, and viscosity adjusters).
8. In analyzing data from numerous hydraulic fracturing operations, the U.S. Envir. Protection Agency found that 93 percent of the operations used water as the sole base fluid, some of the remaining operations used a mixture of water and other substances as the base fluid. See United States Envr. Protection Agency, Analysis of Hydraulic Fracturing Fluid Data from the FracFocus Chemical Disclosure Registry, 1.0 (March 2015) at 42.
9. In analyzing data from numerous hydraulic fracturing operations, the EPA found that more than 90 percent of the operations used sand as the sole type of proppant, and that about 98 percent used sand alone or both sand and some other substance as proppant. Id. at 60.
10. The various functions that are served by additives are discussed in more detail in Chapter 8 of this book, which discusses the mandatory disclosure of fracturing fluid additives.
operation. With slickwater fracturing, typically 30 to 70 percent of the fluid initially used in the fracturing process is recovered as flowback during a relatively short period. (But in some formations, it is not uncommon for the initial recovery to be below this range.) The remainder of the fluid gradually returns to the surface along with the oil or gas produced by the well or remains in the target formation’s pore spaces.27

Virtually all hydraulic fracturing operations are performed using the basic process described here, but the details of these operations can vary considerably. The following sections discuss (1) gelled-fluid fracturing and slickwater fracturing, which probably are the most important forms of fracturing; (2) acid fracturing, which generally does not use proppants; (3) "frac pack" operations, which have a primary purpose other than well stimulation and which tend to be much smaller than many other hydraulic fracturing operations; and (4) hydraulic fracturing using base fluids other than water. The geothermal energy industry also sometimes uses hydraulic fracturing, but those operations will not be discussed further in this book.

Finally, although this chapter often refers to the operator performing the tasks of drilling and completing the well (with hydraulic fracturing being part of the well completion process), it should be noted that the operator often hires one or more service companies to perform all or a portion of the tasks involved in drilling and completing a well. Thus, many fracturing operations are performed by an entity other than the company responsible for drilling the well—often by numerous contractors and subcontractors who work for the fracturing service company.

A. Gelled Fracturing and Slickwater Fracturing

In the earliest days of hydraulic fracturing, the base fluid was often a petroleum-based fluid. Additives were used to give the fluid a high viscosity or "thickness," so that the fluid had the consistency of a gel. Later, water often was used as the base fluid, but additives still were used to increase the fluid’s viscosity to the point that the fluid was a gel.28 A high viscosity helps the fracturing fluid carry proppants into fractures. (With a low viscosity fluid, proppant particles tend to sink or settle to the bottom of the flow path.) Various "viscosifiers" or gelling agents can be used. Some of the most common gelling agents are guar gum and guar gum derivatives. (Guar gum is also added as a thickener to various foods, such as instant oatmeal and ice cream.) Sometimes, chemicals are used to cause the molecules in the gelling agent to "crosslink" together. Other times, simple "linear" gels (in which the long or linear molecules of the viscosifier are not crosslinked together) are used.

In the 1990s, slickwater fracturing was developed as a technique that often is more effective than older techniques when used in shale formations. Slickwater fracturing uses a lower concentration of additives than earlier hydraulic fracturing techniques, and the water is not converted into a gel. The technique is called "slickwater" because friction reducers that are added to the water make the water slippery or "slick." On the other hand, slickwater fracturing generally involves the use of more water than some of the earlier hydraulic fracturing techniques, particularly when slickwater fracturing is

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27See Shale Gas Primer, supra note 17, at 66 (explaining that the flowback period might last several months).
combined with horizontal drilling. Slickwater fracturing has not wholly displaced fracturing with gels, but it is by far the most commonly used technique in some shale formations, such as the Marcellus Shale.

As between gel fracturing and slickwater fracturing, each technique has certain advantages over the other. For example, an advantage of gel fracturing is that it tends to produce longer, wider fractures, which provide a good pathway for hydrocarbons to flow to the well. Furthermore, because gels have a high viscosity, they are more effective than slickwater in carrying proppants into fractures. Finally, gel fracturing tends to use less water than slickwater fracturing, in which water is pumped at a higher rate than in gel fracturing to partially offset the reduced proppant-carrying ability that results from the slickwater’s lower viscosity.

On the other hand, slickwater operations tend to have lower chemical costs because they use fewer chemical additives. Furthermore, slickwater fracturing tends to create more complex fracture networks than gel fracturing (a more complex network is desirable). And slickwater tends to “clean up” better. That is, less of the slickwater (compared with a gel) remains behind in the fracture network, where it can interfere with the flow of oil or gas through the fractures.

Whether it is more effective to fracture with a gel or with slickwater depends on the formation. In some formations, such as the Marcellus Formation that runs through Pennsylvania and neighboring states, slickwater is almost always used. In other formations, such as the Bakken in North Dakota, it is still common to use gel fractures, although there has been an increasing trend toward using hybrid fracturing operations.

This approach involves pumping a gel for a period of time to get the advantages that come with gel fracturing, and then pumping slickwater to get some of the advantages that are associated with slickwater operations.

B. Acid Fracturing

Acid fracturing (or “fracture acidizing”) is a type of hydraulic fracturing in which an acid is pumped into the fracture network in order to dissolve minerals, thereby etching channels in the walls of the fractures. Because proppants generally are not used in acid fracturing, the fractures close after the fracturing is completed. But the opposing faces of the fracture do not close tightly because neither of the rock faces on either side of the fracture is smooth. Instead, each face is slightly irregular because the depth of the etching is not uniform. For that reason, the fracture only closes until asperities—essentially, high points on the etched surface—from opposing fracture faces come

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29Palisch et al., supra note 28, at 2, 13.
30Id. at 2, 3, 13.
31Id. at 3, 13.
32Id. at 3, 13.
33Id. at 2, 3, 13.
34P.S. Patel et al., Analysis of U.S. Hydraulic Fracturing Fluid System and Proppant Trends, SPE 168645 (Society of Petroleum Engineers 2014) at 5.
35Id. at 5–6, 11; see also Christopher Robart et al., Analysis of U.S. Hydraulic Fracturing Fluid System Trends, SPE 163875 (Society of Petroleum Engineers 2013) at 4.
36Hyne, supra note 2, at 422; Arther Bale et al., Stimulation of Carbonates Combining Acid Fracturing with Proppant (CAPF): A Revolutionary Approach for Enhancement of Sustained Fracture Conductivity and Effective Fracture Half-Height, SPE 134307 (Society of Petroleum Engineers 2010) at 1.
into contact with each other. This leaves the deeper portions of the etched channels open for the flow of oil or gas.

Often, acid fracturing is used in carbonate formations, such as limestones. The acid most commonly used in these formations is hydrochloric acid. In special circumstances, acetic acid or formic acid might be used, but they are more expensive and thus are used less often. Acid fracturing is used less often in sandstones, but when acid fracturing is used in sandstone or shale, hydrofluoric acid or a combination of hydrochloric and hydrofluoric acid are common candidates for the fracturing job.

Whether acid fracturing and conventional fracturing using proppants will be more effective depends on the circumstances. For example, acid is consumed during the chemical reaction in which the acid dissolves minerals from the fracture wall; therefore, a challenge when using acid fracturing is to get the acid to travel a long distance into the fracture network before the acid is consumed. Because the reaction rate (and hence the rate of consumption of acid) is faster at higher temperatures, it becomes difficult to get acid to penetrate deeply into the fracture network at higher temperatures. Thus, at high temperatures, the use of acid fracturing might not be effective.

Furthermore, if the formation is too soft or if the formation pressure is too high, the closing pressure (also called “closure pressure,” i.e., the force pushing the rock faces on opposing sides of a fracture back together) can cause crushing of the asperities, thereby causing closure of the channels etched by the acid. For this reason, acid fracturing becomes less attractive in formations with high closing pressures.

C. Frac Packs

Most hydraulic fracturing operations are conducted in low permeability formations, which are formations with pores that are not well connected, meaning that oil or gas cannot flow easily between different pores. But a special type of fracturing operation is sometimes used in formations with high permeability, including high permeability formations offshore. Such fracturing jobs are sometimes called “frac packs.” Frac packs serve at least two purposes. First, they can help to overcome near-wellbore damage. This clogging can interfere with the flow of oil or natural gas to the well. A small fracturing job that opens and props fractures to points beyond the region that contains near-wellbore damage can increase flow to the well. Second, frac packs can help with sand control. In some formations, the sand is unconsolidated—that is, the sand particles are not cemented together very strongly—and a significant number of sand particles can break away from the formation and be swept into the well along with the oil and gas that flow into it. The proppant particles placed into the formation during the frac pack can act as barriers that minimize the migration of sand into the well. Operators also often

38Id.
39A.M. Gomaa et al., Acid Fracturing: The Effect of Formation Strength on Fracture Conductivity, SPE 119623 (Society of Petroleum Engineers 2009).
40Id.; M.S. Anderson et al., Dynamic Etching Tests Aid Fracture Acidizing Treatment Design, SPE/DOE 16452 (Society of Petroleum Engineers 1989).
41"Damage" refers to clogging of the interconnections between pore throats (the interconnections between pore spaces) by drilling mud and fine rock particles (“fines”) created during the drilling process. Drilling mud is a mixture of clay and either water or oil. During drilling, mud is pumped down the center of the drill pipe. The mud exits the drill pipe through holes in the drill bit. The mud then flows back to the surface, traveling upward through the annular space between the drill pipe and inner wall of the wellbore casing. The mud serves several purposes. It helps cool the drill bit, removing some of the heat that is generated by friction as the drill bit bores through rock. Second, the mud helps carry small bits of rock (called “cuttings”) created during the drilling process out of the well. Also, the weight of the mud helps to maintain well control and prevent blowouts.
put a mesh screen near the wellbore and pack the area around it with gravel. The gravel-pack screen prevents proppants from flowing back into the well and serves as an additional barrier to sand.

The zone that contains damage does not extend far from the wellbore. For this reason and because the formation itself has high permeability, there generally is no need for the operator to create fractures that extend very far from the well. Accordingly, frac packs tend to be smaller fracturing jobs than the operations conducted in shales and other low permeability formations.

**D. Hydraulic Fracturing Using Base Fluids Other Than Straight Water**

Since the late 1990s, water has been the base fluid used in most hydraulic fracturing operations. The use of water has several advantages. Often, it is readily available and inexpensive. It is not explosive, flammable, carcinogenic, or toxic. It is sufficiently dense that, when it is pumped into a formation that is thousands of feet underground, the weight of the water itself provides much of the pressure that is needed to fracture the formation. Also, because it is so often used as a base fluid, companies have extensive experience using it.

But water also can have disadvantages. Sometimes, it is in short supply. To achieve ideal properties, chemical additives often have to be mixed into the fracturing water, and this increases the expense of the fracturing operation. Furthermore, the use of additives sometimes partially offsets water's safety factor and drives much of the public's concern about fracturing. Also, the water that is recovered during flowback must be managed—whether by injection disposal, recycling, or treatment and discharge. Moreover, the high density that allows the weight of a water column to provide much of the pressure that is needed to fracture a formation can work against the operator during flowback or cleanup, when the operator wants the water to flow upward and out of the well. This is particularly an issue in low-pressure formations. Finally, water can damage some formations, such as formations containing certain types of clays that tend to swell when exposed to water, thereby closing the fractures or other pathways that oil or gas need to flow through to the well. These considerations drive some companies to conduct their hydraulic fracturing operations with a base fluid that is composed in whole or part of a fluid other than straight water.

**III. Foams**

To combat the swelling of formations that have high clay content, operators sometimes use a foam that is made using water and either carbon dioxide or nitrogen. By volume, the foam typically is about 50 to 95 percent gas, with the remainder of the volume being water. The use of foam decreases the amount of contact between water and the formation. Decreasing water-formation contact often is the primary incentive to use foam, but foam also decreases the amount of water that is needed and the amount of flowback water that must be managed. It also reduces the amount of chemicals needed for the fracturing treatment.

A drawback, however, is that the lower density of the foam makes it less suitable for deep formations. In these formations, the pressure needed to fracture the formation
often is higher, and it is particularly desirable that the weight of the fracturing fluid provides much of the pressure needed to fracture a formation so that the discharge pressure of the fracturing fluid pumps need not be so high. Furthermore, the nitrogen or carbon dioxide increases the cost of the fracturing operation.

If the formation is sufficiently sensitive to water, even contact with a water-based foam can harm the formation. In such cases, a foam in which the liquid is a mixture of water and methanol, and the gas is either nitrogen or carbon dioxide, can be used. If the formation is severely sensitive to water, methanol can be used as the sole liquid in the foam. A small number of fracturing operations have been performed using a foam in which carbon dioxide is the liquid and nitrogen is the gas.

IV. Energized Fluids

Another hydraulic fracturing technique uses an “energized fluid” that includes both a liquid and a gas (although the gas content is lower than in a foam). A major advantage of an energized fluid is that the gas can expand as pressure drops during flowback, which helps provide some of the energy needed to bring the fracturing fluid back to the surface after the fracturing operation is complete. This advantage can be important in fracturing a low-pressure reservoir because the reservoir’s own pressure may be insufficient to efficiently drive the fracturing flowback to the surface after the fracturing operation is complete. Nitrogen and carbon dioxide often are used as the gases in energized base fluids.

V. Liquid Nitrogen or Carbon Dioxide

Some fracturing operations have also been performed using liquid carbon dioxide or cryogenic liquid nitrogen as a base fluid. The use of these substances can avoid some of the damage that a water-based fluid would cause in a formation that is sensitive to water. Other advantages of carbon dioxide are that it can dissolve into the oil, thereby decreasing its viscosity, and that carbon dioxide is less prone than water to exhibit certain capillary effects that can inhibit flow of natural gas or oil through a narrow pore throat. Cryogenic nitrogen, in turn, can produce a thermal shock to the formation, thereby assisting in fracturing. As with other alternatives to water, a downside is the expense of purchasing the carbon dioxide or nitrogen. Furthermore, cryogenic nitrogen is so cold that typical steel (“carbon steel”) cannot be used with it. Instead, more expensive stainless steel pipes and equipment must be used in the well and fracturing equipment that will be exposed to the cryogenic nitrogen.

VI. Liquefied Petroleum Gas or Liquid Propane

Some companies have fractured using liquefied petroleum gas (LPG), which primarily consists of propane. Fracturing with LPG has several potential advantages. As with other non-water-fracturing techniques, if a formation is sensitive to water, fracturing with LPG may help to avoid the formation damage that might be caused by fracturing with water. Furthermore, fracturing with LPG can eliminate the need for a large supply of
water, and this can be an advantage if water is in short supply in an area. Because LPG has limited miscibility in water, it is less likely to cause groundwater contamination than a water-based fracturing fluid. Finally, during flowback, the propane vaporizes and can be recovered and recycled, eliminating the need to manage a flowback stream.

On the other hand, LPG is flammable. Also, it is not as dense as water, so fracturing pumps will have to supply a higher pressure because the weight of a column of propane supplies less static pressure than the weight of a column of water supplies. Often, LPG is more expensive than water (although this might not be the case in areas where water is in short supply). Additionally, special equipment is needed to recover the propane and operators have less experience fracturing with LPG than with water-based fracturing fluids.

VII. Gas Fracturing

A straight gas, such as nitrogen, also can be used in hydraulic fracturing. This type of waterless fracturing can avoid the clay swelling that can occur in some formations when water is used as the base fluid. One of the disadvantages of fracturing with nitrogen gas is that it has a much lower viscosity than water. Hence, it is not as effective as water at carrying proppants. Furthermore, because nitrogen is less dense than water, it often will not be suitable for fracturing at a deep depth, where fracturing pressures tend to be higher and where it is therefore particularly desirable for the weight of the fracturing fluid to provide much of the pressure needed to fracture the formation. Also, as with the other water alternatives described above, purchase of the nitrogen adds expense.

Although all of these alternative fracturing techniques are not as common as water-based techniques, they have an important role in certain types of formations. Non-water-based fracturing techniques are likely to be particularly attractive in areas with scarce water. For example, in China, where abundant gas reserves are located in shales underlying very dry and mountainous areas, alternative fracturing techniques could be important.42

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