# HYDRAULIC FRACTURING

## History of

### AN ENDURING TECHNOLOGY

**Carl T. Montgomery and Michael B. Smith, NSI Technologies**

**Editor's note:** In 2006, SPE honored nine pioneers of the hydraulic fracturing industry as Legends of Hydraulic Fracturing. Claude E. Cooke Jr., Francis E. Dollarhide, Jacques L. Elbel, C. Robert Fast, Robert R. Hannah, Larry J. Harrington, Thomas K. Perkins, Mike Prats, and H.K. van Poollen were recognized as instrumental in developing new technologies and contributing to the advancement of the field through their roles as researchers, consultants, instructors, and authors of ground-breaking journal articles.

Following is an excerpt from SPE's new Legends of Hydraulic Fracturing CDROM, which contains an extended overview of the history of the technology, list of more than 150 technical papers published by these industry legends, personal reflections from a number of the Legends and their colleagues, and historic photographs. For more information on the CDROM, please go to http://store.spe.org/Legendsof-Hydraulic-Fracturing-P433.aspx.

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Since Stanolind Oil introduced hydraulic fracturing in 1949, close to 2.5 million fracture treatments have been performed worldwide. Some believe that approximately 60% of all wells drilled today are fractured. Fracture stimulation not only increases the production rate, but it is credited with adding to reserves–9 billion bbl of oil and more than 700 Tscf of gas added since 1949 to US reserves alone–which otherwise would have been uneconomical to develop. In addition, through accelerating production, net present value of reserves has increased.

Fracturing can be traced to the 1860s, when liquid (and later, solidified) nitroglycerin (NG) was used to stimulate shallow, hard rock wells in Pennsylvania, New York, Kentucky, and West Virginia. Although extremely hazardous, and often used illegally, NG was spectacularly successful for oil well "shooting." The object of shooting a well was to break up, or rubblize, the oil-bearing formation to increase both initial flow and ultimate recovery of oil. This same fracturing principle was soon applied with equal effectiveness to water and gas wells.

In the 1930s, the idea of injecting a nonexplosive fluid (acid) into the ground to stimulate a well began to be tried. The "pressure parting" phenomenon was recognized in well-acidizing operations as a means of creating a fracture that would not close completely because of acid etching. This would leave a flow channel to the well and enhance productivity. The phenomenon was confirmed in the field, not only with acid treatments, but also during water injection and squeeze-cementing operations.

**Fig. 1—**In 1947, Stanolind Oil conducted the first experimental fracturing in the Hugoton field located in southwestern Kansas. The treatment utilized napalm (gelled gasoline) and sand from the Arkansas River.

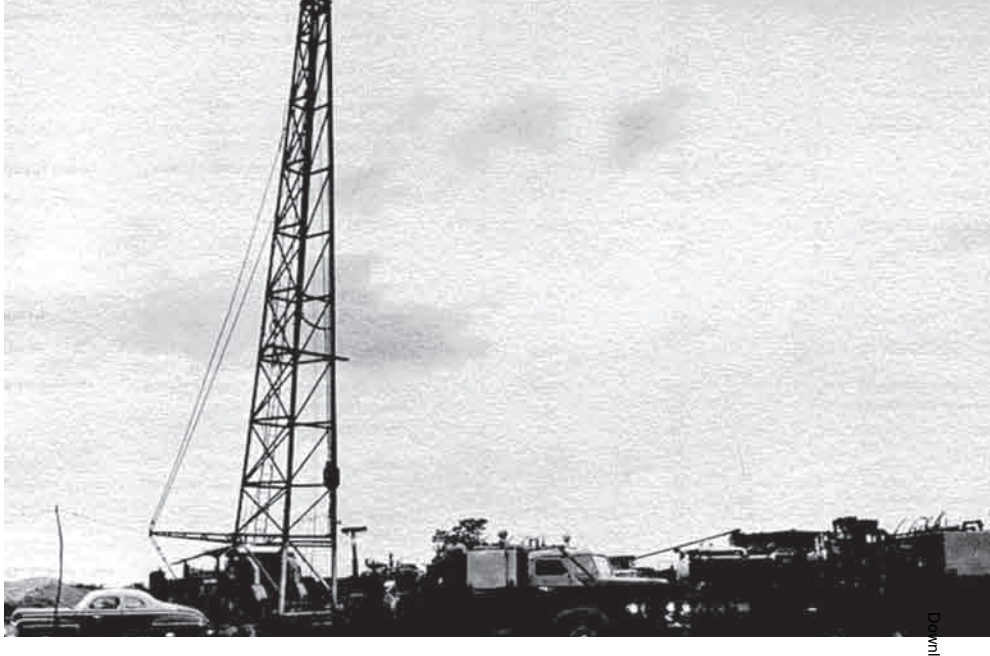

**Fig. 2—**On 17 March, 1949, Halliburton conducted the first two commercial fracturing treatments in Stephens County, Oklahoma, and Archer County, Texas.

But it was not until Floyd Farris of Stanolind Oil and Gas Corporation (Amoco) performed an in-depth study to establish a relationship between observed well performance and treatment pressures that "formation breakdown" during acidizing, water injection, and squeeze cementing became better understood. From this work, Farris conceived the idea of hydraulically fracturing a formation to enhance production from oil and gas wells.

The first experimental treatment to "Hydrafrac" a well for stimulation was performed in the Hugoton gas field in Grant County, Kansas, in 1947 by Stanolind Oil **(Fig. 1).** A total of 1,000 gal of naphthenic-acid-and-palm-oil- (napalm-) thickened gasoline was injected, followed by a gel breaker, to stimulate a gas-producing limestone formation at 2,400 ft. Deliverability of the well did not change appreciably, but it was a start. In 1948, the Hydrafrac process was introduced more widely to the industry in a paper written by J.B. Clark of Stanolind Oil. A patent was issued in 1949, with an exclusive license granted to the Halliburton Oil Well Cementing Company (Howco) to pump the new Hydrafrac process.

Howco performed the first two commercial fracturing treatments–one, costing USD 900, in Stephens County, Oklahoma, and the other, costing USD 1,000, in Archer County, Texas–on March 17, 1949, using lease crude oil or a blend of crude and gasoline, and 100 to 150 lbm of sand **(Fig. 2).** In the first year, 332 wells were treated, with an average production increase of 75%. Applications of the fracturing process grew rapidly and increased the supply of oil in the United States far beyond anything anticipated. Treatments reached more than 3,000 wells a month for stretches during the mid-1950s. The first one-half-million-pound fracturing job in the free world was performed in October 1968, by Pan American Petroleum Corporation (later Amoco, now BP) in Stephens County, Oklahoma. In 2008, more than 50,000 frac stages were completed worldwide at a cost of anywhere between USD 10,000 and USD 6 million. It is now common to have from eight to as many as 40 frac stages in a single well. Some estimate that hydraulic

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**Fig. 3**—A 1955 frac pump manufacturing facility. These remotely controlled pumps were powered by 1,475 hp surplus Allison aircraft engines used during World War II.

fracturing has increased US recoverable reserves of oil by at least 30% and of gas by 90%.

## Fluids and Proppants

Soon after the first few jobs, the average fracture treatment consisted of approximately 750 gal of fluid and 400 lbm of sand. Today treatments average approximately 60,000 gal of fluid and 100,000 lbm of propping agent, with the largest treatments exceeding 1 million gal of fluid and 5 million lbm of proppant.

## Fluids

The first fracture treatments were performed with a gelled crude. Later, gelled kerosene was used. By the latter part of 1952, a large portion of fracturing treatments were performed with refined and crude oils. These fluids were inexpensive, permitting greater volumes at lower cost. Their lower viscosities exhibited less friction than the original viscous gel. Thus, injection rates could be obtained at lower treating pressures. To transport the sand, however, higher rates were necessary to offset the fluid's lower viscosity.

With the advent in 1953 of water as a fracturing fluid, a number of gelling agents were developed. The first patent (US Patent 3058909) on guar crosslinked by borate was issued to Loyd Kern with Arco on October 16, 1962. One of the legends of hydraulic fracturing, Tom Perkins, was granted the first patent (US Patent 3163219) on December 29, 1964 on a borate gel breaker. Surfactants were added to minimize emulsions with the formation fluid, and potassium chloride was added to minimize the effect on clays and other water-sensitive formation constituents. Later, other clay-stabilizing agents were developed that enhanced the potassium chloride, permitting the use of water in a greater number of formations. Other innovations, such as foams and the addition of alcohol, have also enhanced the use of water in more formations. Aqueous fluids such as acid, water, and brines are used now as the base fluid in approximately 96% of all fracturing treatments employing a propping agent.

In the early 1970s, a major innovation in fracturing fluids was the use of metal-based crosslinking agents to enhance the viscosity of gelled water-based fracturing fluids for higher-temperature wells. It is interesting to note that the chemistry used to develop these fluids was "borrowed" from the plastic explosives industry. An essential parallel development meant fewer pounds of gelling agent were required to obtain a desired viscosity. As more and more fracturing treatments have involved high-temperature wells, gel stabilizers have been developed, the first of which was the use of approximately 5% methanol. Later, chemical stabilizers were developed that could be used alone or with the methanol.

Improvements in crosslinkers and gelling agents have resulted in systems that permit the fluid to reach the bottom of the hole in high-temperature wells prior to crosslinking, thus minimizing the effects of high shear in the tubing. Ultraclean gelling agents based on surfactant-association chemistry and encapsulated breaker systems that activate when the fracture closes have been developed to minimize fracture-conductivity damage.

## Proppants

The first fracturing treatment used screened river sand as a proppant. Others that followed used construction sand sieved through a window screen. There have been a number of trends in sand size, from very large to small, but, from the beginning, a –20 +40 US-standard-mesh sand has been the most popular, and currently approximately 85% of the sand used is this size. Numerous propping agents have been evaluated throughout the years, including plastic pellets, steel shot, Indian glass beads, aluminum pellets, high-strength glass beads, rounded nut shells, resin-coated sands, sintered bauxite, and fused zirconium.

The concentration of sand (lbm/fluid gal) remained low until the mid-1960s, when viscous fluids such as crosslinked water-based gel and viscous refined oil were introduced. Large-size propping agents were advocated then.

The trend then changed from the monolayer or partial monolayer concept to pumping higher sand concentrations. Since that time, the

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**Fig. 4—**Early screw-type sand blender.

**Fig. 5—**Modern fluid/proppant blender or proportioning unit.

concentration has increased almost continuously, with a sharp increase in recent years. These high sand concentrations are due largely to advances in pumping equipment and improved fracturing fluids. Now it is not uncommon to use proppant concentrations averaging 5 to 8 lbm/gal throughout the treatment, with a low concentration at the start of the job, increased to 20 lbm/gal toward the end of the job.

## Pumping and Blending Equipment

Hydraulic horsepower (hhp) per treatment has increased from an average of approximately 75 hhp to more than 1,500 hhp. There are cases where, with as much as 15,000 hhp available, more than 10,000 hhp was actually used, in stark contrast with some early jobs, where only 10 to 15 hhp was employed. Some of the early pump manufacturing facilities made remotely controlled pumps powered by surplus Allison aircraft engines used during World War II **(Figs. 3, 6).**

Initial jobs were performed at rates of 2 to 3 bbl/min. This increased rapidly until the early 1960s, when it rose at a slower rate, settling in the 20 bbl/min range (even though there were times when the rate employed in the Hugoton field was more than 300 bbl/min). Then in 1976, Othar Kiel started using high-rate "hesitation" fractures to cause what he called "dendritic" fractures. Today, in the unconventional shale-gas plays, Kiel's ideas are used where the pump rates are more than 100 bbl/min. Surface treating pressures sometimes are less than 100 psi, yet others may approach 20,000 psi.

Conventional cement- and acid-pumping equipment was used initially to execute fracturing treatments. One to three units equipped with one pressure pump delivering 75 to 125 hhp were adequate for the small volumes injected at the low rates. Amazingly, many of these treatments gave phenomenal production increases. As treating volumes increased, accompanied by a demand for greater injection rates, special pumping and blending equipment was developed. Development of equipment including intensifiers, slinger, and special manifolds continues. Today, most treatments require that service companies furnish several million dollars' worth of equipment.

For the first few years, sand was added to the fracturing fluid by pouring it into a tank of fracturing fluid over the suction. Later, with less-viscous fluid, a ribbon or paddle type of batch blender was used. Shortly after this, a continuous proportioner blender utilizing a screw to lift the sand into the blending tub was developed **(Fig. 4).** Blending equipment has become very sophisticated to meet the need for proportioning a large number of dry and liquid additives, then uniformly blending them into the base fluid and adding the various concentrations of sand or other propping agents. **Fig. 5** shows one of these blending units**.**

To handle large propping-agent volumes, special storage facilities were developed to facilitate their delivery at the right rate through the fluid. Treatments in the past were conducted remotely but still without any shelter. Today, treatments have a very sophisticated control center to coordinate all the activities that occur simultaneously.

**Fig. 6—**Vintage 1950s remotely controlled frac pumper powered by surplus WWII Allison aircraft engines.

## Fracture-Treatment Design

The first treatments were designed using complex charts, nomographs,

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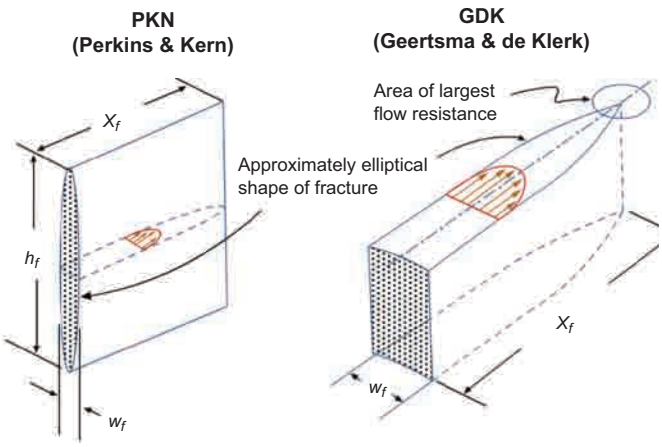



**Fig. 7—**Early 2D fracture-geometry models.

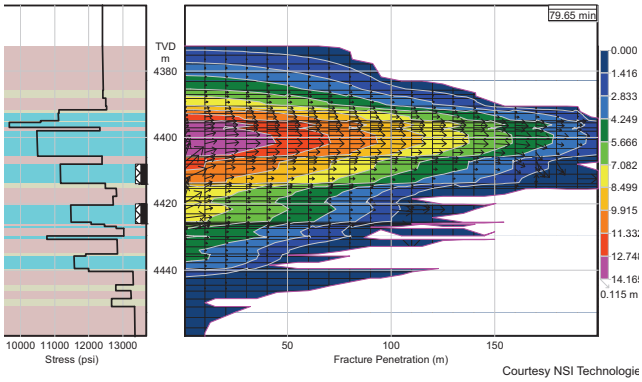
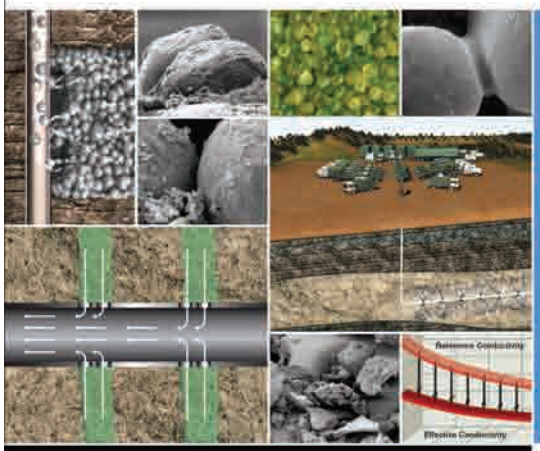



**Fig. 8—**Modern fully gridded frac model showing fluid and proppant vectors.

and calculations to determine appropriate size, which generally was close to 800 gal (or multiples thereof) of fluid, with the sand at concentrations of 0.5 to 0.75 lbm/gal. This largely hit-or-miss method was employed until the mid-1960s, when programs were developed for use on simple computers. The original programs were based on work developed by Khristianovic and Zheltov (1955), Perkins and Kern (1961), and Geertsma and de Klerk (1969) on fluid efficiency and the shape of a fracture system in two dimensions **(Fig. 7).** These programs were a great improvement but were limited in their ability to predict fracture height.

As computer capabilities have increased, frac-treatment-design programs have evolved to include fully gridded finite-element programs that predict fracture geometry and flow properties in three dimensions **(Fig. 8).** Today, programs are available to obtain a temperature profile of the treating fluid during a fracturing treatment, which can assist in designing the concentrations of the gel, gel-stabilizer, breaker, and propping-agent during treatment

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stages. Models have been developed to simulate the way fluids move through the fracture and the way the propping agent is distributed. From these models, production increases can be determined. Models can also be used to historically match production following a fracturing treatment to determine which treatment achieved which actual result. New capabilities are currently being developed that will include the interaction of the induced fracture with natural fractures.

One of the hydraulic fracturing legends, H.K. van Poollen, performed work on an electrolytic model to determine the effect fracture lengths and flow capacity would have on the production increase obtained from wells with different drainage radii. Several others developed mathematical models for similar projections. Today, there are models that predict production from fractures with multiphase and non-Darcy flow using any proppant available.

## Fracturing's Historic Success

Many fields would not exist today without hydraulic fracturing. In the US, these include the Sprayberry trend in west Texas; Pine Island field, Louisiana; Anadarko basin; Morrow wells, northwestern Oklahoma; the entire San Juan basin, New Mexico; the Denver Julesburg basin, Colorado; the east Texas and north Louisiana trend, Cotton Valley; the tight gas sands of south Texas and western Colorado; the overthrust belt of western Wyoming; and many producing areas in the northeastern US.

As the global balance of supply and demand forces the hydrocarbon industry toward more unconventional resources including US shales such as the Barnett, Haynesville, Bossier, and Marcellus gas plays, hydraulic fracturing will continue to play a substantive role in unlocking otherwise unobtainable reserves. JPT

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