Historical Development of Well Stimulation and Hydraulic Fracturing Technologies*

Stephen M. Testa[1]

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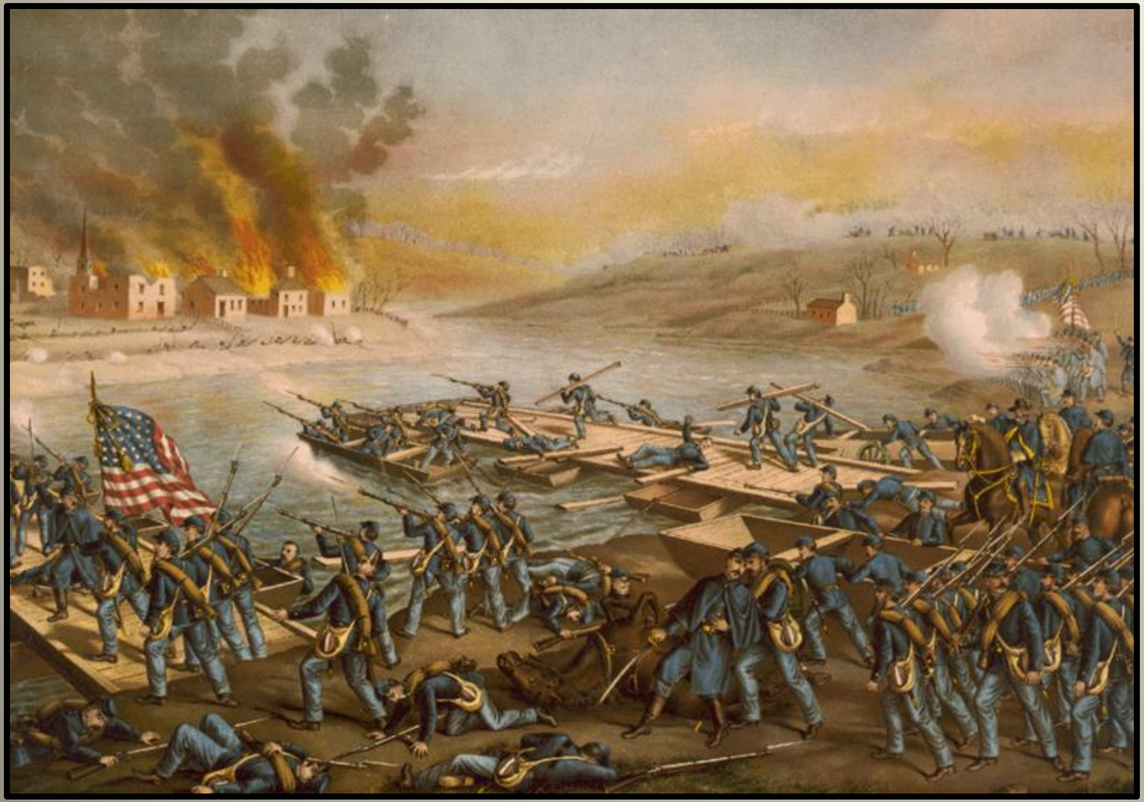
Abstract

The well completion and enhancement technique known as hydraulic fracturing is a highly visible and controversial topic as evidenced by multitudes of news articles, regulatory workshops, local public hearings, and documentaries and films such as Gasland, FrackNation and Promised Land. From an historical perspective, interest in the production of natural gas from shale has its roots in the early 1820s, whereas, technological innovation and entrepreneurship in enhancing oil production takes hold during the 1860s. Since such time, a myriad of innovative techniques have been pursued to enhance oil and gas production. Many of these techniques owe their origins to technological developments and advances within the military complex. Hydraulic fracturing is a well stimulation technique where rock is fractured via pressurized liquid. Historic development can be divided into four major phases: Explosives and Guns (1820s-1930s); The Birth of the Petroleum Engineer (1940s-1950s); Going Nuclear during Peak Oil (1960s-mid1970s); and The Rise of the Unconventionals (mid1970s-present).

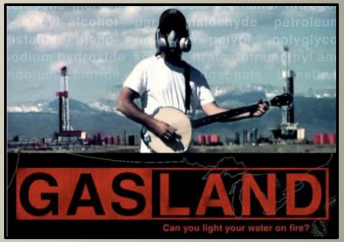
The concept of fracturing rock adjacent to a well bore can be traced back to the mid-1860s with the use of explosives and development of the petroleum torpedo. Following World War I, the use of technology developed during the war years would lead to downhole well casing perforators and perforating guns. Chemistry comes into play in the early 1930s with the development of acidizing treatments under pressure. Hydraulic fracturing in a more modern context has its domestic roots in the late 1940s, and by the 1950s was also being developed in the Soviet Union, and by the 1970s and 1980s in Western Europe. After World War II well stimulation would go nuclear. Nuclear fracturing makes a cameo appearance in the 1960s. Other techniques during this period such as water injection and squeeze-cementing techniques were also being developed. With the later development of horizontal drilling techniques, along with developments in the use of fluids and proppants, pumping and blending equipment, and fracture-treatment design, these advances would have a profound and dramatic impact in the number of producing oil and gas fields nationwide, and the significant role unconventional resources would play in the future.

Historic Development of Well Stimulation – Hydraulic Fracturing Techniques

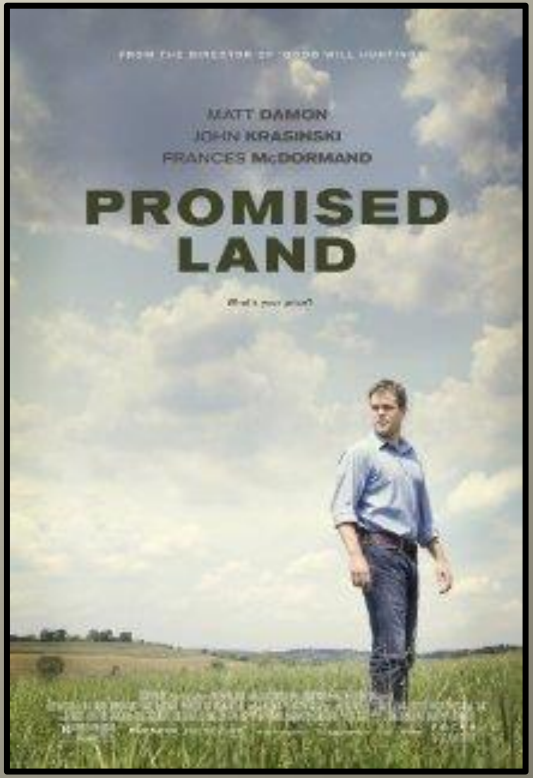


FracNation

Gas Lands



Dear Mr. Obama



Pacific & Rocky Mountain Section American Association of Petroleum Geologists
Annual Joint Meeting
October 2-5, 2016
Las Vegas, Nevada

Stephen M. Testa
President
Testa Environmental Corporation
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Frackramento

Not since Climategate, the BP spill or the Japan Tohoku Earthquake/Tsunami and Fukushima disaster, has something in earth science captured the public's attention at the local coffee shop and just about every corner downtown Frackramento.
I am not referring to the Wall Street Journal, Los Angeles Times or the Bakersfield Californian – but there it was…

Sacramento News and Review
March 29, 2012

Other SN&R Releases

[Fighting the frack](#)
Environmental groups and some state legislators are pushing for new rules on fracking in California. **SN&R**, 08.02.12.

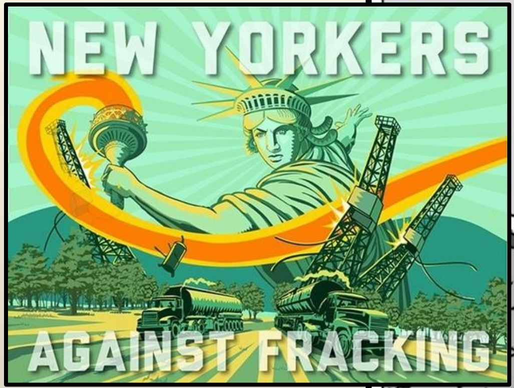
[Fracking in Sacramento: Gasland cometh?](#)
The controversial natural-gas extraction method seen in the recent Oscar-nominated documentary slowly creeps into the region. **SN&R**, 08.25.11.

[Oh, frack!](#)
Do you know where gas is being extracted? Neither does the state. **SN&R**, 03.29.12.

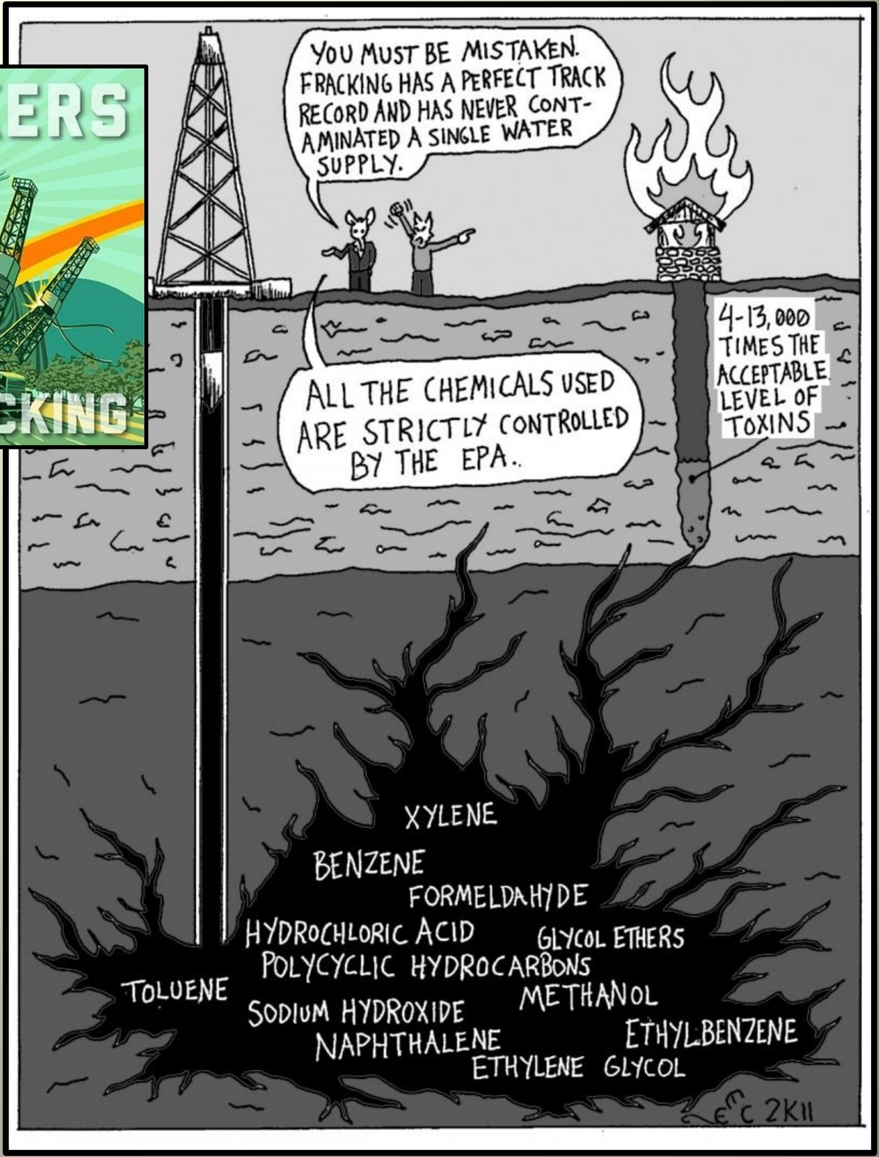
[Environmentalists sue California, spark fracking feud](#)
California doesn't regulate this new method of oil and gas exploration, so activists sued. **SN&R**, 12.13.12.

[California lawmakers need to control fracking](#)
Sen. Fran Pavley's bill represents the hope for regulating hydraulic fracturing. **SN&R**, 08.29.13.

Fracking Bans



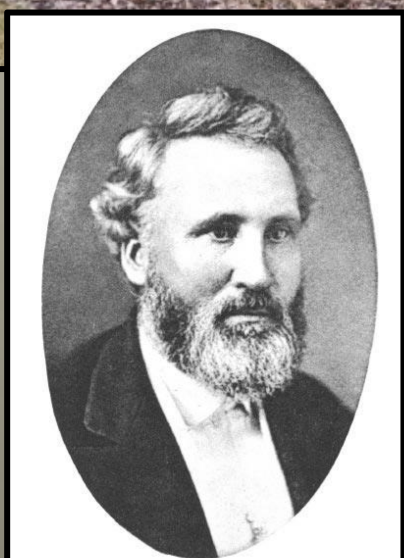
"I don't have any reasons.
I left them all behind.
I'm In a New York State of Mind"
Billy Joel (1976)



- **Amherst, MA; Kirkland, NY; Dryden, PA; Wellsburg City, OH…**
- **Maryland, New Jersey & New York.**
- **Bulgaria, The Czech Republic, France, Germany, Ireland, Luxemburg, Northern Ireland, Scotland, Spain, Wales…**
- **The Canton of Fribourg, Switzerland…**
- **Numerous other cities, counties and regions.**

- **Texas Bans Bans on Fracking (May 2014)**
- **Fracking Bans No Longer Allowed In Oklahoma (June 2015)**

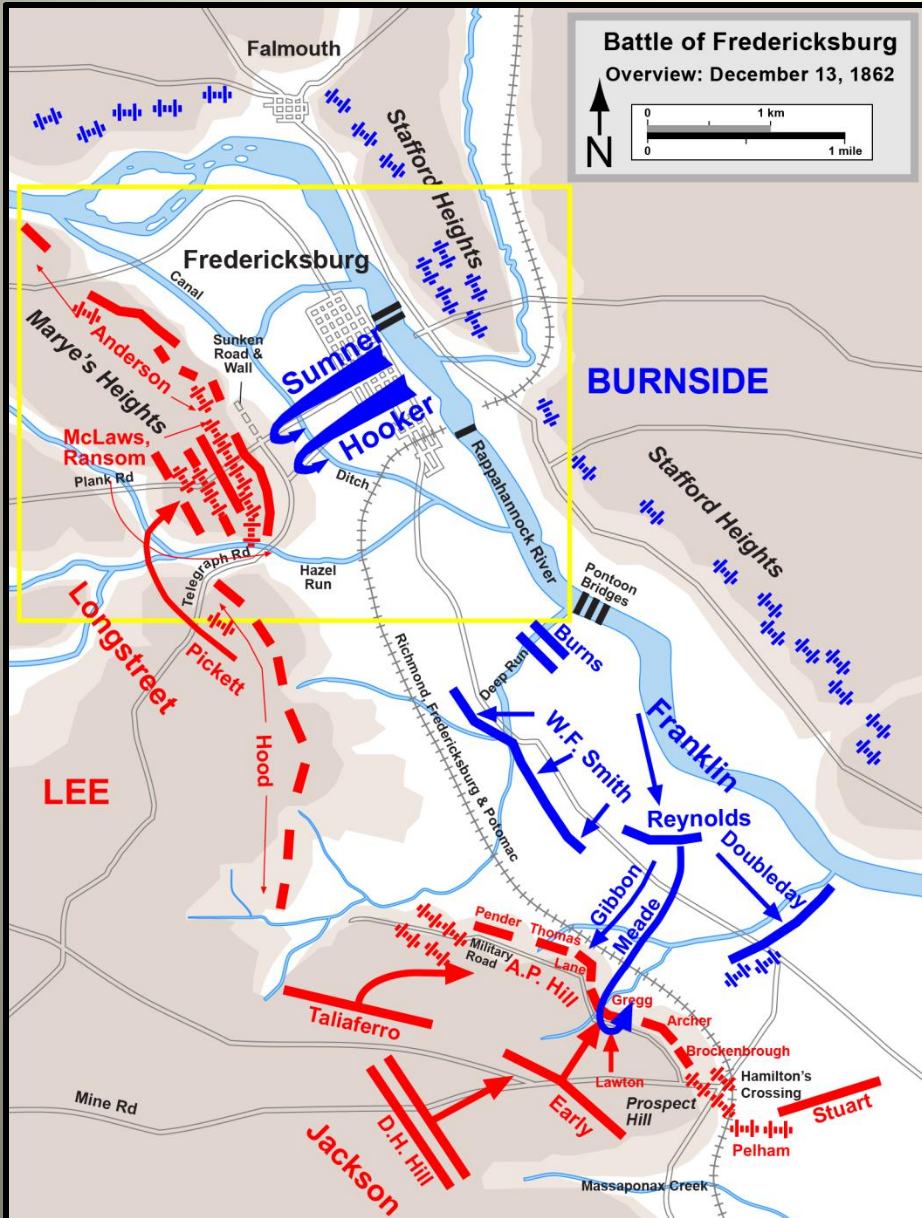
Explosives and Guns (1860s - 1930s)



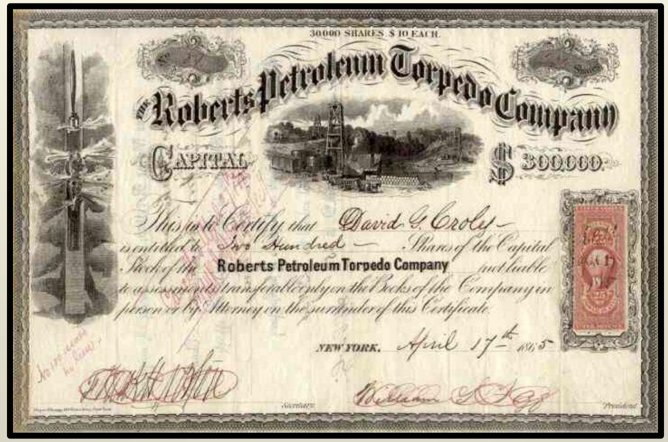
1860-1864 - Civil War and the story of Edwards A. Roberts (1829-1881)

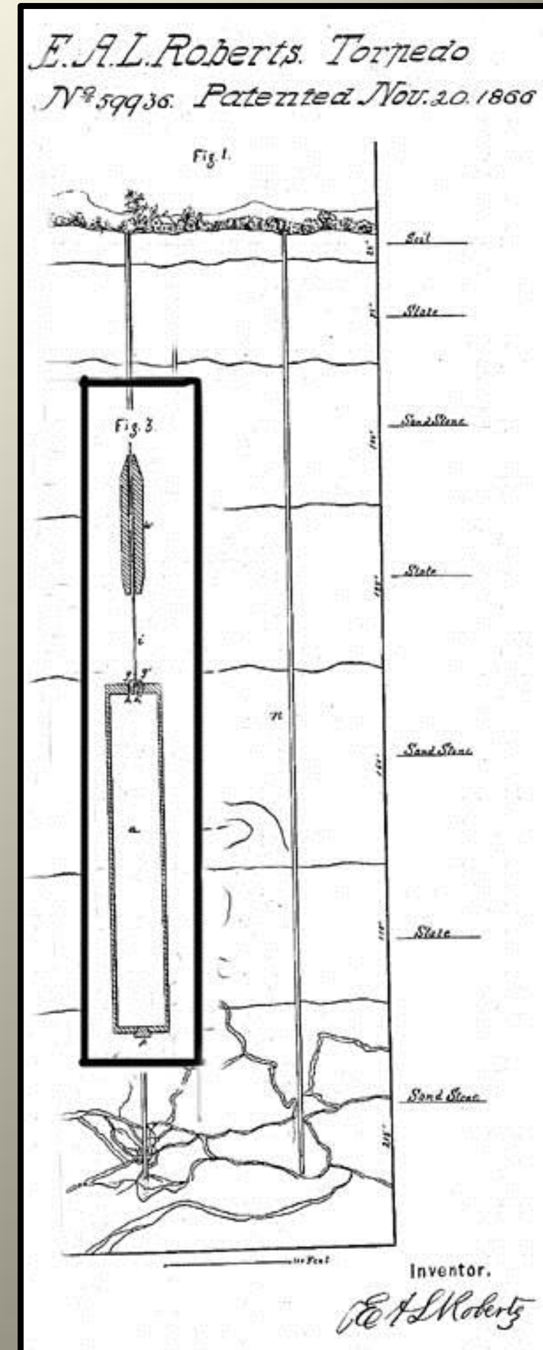
Pre-Noteworthy Events

- 1825 – First well drilled for gas from shale in Fredonia, New York.
    - Shale use limited to small-scale operations mostly for streetlight illumination.
- William Hart noticed gas bubbling out of the bed of Canadaway Creek in the village of Fredonia, Chautauqua County, New York. He dug, with pick and shovel, a 27-foot deep gas well into Devonian shale.
- The gas provided the light of “two good candles”, and shortly enough natural gas for lights in two stores, two shops, and a grist mill.
- 1859 – Edwin Drake will drill the first commercially successful oil well in Titusville, Pennsylvania, 34 years later.



- **Civil War (1860-1864) –**
  - **Battle of Fredericksburg (Dec. 11-15, 1862).**
    - **Remembered as one of the most one-sided battles of the Civil War.**
    - **Largest concentration of combatants (nearly 172K;G/158K)).**
- **Confederate victory.**
- **First instance of urban warfare during the Civil War.**





Edwards A. Roberts (1829-1881), an American Civil War veteran, came up with the concept of using water to "tamp" the resulting explosion, after watching Confederate artillery rounds explode in a canal at the Battle of Fredericksburg.

- **First developed in 1865 – 1866.**
- **Patent granted 1866; expired in 1879.**
- **$100-$200 per torpedo plus royalty 1/15 of inc. production est. at 1200% .**
- **Spent $250,000 to protect his patent hiring the Pinkerton Detective Agency and filing numerous lawsuits.**

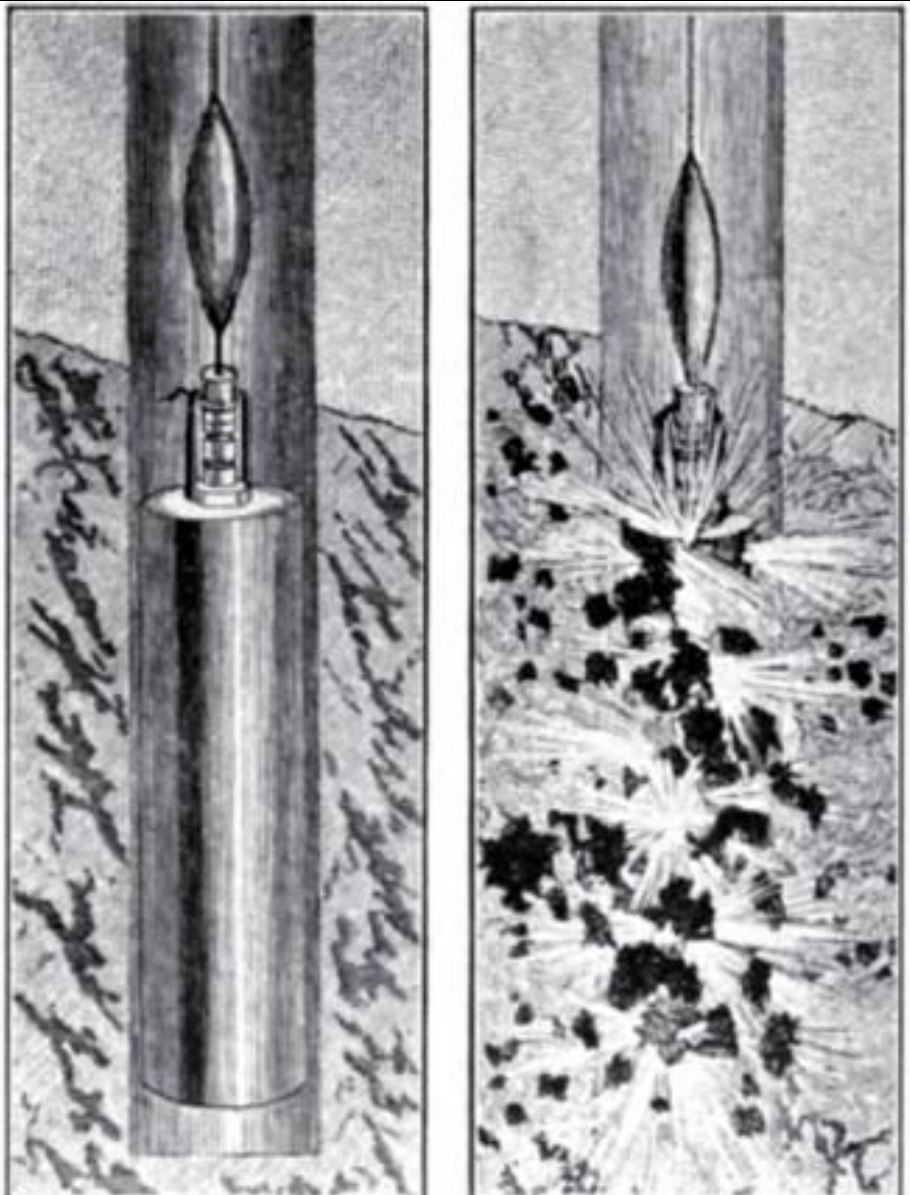
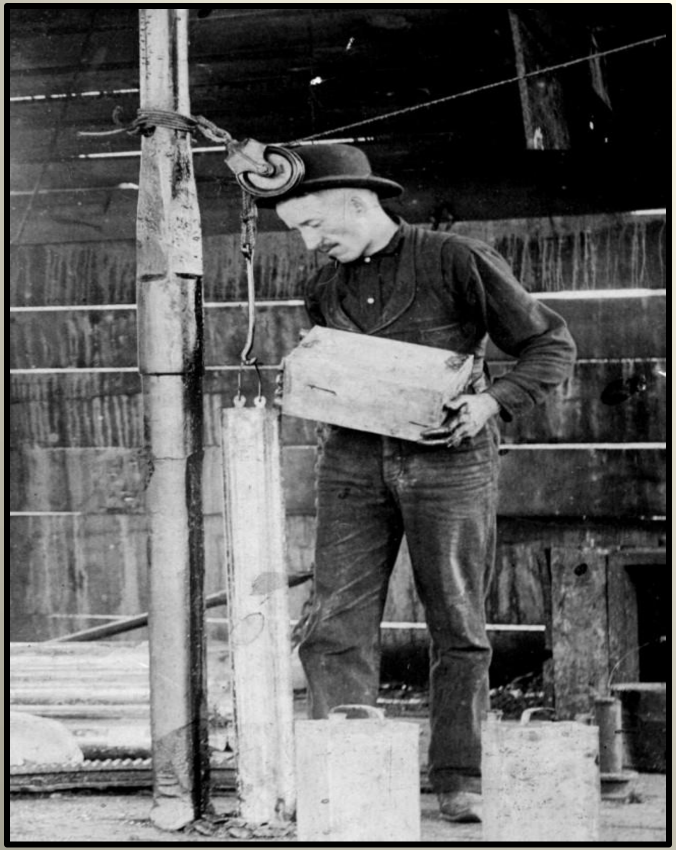


FIG. 134.—The Roberts torpedo, before and during explosion.

- Gunpowder (15-20 lbs. of powder) first used followed by nitroglycerin until 1990.
- Well filled with water to prevent explosion from escaping upward.
- Topmost canister had a "percussion cap".
- Later design had an inner explosive tube within a larger tube packed with sand.

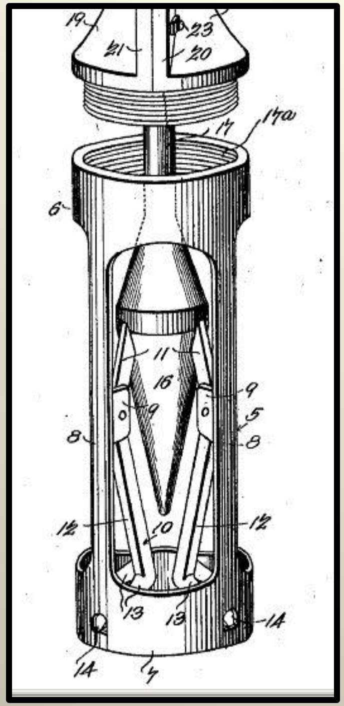


Shooters

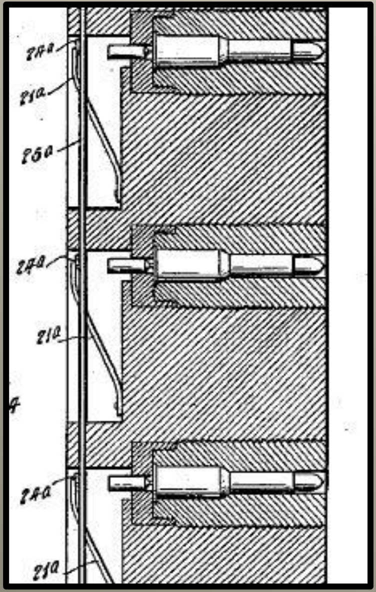
- **Competitors illegally produced torpedoes and used them at night ("moonlighters").**
- **Upon Roberts death, business sold to employees forming the Independent Explosives Company.**
- **Applied legally or illegally, by 1868 nitroglycerin was preferred to black powder, despite its frequently fatal tendency to detonate accidentally.**

"A flame or a spark would not explode Nitro-Glycerin readily, but the chap who struck it a hard rap might as well avoid trouble among his heirs by having had his will written and a cigar-box ordered to hold such fragments as his weeping relatives could pick from the surrounding district," **(noted John J. McLauren in 1896 in his book *Sketches in Crude Oil — Some Accidents and Incidents of the Petroleum Development in all parts of the Globe*).**

Perforators & Guns

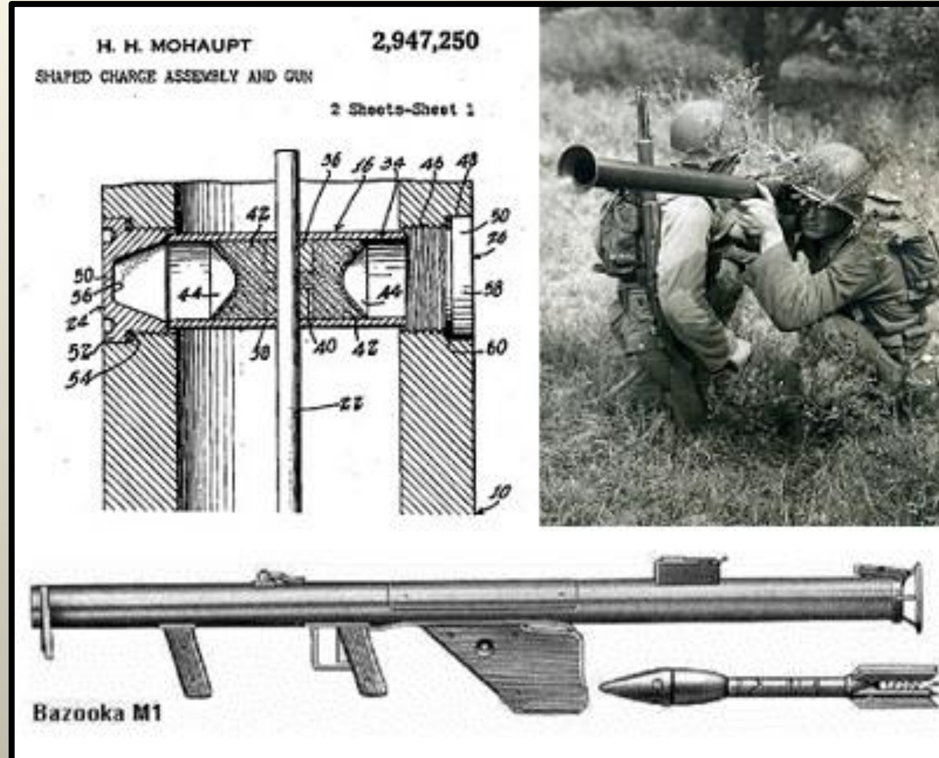


A 1902 invention used a scissors-like expanding mechanism to drive and then retract "perforating levers" through the casing. (http://aoghs.org/oilfield-technologies/downhole-bazooka)



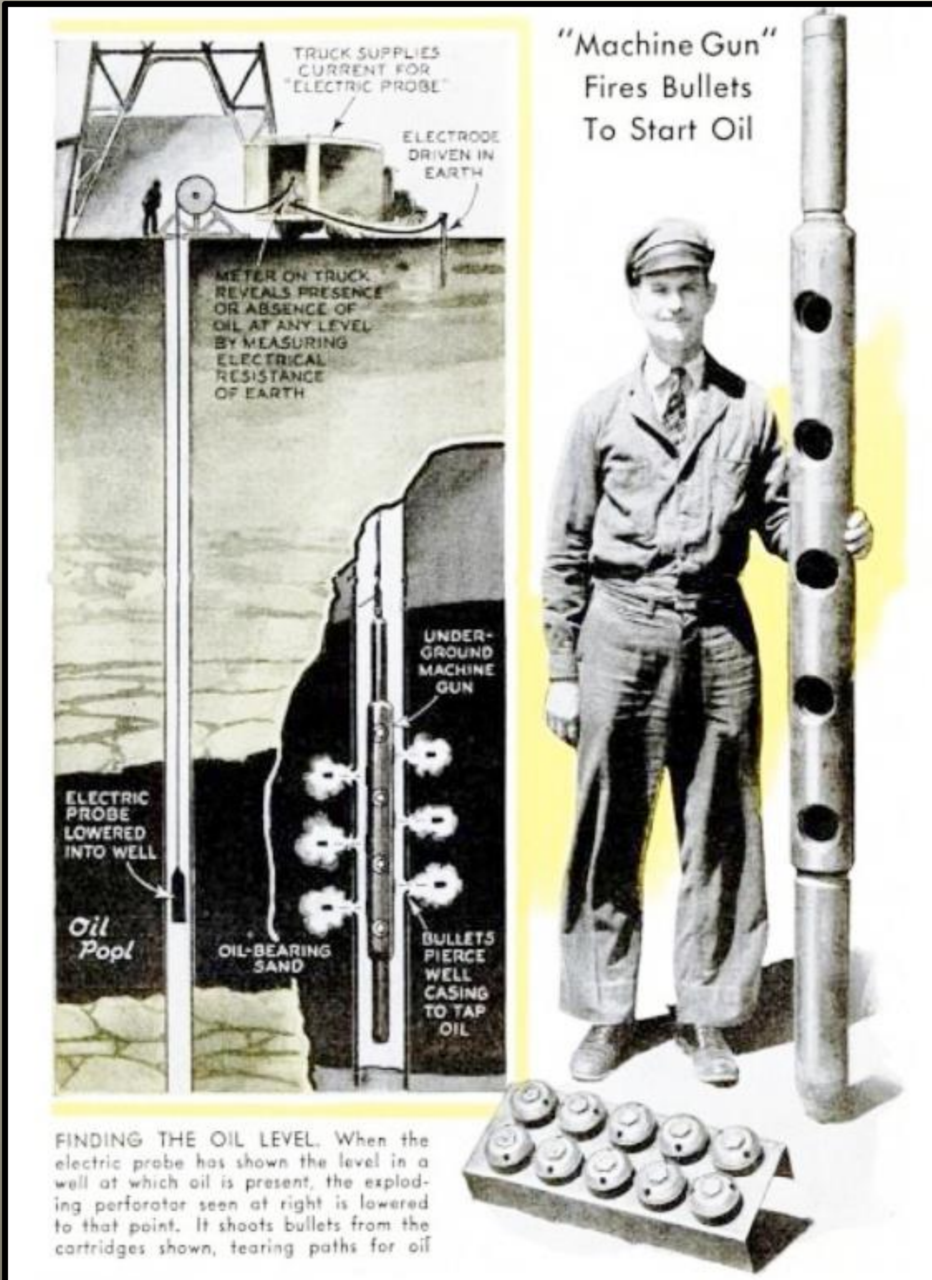
The 1930s brought various downhole "guns" that shot steel-jacketed bullets through casing and about a foot into the producing formation. (http://aoghs.org/oilfield-technologies/downhole-bazooka)

Henry (Heinrich) Mohaupt
(1915-2001)



- **Swiss American inventor and machine gunner in the Swiss Army preparing for WWII.**

- **Mohaupt's revolutionary idea was to use a conically hollowed-out explosive charge to direct and focus the detonation's energy.**
  (http://aoghs.org/oilfield-technologies/downhole-bazooka) (US Patent Office No. 2,947,250, 1960)



Although not a "machine gun" as noted in this August 1938 Popular Science Monthly article, vital production technologies provide explosive energy to cut through casing and strata – and produce petroleum. **(August 1938 Popular Science Monthly)**

- **Shaped charge warheads/perforators.**
- **First mechanical perforator patented in 1910.**
- **Gun perforators successfully used since 1927, patented in 1926.**
- **Early forms were "bullet devices" using actual projectiles.**
- **Lined-shaped charges would follow for deeper penetration (1935-1939).**

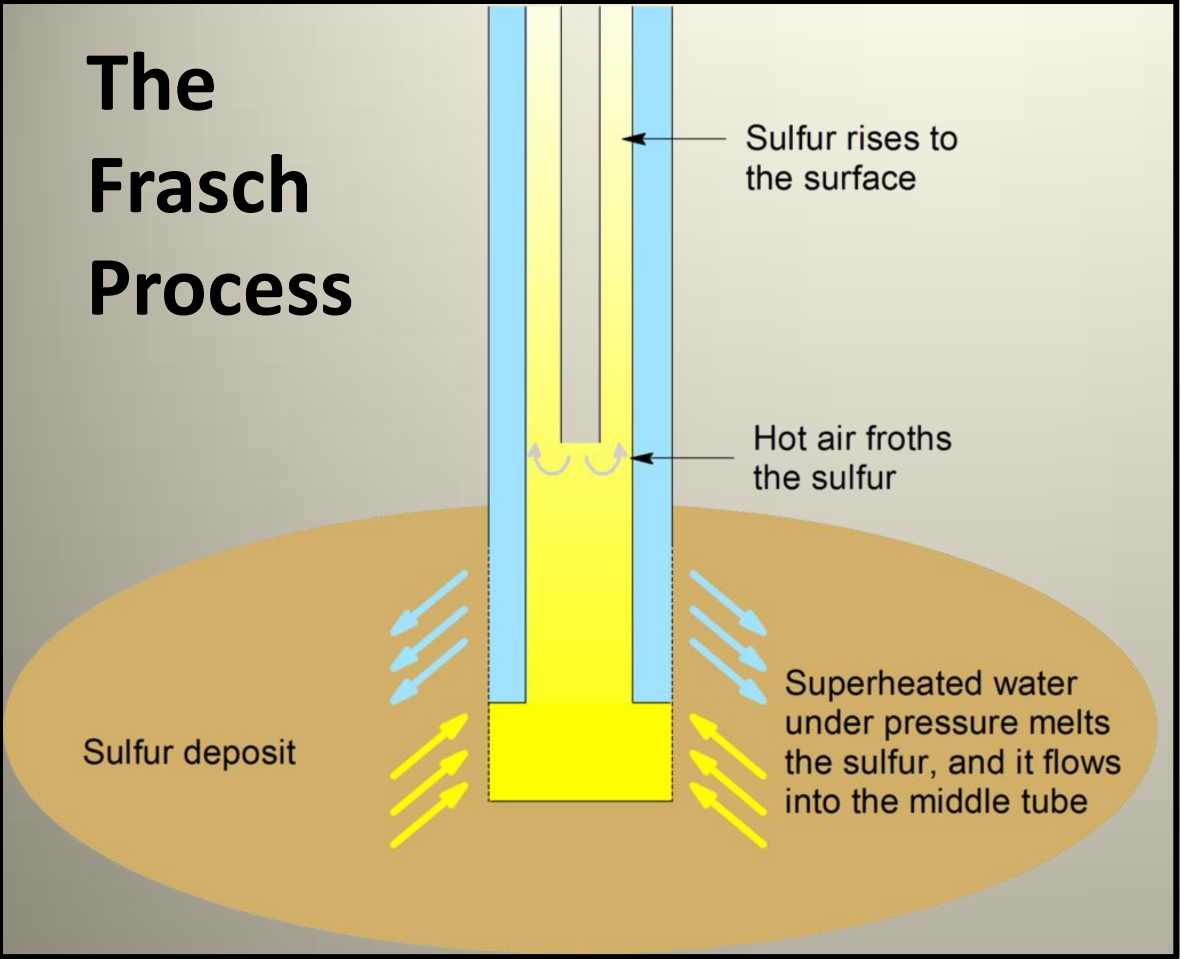
The Sulphur King

- In 1890, German born Herman Frasch invented a new way of mining for sulphur at Sulphur, Louisiana, which within twenty years changed the U.S. from an importer of the mineral to a country with such an abundant new supply that Frasch-produced sulphur dominated the world market.
- Assisted in winning WWI (with abundant S – U.S. could manufacture munitions quickly and cheaply.
- Invented wax paper.

U.S. chemist Herman Frasch (1851-1914) developed the sulfur mining process - a method for removing sulfur from crude oil, both referred to as the Frasch process.

When John D. Rockefeller found he had a virtually worthless oil field in Ohio, it was Herman Frasch who saved the day. So-called 'sour' oil was so-named because of too much sulphur in the mix. Frasch figured out how to extract that sulphur. That made the difference between Rockefeller getting sixteen cents per barrel, to getting over a dollar. With over 25 million barrels at stake, that amounted to quite a fortune!

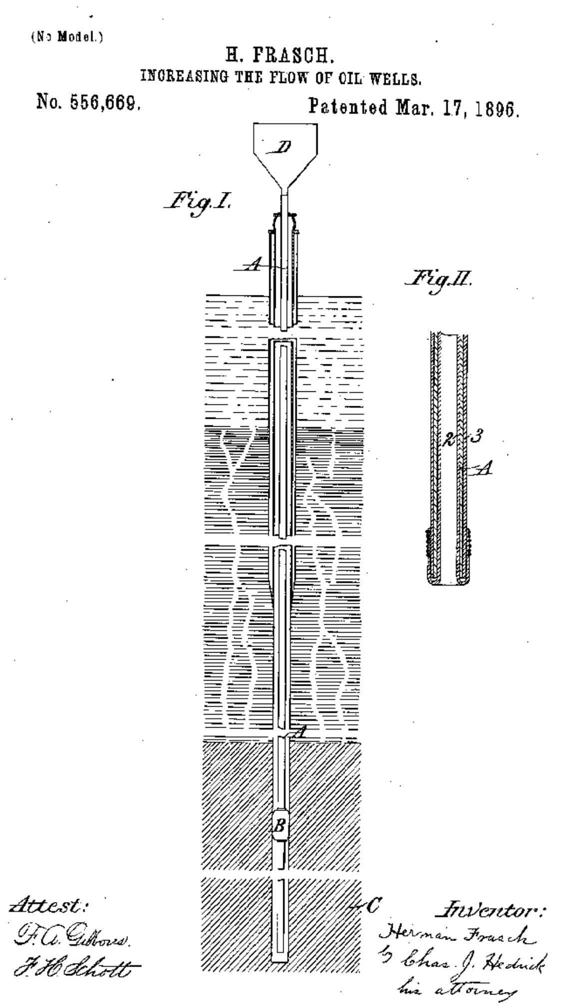
The Frasch Process



- In the Frasch process, three concentric tubes are introduced into the sulfur deposit.
- Superheated water (165 °C, 2.5-3 MPa) is injected into the deposit via the outermost tube.
- Sulfur (m.p. 115 °C) melts and flows into the middle tube.
- Water pressure alone is unable to force the sulfur into the surface due to the molten sulfur's greater density, so hot air is introduced via the innermost tube to froth the sulfur, making it less dense, and pushing it to the surface.

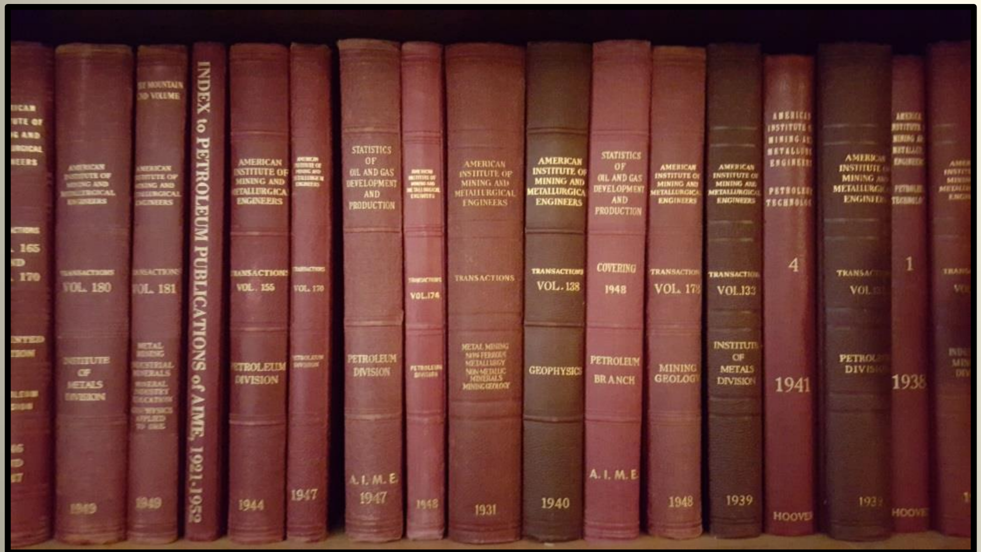
Frasch's Interest in the Oil Fields

- In 1885 Frasch entered upon experiments leading to one of his most important discoveries, the purification of sulphur-tainted oils, such as are found in the oil fields of Canada, Ohio, Indiana and Illinois.
- The presence of sulphur in these oils greatly limited their range of utility, because of the offensive odors and suffocating fumes liberated when they were burned.
- Such defects, of course, reduced their value to the lowest terms, the usual price at the wells being as low as fourteen cents per barrel.
- Apart from the presence of these impurities, however, the oils were of excellent quality, capable of refinement into illuminating oils of high grade, as well as into the coarser products fit only for fuel purposes.



Herman Frasch U.S. Patent No. 556,669 illustrating the increasing the <u>flow of oil in a well (Frasch,</u> 1896).

- **On one occasion Frasch was appealed to devise a method for rejuvenating "tired wells" suitable to conditions of western fields.**
- **In PA the usual method had been to drop a charge of nitroglycerine into the well, to shatter the surrounding rock by explosion and thus promote new flow of oil.**
- **Geological considerations, relating principally to the quality of the rock, also to its depth below the surface rendered this procedure inapplicable to wells in IN and OH.**
- **Use of hydrochloric or sulphuric acid, the one or the other, according to specified. conditions in a given case, to be poured down the well, and the mouth securely plugged.**
- **<u>The result was that the generation of gases, due to the chemical reactions taking place in the subterranean depths, acted to shatter the surrounding rocks and open up new oil cavities, quite as effectively and more certainly than by the use of explosives</u>. This took hold in the industry during the 1930s.**



The Age of the Petroleum Engineer (1930s-1950s)

A Study of Some Factors Affecting Gun Perforating

By S. C. Oliphant,* Junior Member AIME, and R. Floyd Farris*

(Galveston Meeting, October 1946)

- **The first hydraulic fracturing treatments were probably performed with acid, although they were not recognized at the time. Wells in tight carbonate formations would usually not accept acid until a critical pressure was reached.**

NEW APPARATUS for STUDYING PRESSURE INDUCED FRACTURING in REFERENCE to LOST CIRCULATION

A. J. TEPLITZ
E. M. POHORILES
JUNIOR MEMBER AIME
J. K. RODGERS

GULF RESEARCH & DEVELOPMENT CO.
PITTSBURGH, PA.

- **However, after this pressure was reached, acid could be easily injected at high rates. It was later recognized that these wells had been hydraulically fractured.**

DEVELOPMENT and APPLICATION of "FRAC" TREATMENTS in the PERMIAN BASIN

R. E. HURST
J. M. MOORE
MEMBERS AIME
D. E. RAMSEY
JUNIOR MEMBER AIME

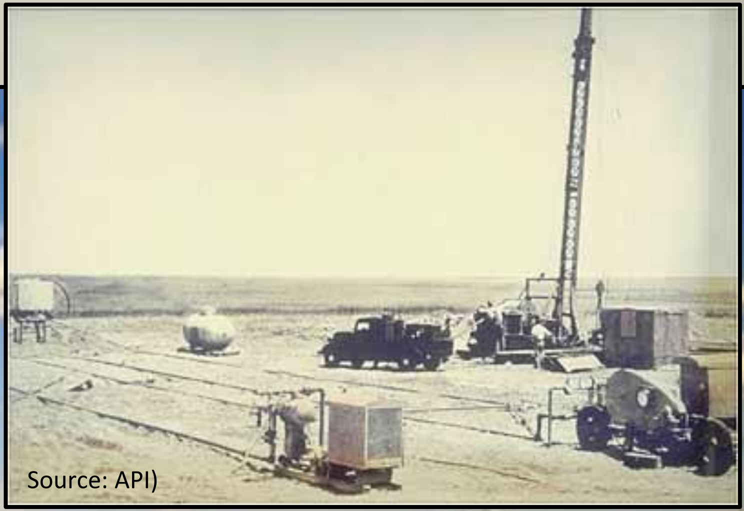
DOWELL INCORPORATED
MIDLAND, TEX.

- **<u>For this reason, later hydraulic fracturing patents were never enforced against acid fracturing treatments</u>.**

The Hydrafrac Process
Floyd Farris with Stanolind Oil

1947 Dodge Power Wagon used to transport torpedoes

The first experiment of hydraulic fracturing, occurred at the Hugoton gas field, located in Grant County, Kansas in 1947. In this experiment, 1,000 gallons of napalm (gelled gasoline) and sand were injected into a gas producing limestone formation with a depth of 2,400 feet. This was then followed by an injection of a gel breaker. While this experiment failed to produce a significant_production increase, it did mark the beginning of hydraulic fracturing.

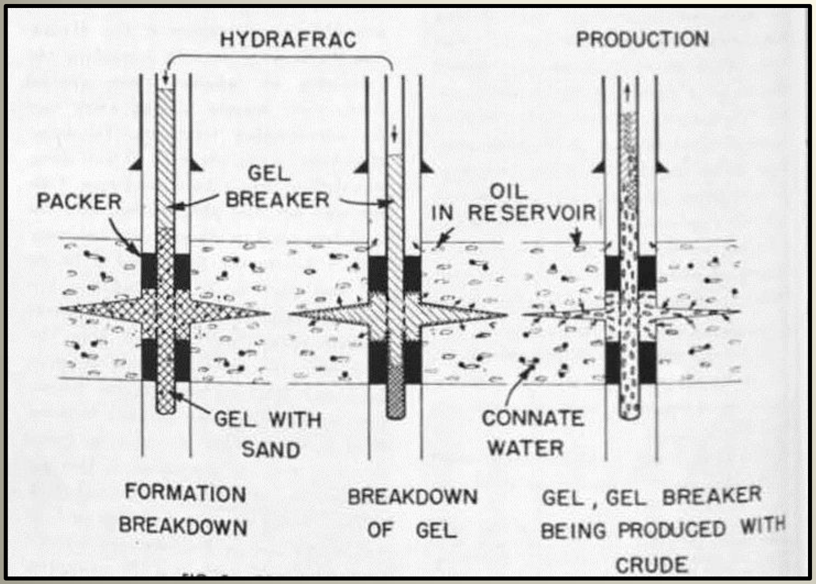


Source: API)

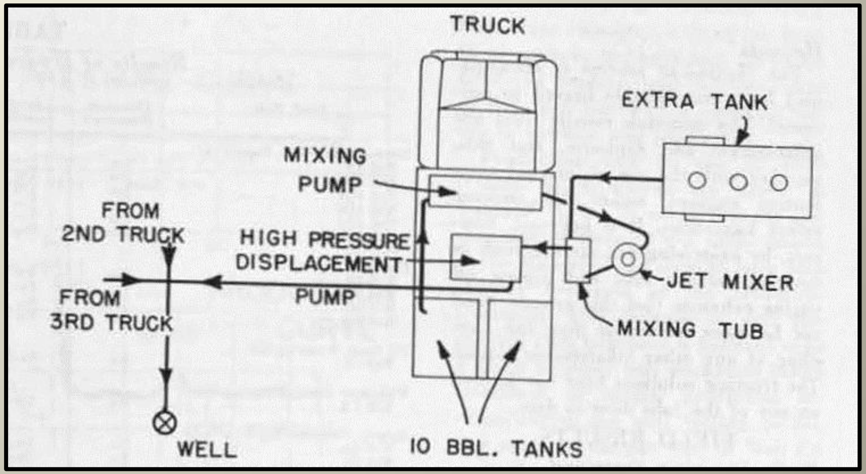
The first paper published on hydraulic fracturing, or also referred to at the time as the "*hydrafrac*" process was by J.B. Clark with Stanolind Oil and Gas Company, Tulsa Oklahoma, titled "*A Hydraulic Process for Increasing the Productivity of Wells*" (Clark, 1949) who also credited R.F. Farris, C.R. Fast, G.C. Howard, J.A. Stinson, and other members of Stanolind Oil and Gas Company. The paper was first presented however at the American Institute of Mining Engineers, Petroleum Division Fall Meeting, held in Dallas, Texas, from October 1-4, 1948. At the time of publication, the Hydrafrac process had been applied to 23 wells in 7 fields, with sustained increase in production in 11 wells.

The Hydrafrac process was applied to wells partially depleted, but it was also remarked that new wells could improve their productivity by application of the process.

The concluding statement by Clark in his 1949 paper was "*It is significant that the value of the oil and gas produced to date through the benefits of this process has already exceeded the combined cost of research, development, and all field tests*."



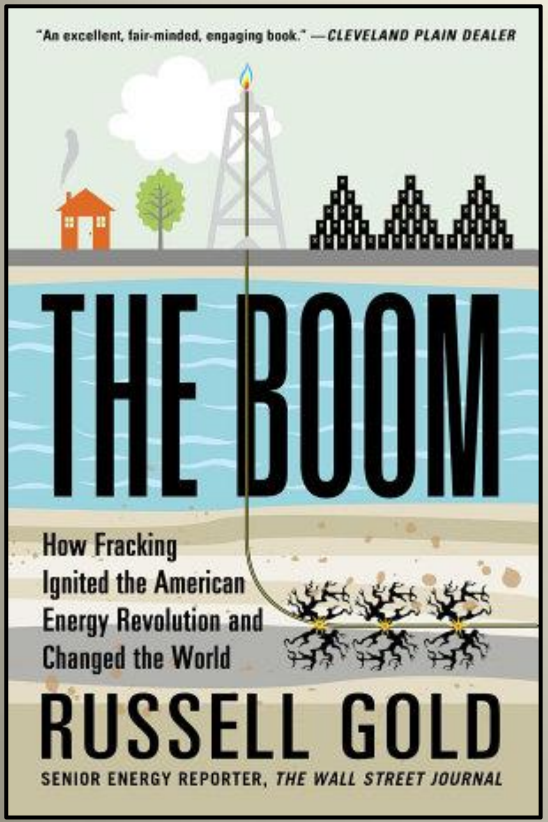
Sequence of steps in the Hydrafrac process



Typical well set-up for the Hydrafrac process

The process consisted of two steps.

1. **The first step consisted with the injection of "*a viscous liquid containing a granular material, such as sand for a propping agent, high hydraulic pressure to fracture the formation*".**
2. **The second step was to cause "*the viscous liquid to change from a high to a low viscosity so that it may be readily displaced.*"**



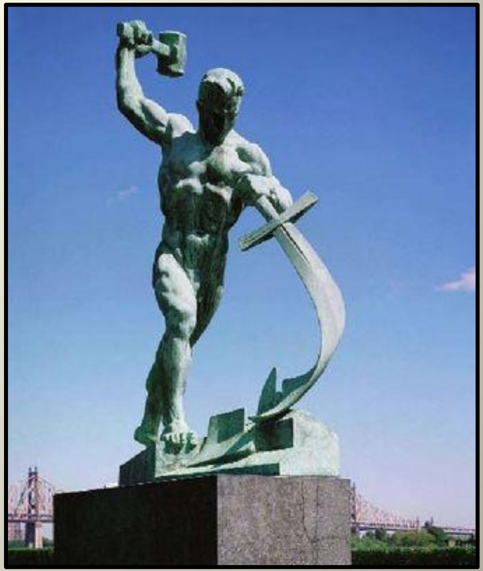
- **Since Clark's work in 1949, its use has progressively expanded so that, by the end of 1955, more than 100,000 individual treatments had been performed (Hubbert and Willis, 1957).**

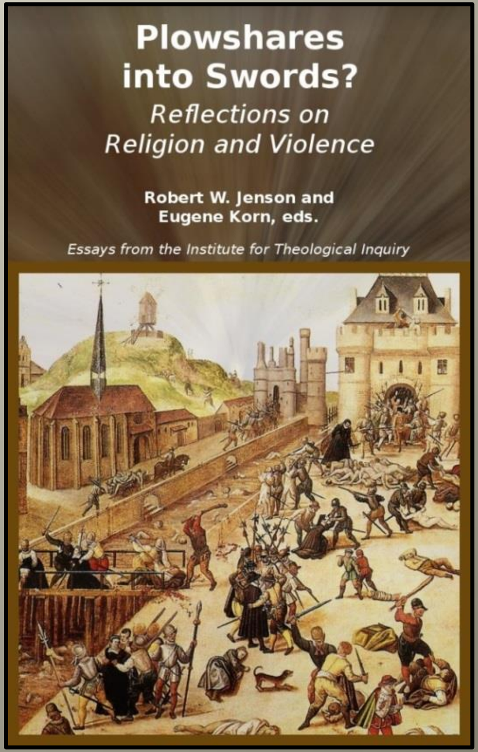
- **Hubbert and Willis (1957) noted that hydraulic-fracturing techniques for well stimulation were one of the major developments in petroleum engineering over the past decade.**

- **Gold (2014) would note this early period of innovation and well stimulation would lessen the role of the wildcatter and the beginning of the <u>age of the petroleum engineer</u>.**

Going Nuclear (1960s)

The 1960s brought on a new style of fracking referred to as *"nuclear fracking".* Known as Project Plowshare, a program designed "to find practical industrial and scientific uses for nuclear explosives" (Carlisle and Carlisle, 1967).

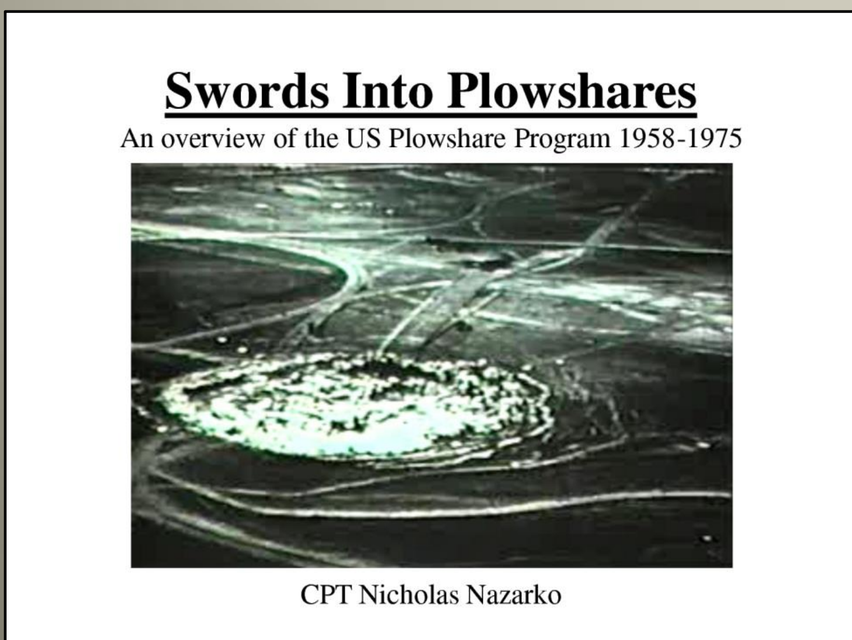


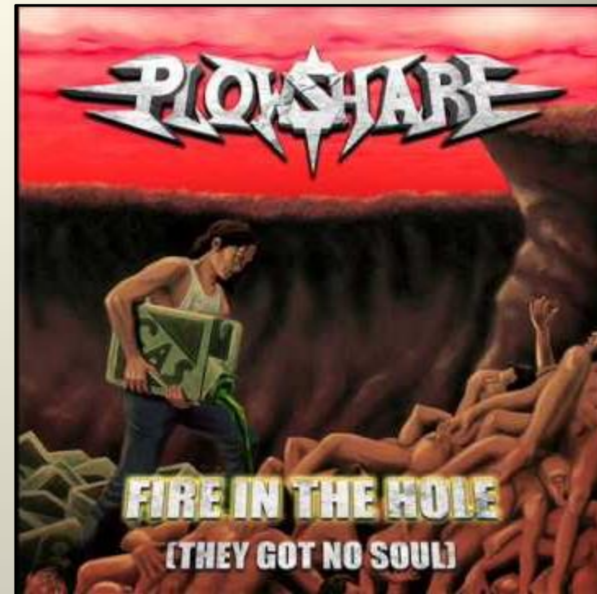


Project Plowshare

On June 6, 1958, the AEC publicly announced the establishment of the Plowshare Program, named for the biblical injunction to ensure peace by beating swords into plowshares (Isaiah 2:4).

"And they shall beat their swords into plowshares, and their spears into pruning hooks; nation shall not lift up sword against nation, neither shall they learn war any more."



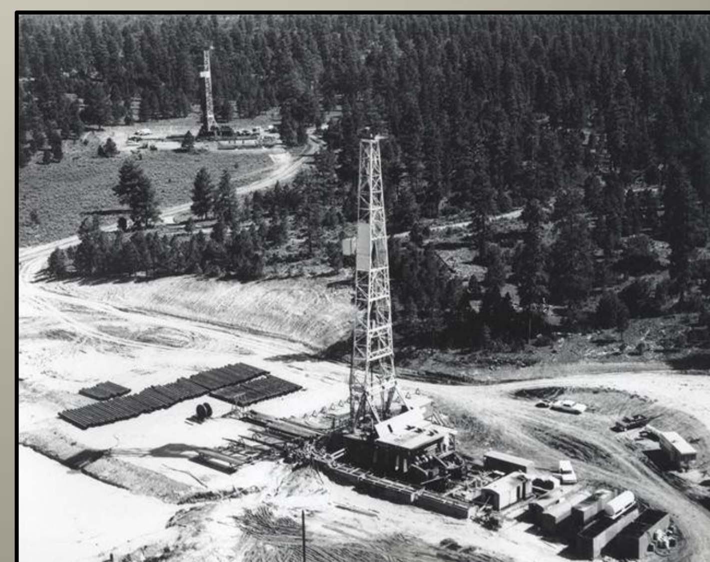


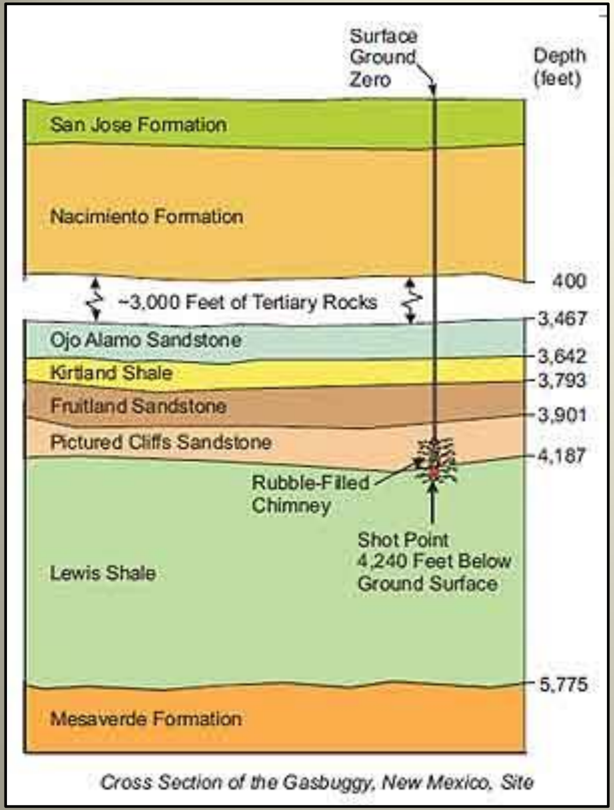
- 1958 – 1975 - The Plowshare Program
- 1961 to 1973 - 27 separate experiments resulting in 35 nuclear detonations. Most of the experiments focused on creating craters and canals, with some optimistic applications such as widening the Panama Canal.
- Early 1960s – early 1970s - Individual endeavors pertaining to fracturing to enhance gas and oil well stimulation, included numerous projects many of which were not executed. Individual projects included Pinot, Oil sands, Oil Shale, Project Gasbuggy, Project Dragon Tail Study, Project Ketch, Project Bronco Study, Project Wagon Wheel, Project Wasp, Rulison nuclear test, and Rio Blanco.
- Nuclear tests were mostly conducted in Nevada, but also took place in the oil and gas fields of New Mexico and Colorado, and were planned but never implemented in Wyoming.

Project Gasbuggy

Scientists lower a 13-foot by 18-inches diameter nuclear warhead into a well in New Mexico - the experimental 29-kiloton Project Gasbuggy device to be detonated. (Los Alamos Lab photo. http://aoghs.org/oilfield-technologies/project-gasbuggy

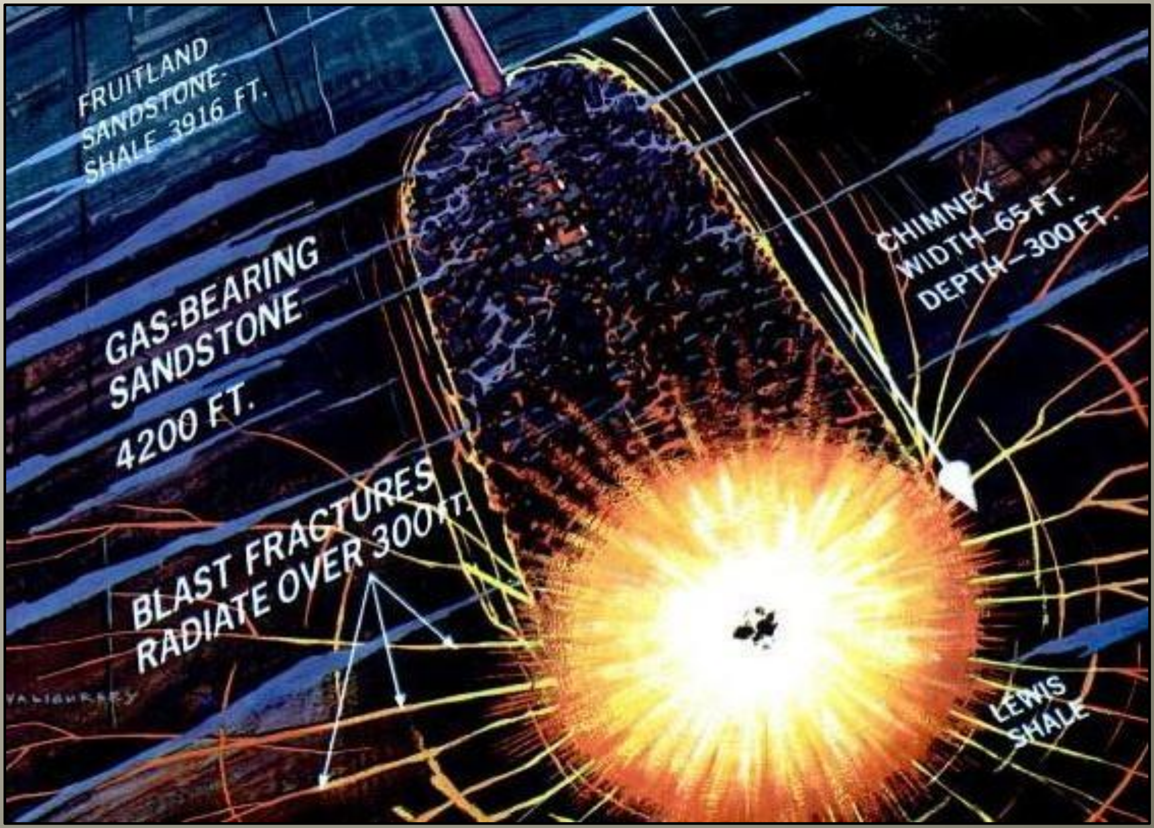
Project Gasbuggy: the first U.S. underground nuclear experiment for the stimulation of low-productivity gas reservoirs.

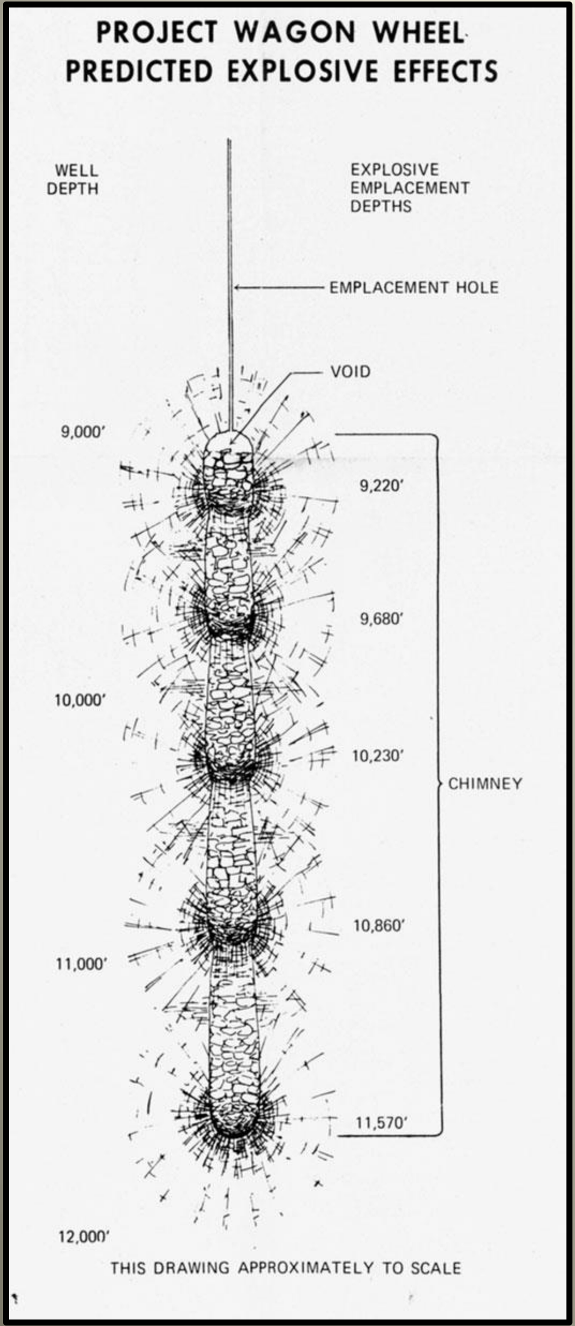




Cross Section of the Gasbuggy, New Mexico, Site

- **Depth 4,240 feet.**
- **Popular Mechanic article noted how nuclear explosives could improve previous fracturing technologies.**
- **1967 nuclear detonation produced 295 million cu ft of natural gas.**
- **Also produced Tritium radiation contamination.**

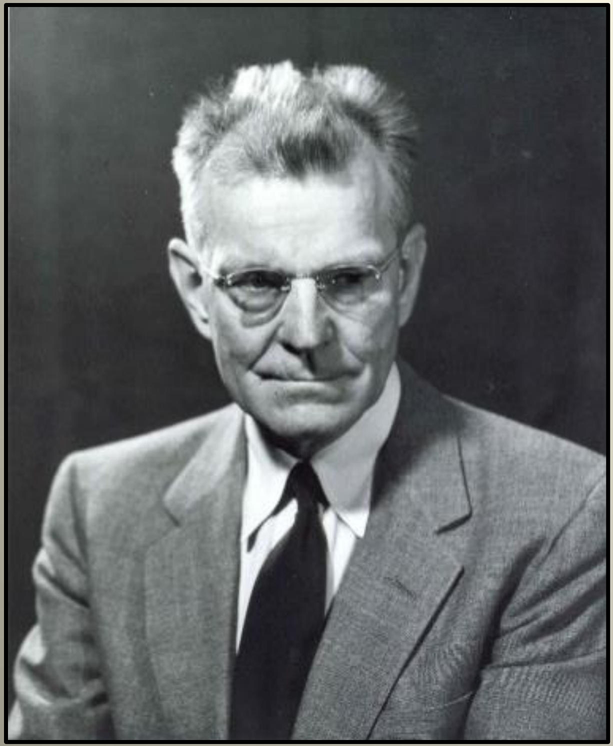




Project Wagon Wheel

Project Wagon Wheel differed from Gasbuggy because its goals include obtaining cost information as well as technical information. Gasbuggy's objectives were to determine the engineering, but not necessarily profitability.

Unlike its predecessors Project Wagon Wheel was not initiated. Had it been tested, five nuclear devices would have been detonated sequentially from bottom to top between 9,220 feet and 11,570 feet below the surface. The five nuclear devices would have been 100 kilotons each and detonated approximately five minutes apart, and estimated to be about 35 times as great as the energy of the gas which was expected to be produced. The detonations would have created an underground rubble chimney approximately 2,800 feet high and about 1,000 feet in diameter. After the blast, four and six months would have to past before test production of natural gas to allow for the decay of "short-lived radioisotopes, albeit, there would be anticipated release of radiation during the 325-day flaring of the well.

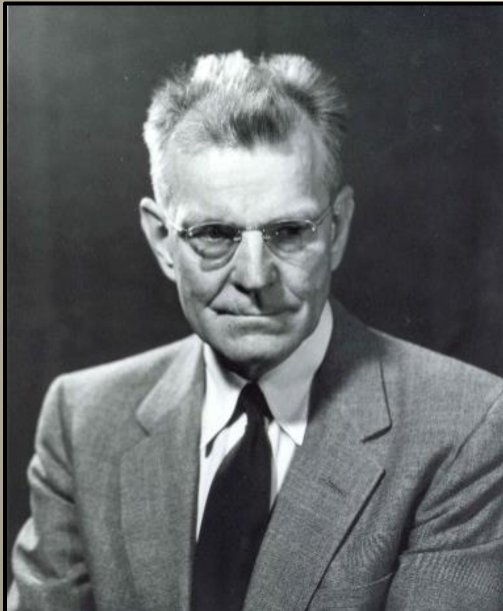


Peak Oil and Hubbert's Curve

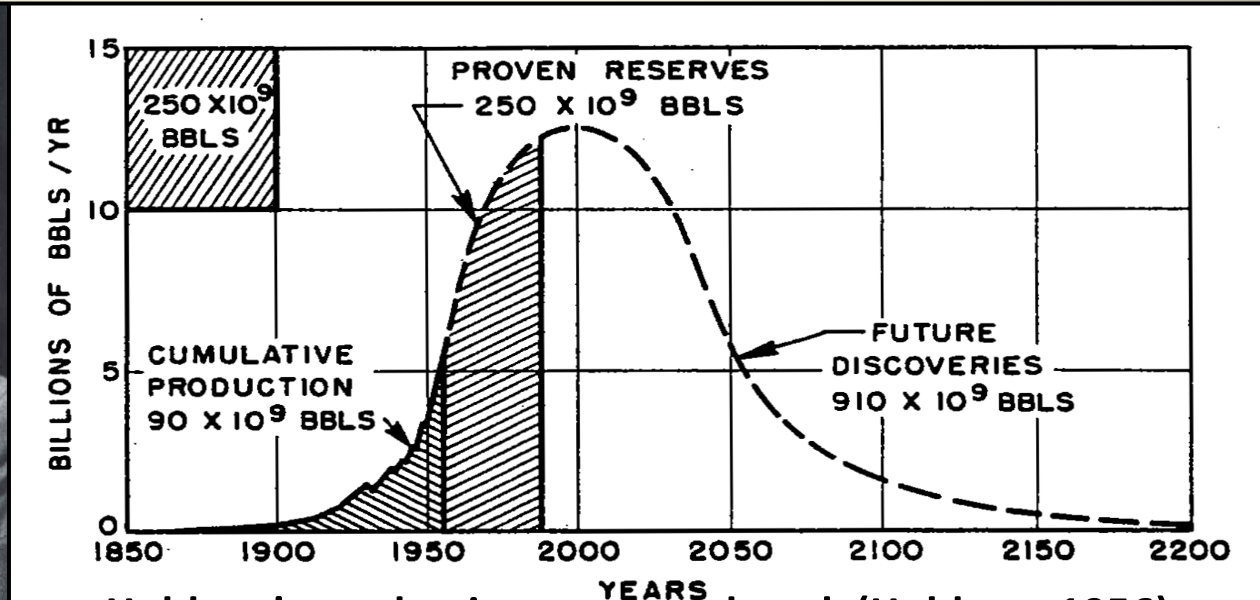
M. King Hubbert (1903 – 1989)

- Hubbert was born in San Saba, Texas, attending the University of Chicago, where he received his B.S. (1926), M.S. (1928), and Ph.D. (1937), studying geology, math, and physics.
- Assistant geologist for the Amerada Petroleum Company for two years while pursuing his Ph.D., additionally teaching geophysics at Columbia Univ.
- Senior analyst at the Board of Economic Warfare and joined the Shell Oil Company in 1943, retiring from that firm in 1964.
- Afterwards he became a senior research geophysicist for the USGS until his retirement in 1976.
- Held positions as a professor of geology and geophysics at Stanford Univ. (1963 to 1968), and as a professor at UC Berkeley (1973 to 1976).

Peak Oil and Hubbert's Curve



M. King Hubbert (1903 – 1989)

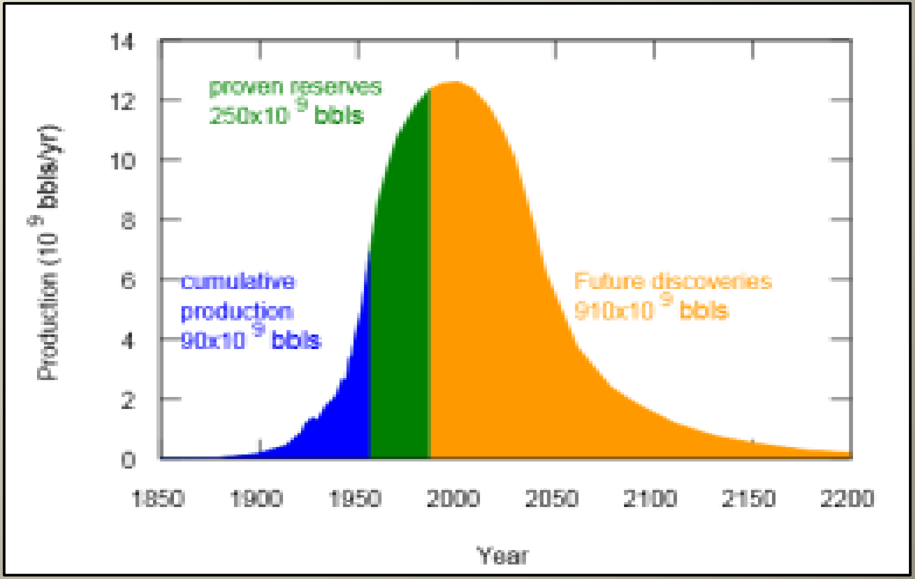


Hubbert's production curve and peak (Hubbert, 1956)

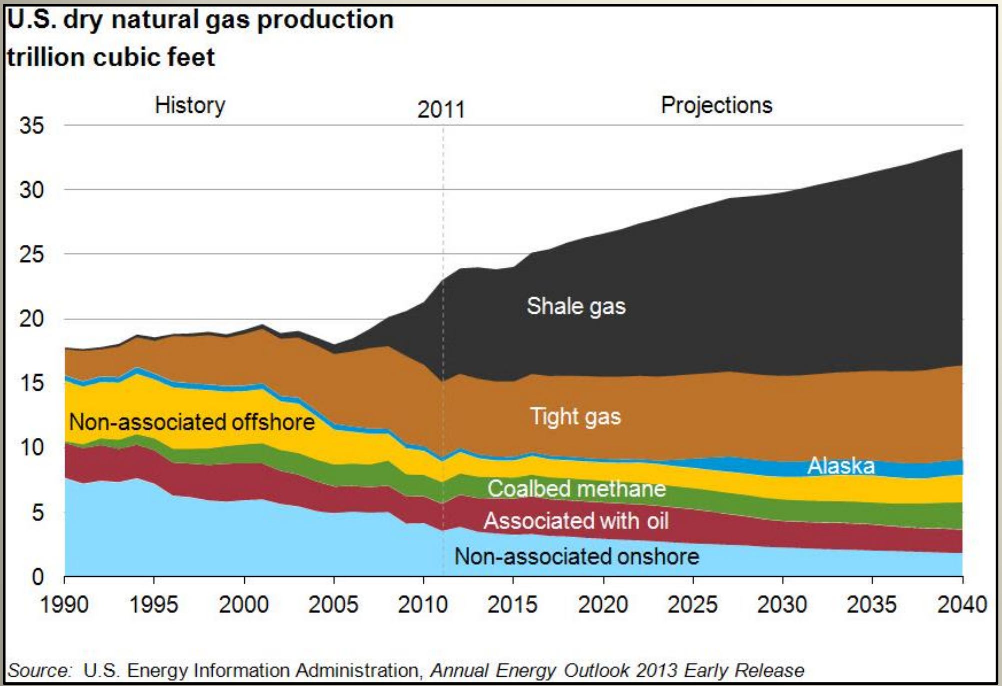
- Peak oil is the point in time when the maximum rate of oil and gas extraction is reached, after which the rate of production is expected to enter terminal decline. It accurately reflects individual production in wells and fields.
- Initially, every oil and gas well and field exhibits an increase in production, and eventually reaches a peak production before production subsequently declines.
- Enhanced efforts can prolong production but overall production of each well typically follows a production curve, peaking at one point, then trailing off in an inevitable decline. Despite enhanced recovery, ultimately production decline occurs nonetheless.

Peak Oil and Hubbert's Curve

- The 100 year period when most of the world's oil was being discovered became known as "Hubbert's Peak".
- The peak stands in contrast to the hundreds of millions of years the oil deposits took to form.
- Hubbert's methods predicted a peak in world oil production less than five years away with current technology.



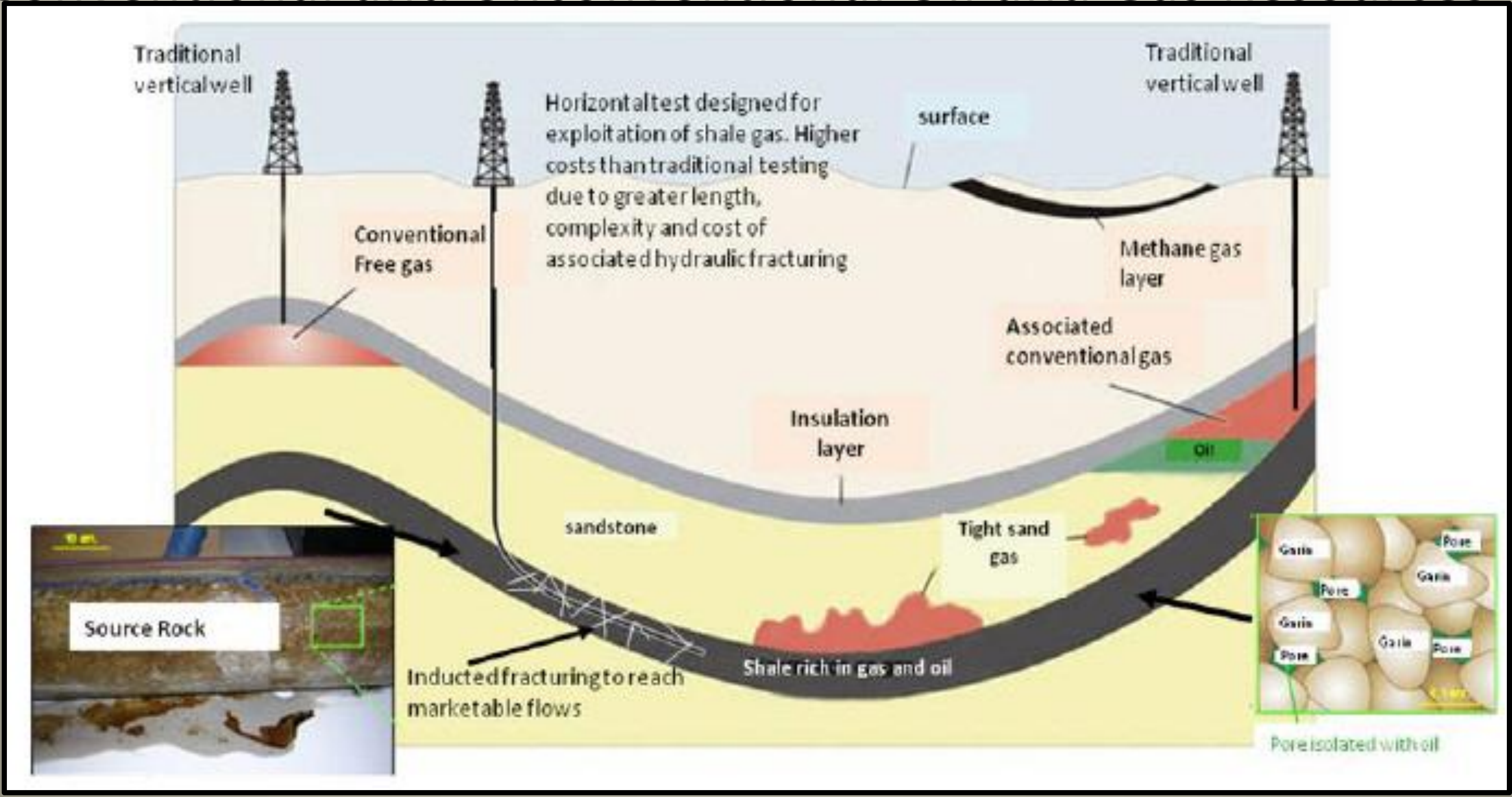
The Rise of the Unconventionals (1980s-Present)



U.S. dry natural gas production in trillion cubic feet and billion cubic feet per day for shale resources which as of 2015 remain the dominant source of U.S. natural gas production growth (EIA, 2015). Note shale gas production becomes significant by 2010, and projected to be dominant by 2040.

- **It was not that many years ago when such unconventional resources were considered inaccessible or virtually nonexistent as a potential energy source.**
- **During the 1990s, not many exciting techniques were visible to the novice; however, by 2000 slight increases in the production of natural gas were being observed.**
- **When it comes to energy, in some strange but wonderful twist of fate, we now live in an unconventional and alternative world. The rise began in the 1990s but not without a significant role played by the advancements made in horizontal drilling technology and some federal assistance during the mid-1980s.**

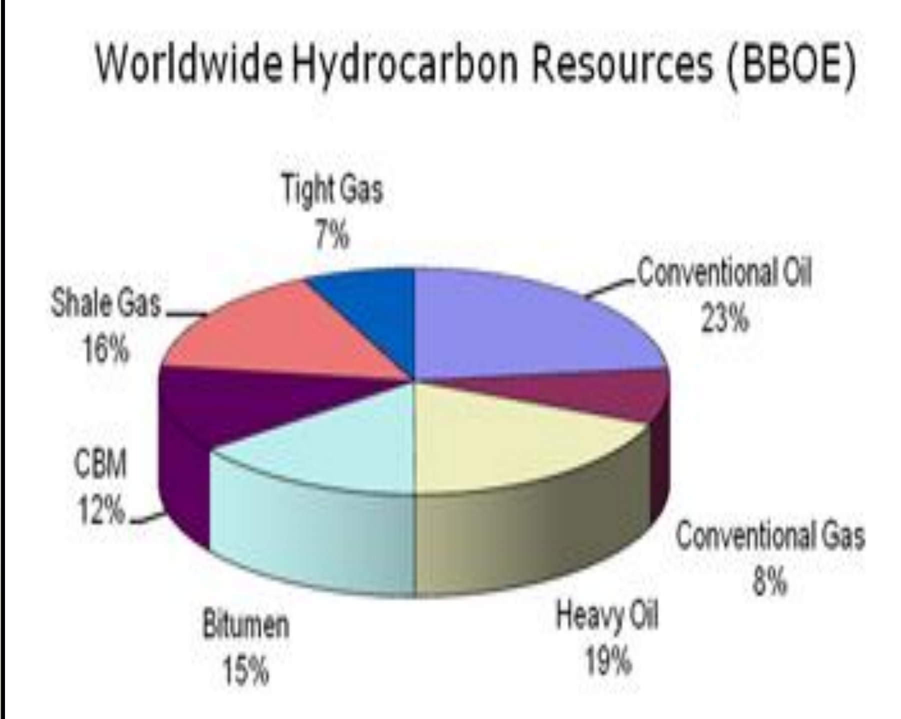
Geologic Setting of Conventional and Unconventional Oil and Gas Resources



Schematic diagram of the different types of onshore natural gas plays. Conventional resources are buoyancy-driven hydrocarbon accumulations, with secondary migration and structural and/or stratigraphic closures. Unconventional, continuous gas accumulations, in basin centers and transition zones, are controlled by expulsion-driven secondary migration and capillary seal (USDOI, 2008).

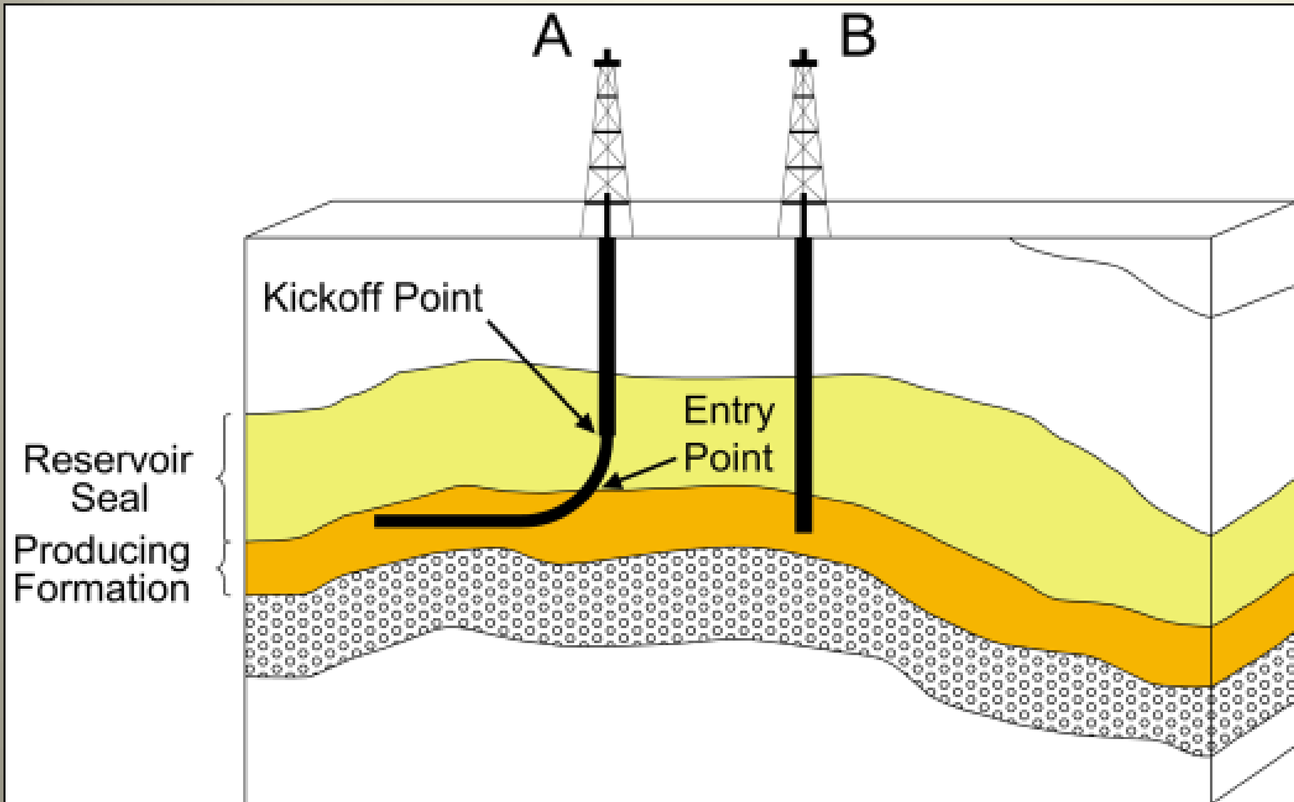
Unconventional Resources

- **"Peak Oil" became politically charged to move from a hydrocarbon-based fossil fuels to other energy alternatives.**
- **Unconventional resources are characterized as hydrocarbon reservoirs that have low permeability and porosity, rendering production of gas and oil from such reservoirs difficult.**
- **With the advent of horizontal drilling and well stimulation techniques, among many other important insights and innovations, came the rise of the unconventionals. These innovative techniques may be performed to enhance recovery, and even more so in an unconventional setting.**



An interesting statistic is that only about one-third of the worldwide oil and gas reserves are conventional in nature – the remainder are unconventional which includes tight gas, coalbed methane (CBM), methane hydrates, shale gas, shale oil, heavy oil, and tar sands.

Horizontal Drilling



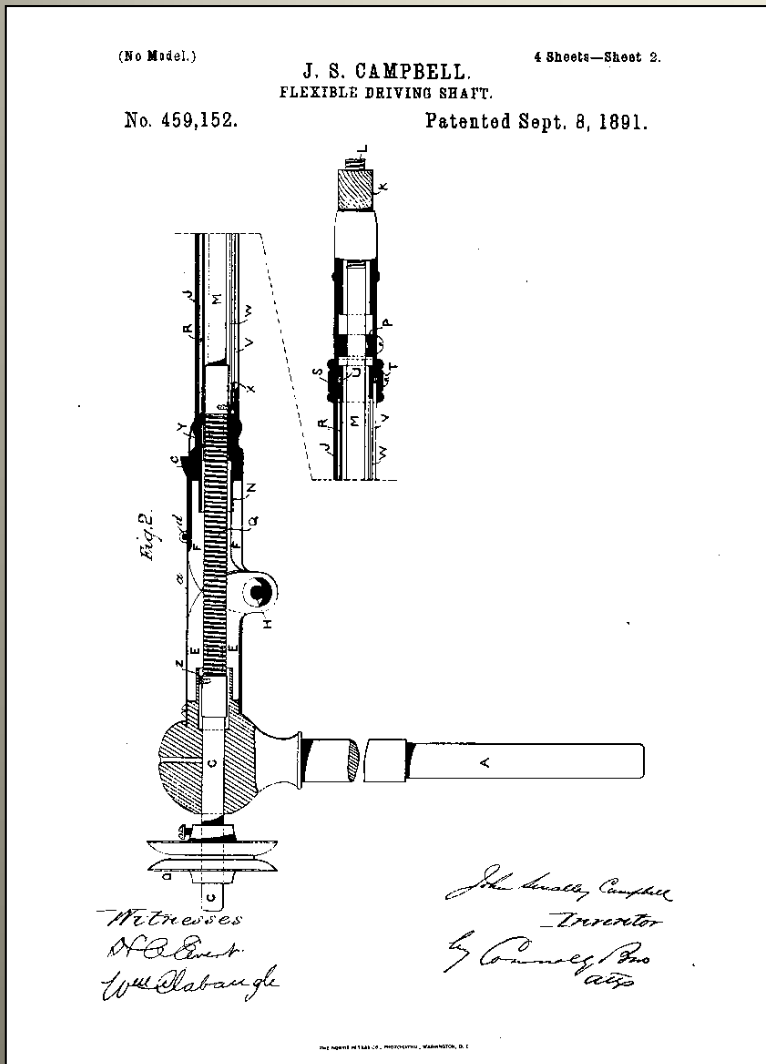
Greater length of producing formation exposed to the wellbore in a horizontal well (A) than in a vertical well (B) (EIA, 1993).

The technology of horizontal drilling moved into the arsenal of the oil industry in the early 1980s (EIA, 1993). Horizontal drilling is the process of drilling a well from the surface to a subsurface location just above the target oil or gas reservoir called the "kickoff point", then deviating the well bore from the vertical plane around a curve to intersect the reservoir at the "entry point" with a near-horizontal inclination, and remaining within the reservoir until the desired bottom hole location is reached.

The Flexible Shaft

A flexible shaft is a device for transmitting rotary motion between two objects which are not fixed relative to one another. It consists of a rotating wire rope or coil which is flexible but has some torsional stiffness. It may or may not have a covering, which also bends but does not rotate. It may transmit considerable power, or only motion, with negligible power.

J.S. Campbell flexible driving shaft
U.S. Patent 459,152
September 8, 1891



- **The modern concept of non-straight line, relatively short-radius drilling, dates back at least to 1891, when the first U.S. patent for the use of flexible shafts to rotate drilling bits was issued to John S. Campbell.**

- **The prime application described in the patent was dental engines. The patent also carefully covered use of his flexible shafts at much larger and heavier physical scales "*My invention relates more particularly to the flexible driving-shaft or cable used in dental engines; but it is also applicable to flexible shafts or cables of larger size such, for example, as those used in engineers shops for 'drilling holes in boiler-plates or other like heavy work. The flexible shafts or cables ordinarily employed are not capable of being bent to and working at a curve of very short radius ...*"**

The first recorded true horizontal oil well was drilled near Texon, Texas, and was completed in 1929 (Popular Horizontal, 1991). Another was drilled in 1944 in the Franklin Heavy Oil Field, Venango County, Pennsylvania, at a depth of 500 feet (Yost et al, 1987). China also tried horizontal drilling as early as 1957, followed by the Soviet Union. Generally, however, little practical application occurred until the early 1980’s, by which time the advent of improved downhole drilling motors and the invention of other necessary supporting equipment, materials, and technologies, were attained. Notably, downhole telemetry equipment brought some kinds of applications within the imaginable realm of commercial viability (EIA, 1993).

Texon was founded on May 23, 1923, when oil was discovered and named for the Texon Oil and Land Company, which drilled the first successful oil well in the Permian Basin.

Texon Oil and Land Company drilled for oil. Their driller, Carl Cromwell, brought in Santa Rita No. 1, the first gusher in the Permian Basin, on May 28, 1923.

The Role of the Feds

- Understanding the technological advances being made during the 1970s and 1980s deserve mention of the federal role and investment following federal price controls on natural gas which led to shortages in the 1970s.

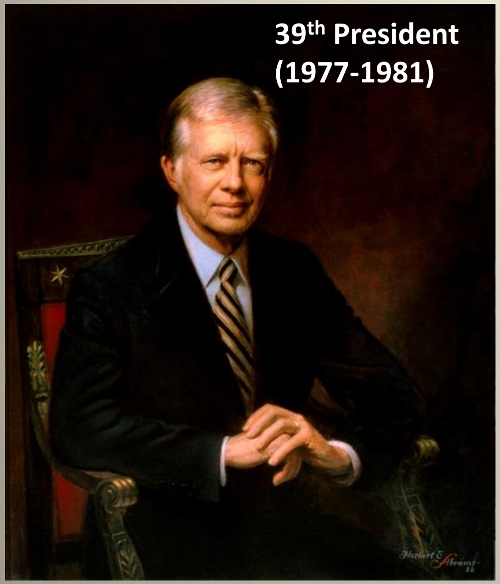
- The federal government in response to declining natural gas production invested in many supply alternatives, including the Eastern Gas Shales Project (EGSP), and the annual FERC-approved research budget of the Gas Research Institute (GRI).

- GRI was funded by a tax on natural gas shipments from 1976 to 2000.

Marcellus Shale, PA

The Department of Energy (DOE) partnered with private gas companies to complete the first successful air-drilled multi-fracture horizontal well in shale in 1986. Microseismic imaging, an important input to both hydraulic fracturing in shale and offshore oil drilling, originated from coalbed research at Sandia National Laboratories.

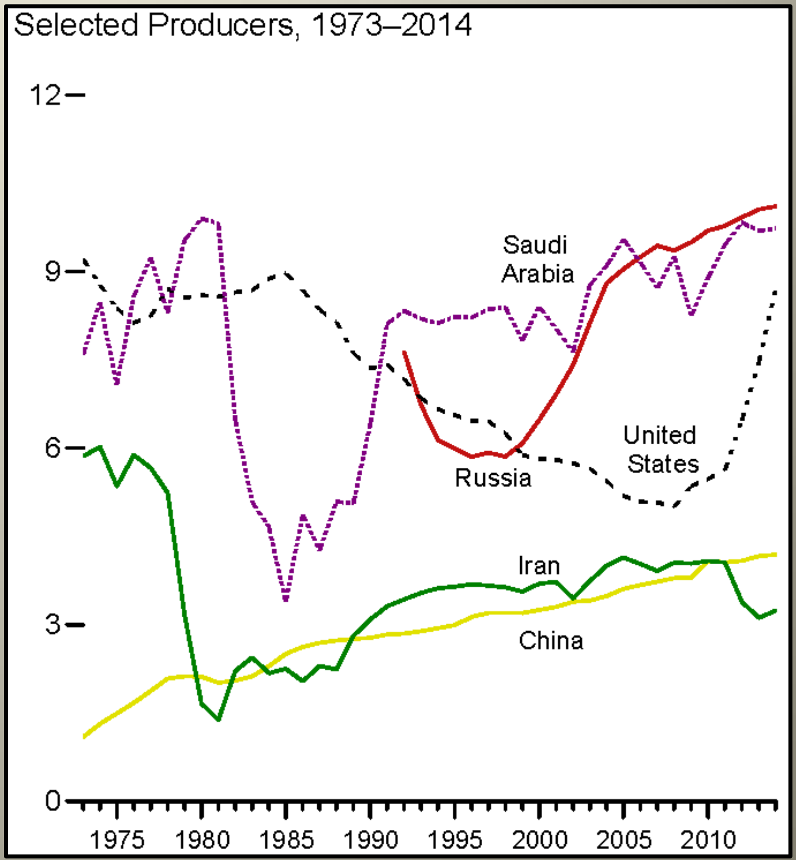
The Carter Doctrine and the Role of the Feds



The Carter Doctrine declared that any interference with U.S. oil interests in the Persian Gulf would be considered an attack on the vital interests of the United States.

- On April 18, 1977, President Carter went on television and declared that we were running out of domestic natural gas.

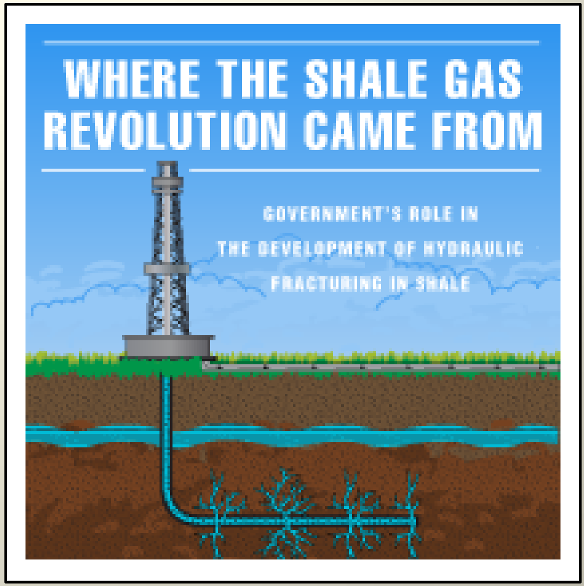
- At the same time, the DOE was conducting the EGSP which had two goals: 1) evaluate the gas potential of Devonian and Mississippian shale basins and 2) develop new drilling, stimulation, and recovery technologies.

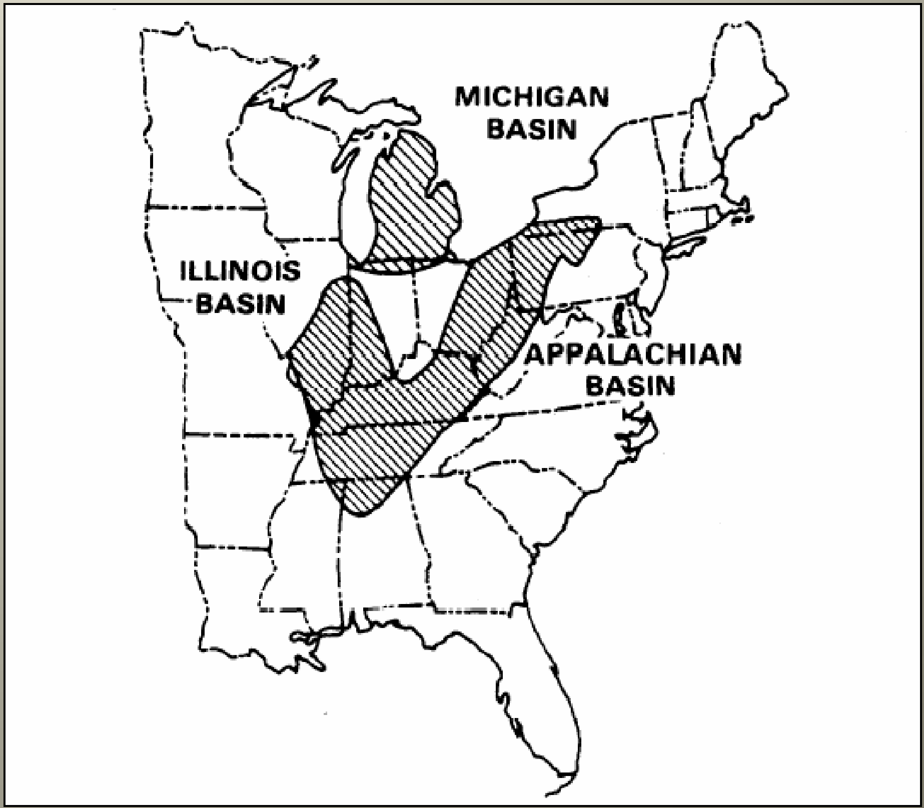


- The EGSP lasted from 1976 to 1992 and focused on extending and improving recoveries in known productive shale gas areas, particularly the greater Big Sandy Gas Field of Kentucky and West Virginia.

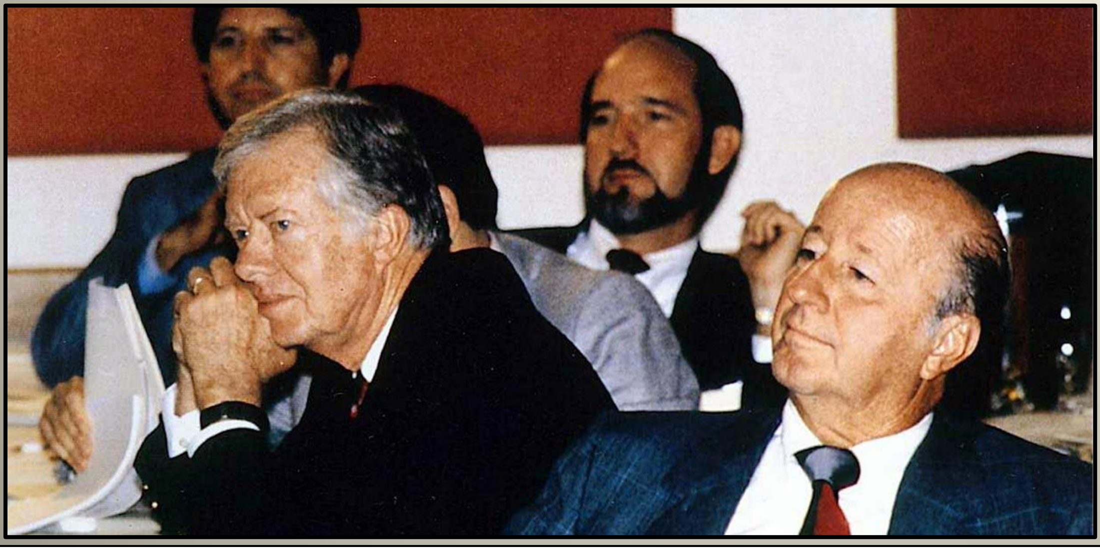
- Two technologies were applied which had been developed previously by industry for shale gas formations: massive hydraulic fracturing and horizontal drilling.

- In 1976 two engineers for the federally funded Morgantown Energy Research Center (MERC) patented an early technique for directional drilling in shale.





George Mitchell
Father of Shale Natural Gas Drilling



- Captain in the Army Corps of Engineers during WWII.
- Texas A&M University; petroleum engineering with emphasis in geology.
- Formed wildcatting company; president in 1959.
- Participated in approx. 10,000 wells.
- 200 oil and 350 gas discoveries.
- Former Chairman and CEO of Mitchell Energy & Development.
- Fortune 500 Company.
- Merge with Devon Energy Corporation in January 2002.

Mitchell Puts It All Together

- DOE subsidized Mitchell to drill his first horizontal wells, covering any costs beyond a typical vertical well, and the federal government provided unconventional gas tax credits.
- The Bureau of Economic Geology created high-resolution images of rock surfaces that yielded information about their porosity.
- Union Pacific Resources, a Fort Worth-based exploration and production company, shared its “superior” method for hydraulic fracturing.
- DOE’s Sandia Labs contributed microseismic fracture mapping software that helped the operator make adjustments to improve the flow of gas.

- **<u>Throughout the 1990s</u> - GRI partnered with Mitchell Energy in applying a number of other technologies in the Barnett Shale. In 1991, Mitchell Energy completed the first horizontal frac in the Texas Barnett shale. This project was subsidized by GRI and funded by a federal tax on gas pipelines, and were not economically successful.**

- **<u>In 1998</u> - Mitchell achieved the first highly economic fracture completion of the Barnett Shale by using slick-water fracturing.**

- **"*It was not until development of the Barnett Shale play in the 1990s that a technique suitable for fracturing shales was developed*" (USGS).**

- **The Barnett Shale boom would become highly successful with vertical wells and it was not until 2005 that horizontal wells being drilled in the Barnett Shale outnumbered vertical wells.**

- **<u>By 2008</u> - 94 percent of the Barnett wells drilled were horizontal.**

Oil-Gas Basins and Shale Gas Plays in the lower United States (API, 2015)

No less than 25 current shale plays, and six prospective plays, were noted in the lower United States as of 2015

- It is estimated that hydraulic fracturing will eventually account for nearly 70% of natural gas development in North America (National Petroleum Council, 2011).

- The U.S. Energy Information Administration (EIA) in 2015 reported that dry natural gas production in the U.S. increased by 35% from 2005 to 2013 resulting largely from the development of shale gas resources (including natural gas from tight oil formations) in the lower 48 states.

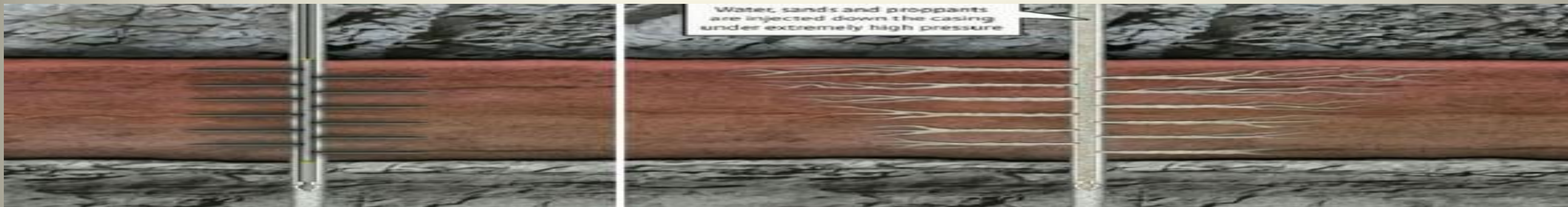
The EIA (2015) summarized:

- Growth in U.S. energy production, led by crude and natural gas, and only modest growth in demand reduces U.S. reliance on imported energy supplies.

- A strong growth in domestic crude oil production from tight formations will lead to a decline in net petroleum imports, and growth in net petroleum product exports in all Annual Energy Outlook cases.

- In 2017, the U.S. will transition from being a modest net importer of natural gas to a net exporter.

Concluding Remarks



- **The U.S. now has 200 years' worth of natural gas… and is predicted to be the largest oil producer in the world by the end of the decade - thanks to hydraulic fracturing and horizontal drilling technologies.**

- **By 1988, hydraulic fracturing had been successfully applied nearly one million times. And as of today, more than 2.5 million hydraulic fracturings have occurred worldwide.**

- **Oh, and by the way... because the U.S. is using more natural gas as a result of the fracking revolution, the U.S.'s CO_2 emissions are at a six-year low.**

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