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IMPROVING THE EFFECTIVENESS AND MANAGING THE IMPACT OF HYDRAULIC FRACTURING

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Abstract

Beginning in 1982, the Gas Technology Institute, in cooperation with the U.S. Department of Energy, led the world's first collaborative research program to develop unconventional gas resources. This program included the application of hydraulic fracturing, which had been in use since 1947.

Along with horizontal drilling, enhanced 3-D seismic imaging, and other technological advancements, the hydraulic fracturing of gas shale and tight gas sands have transformed the U.S. energy picture and hold the potential to have a similar impact globally. But the future is not guaranteed. Concerns have been raised regarding the volume of water required, the risk of ground water contamination, the handling of fluids that flow-back to the surface, and even the potential of earthquakes induced by the hydraulic fracturing process. This paper will review the history of hydraulic fracturing applied to unconventional gas resources, the impact this has had on the U.S. energy mix and identify opportunities for improving the effectiveness of fracturing.

Hydraulic fracturing is used to create permeability to enable commercial flow rates. One of the first experimental fracture treatments on record is reported to have been a stimulation job in 1947 in the Kansas portion of the Hugoton field, which targeted four limestone gas pays at depths ranging from 2,340 to 2,580 feet. That stimulation job was conducted in four separate hydraulic fracturing treatments or stages, each of which involved pumping 1,000 gallons of napalm or thickened gasoline through jointed tubing. Since then, over 1 million hydraulic fracturing jobs have been completed and the fluids used are much more benign. In the 1960s there were trials of stimulating flow by increasing permeability through nuclear explosions. In the 1980s, the industry performed massive hydraulic fractures. Today work continues to further fine-tune the approach with more precise sizing and placement through multi-stage fracturing.

There has been many concerns raised associated with hydraulic fracturing. In part, this is due to significant activity taking place in populated areas that have little experience with natural gas production. There is a large amount of water required and chemicals are introduced into the fracturing fluids. The vast majority of applications are performed without incident, but good news is not news. The internet allows many points of view to be shared and supporting evidence does not need to be provided. The solution for the industry is doing good science and providing transparency to industry activities.

For the most part, hydraulic fracturing is an invisible process with high visibility put on certain activities that support it. These include water delivery trucks (50 or more per well) that bring traffic, noise, dust and local water requirements. Produced water handling then requires lined pits, disposal trucks, "chemical handling," on-site treatment/recycling and these activities provide for the potential for spills. The potential is there for environmental impact and the industry can choose to be proactive in reaching out to affected communities. Several potential concerns get combined under the heading of issues associated with hydraulic fracturing. These include the volume of water required, the potential for ground water contamination, the potential for spills of water at the surface, and the potential for seismic activity.

Beyond the environmental issues, more R&D will enable the effectiveness of hydraulic fracturing to improve. Today, it is an expensive process with only 50% of fractured stages reaching their full potential for various reasons. There is a large economic prize associated with improving fracture design, optimizing proppant loadings, insuring the right fluids are used, and ensuring permeability created is maintained. Much progress has been made but opportunities remain to improve the effectiveness of fracturing through improved diagnostics, better understanding of fracture fluid migration, considering alternatives to hydraulic fracturing, risk modeling to quantify potential negative impacts, and improving rock mechanics models for assessing impacts of well construction and completion techniques. The paper will review the outstanding inter-disciplinary technical challenges associated with hydraulic fracturing and R&D priorities for enhancing its effectiveness.

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Introduction and Historical Background

Introduction

Gas and oil prices are currently at levels that have made our technically challenging unconventional resource base more attractive and economically feasible. But new technology is key to development. Years ago, coalbed methane was an untapped part of our technically recoverable resource base. A focused collaborative research program initiated by the Department of Energy and undertaken by the Gas Technology Institute (then as the Gas Research Institute) turned a nuisance into gas production that now satisfies a significant portion of U.S. gas demand.

Today, much of the increase in our recoverable resource base is found in unconventional resources including tight gas sands, coalbed methane and gas from shales. Like coalbed methane a few years ago, these resources will require additional research to develop the technology that will make them economically feasible.

The National Petroleum Council, as part of its 2003 study on natural gas, estimated the impact of economic growth, LNG imports, technology and other factors on natural gas supplies and prices. (Figure 1) New technology was predicted to have the greatest effect on increasing supply while reducing or controlling cost. Since then, the development of unconventional resources and continuous improvements made to further reduce cost have led to enhanced supplies and lower prices for North America that support this forecast.

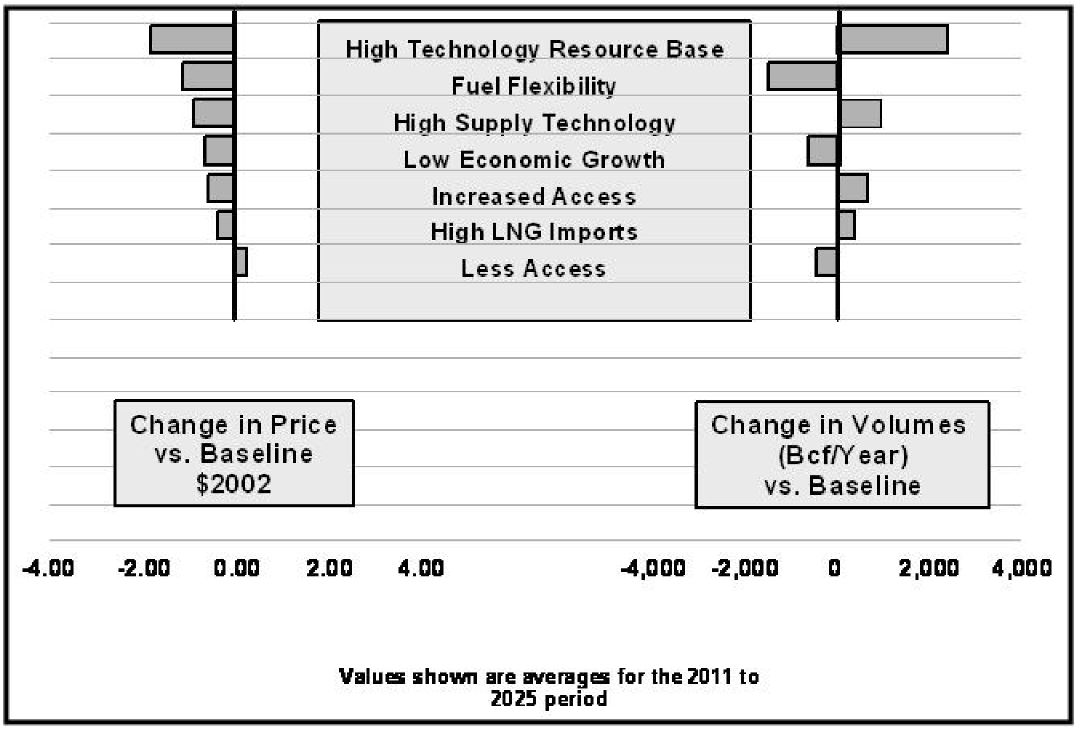

Figure 1: NPC Sensitivity Studies on Gas Price and Supply. Source National Petroleum Council

Hydraulic fracturing technology was developed to stimulate production from new and existing oil and gas wells. Since it was developed in the 1940's it has been used in more than a million wells and it has helped to produce more than 600 trillion cubic feet of natural gas and 7 billion barrels of oil. The first commercial use of the technique was in 1947 and since then, the payoff has been extraordinary in bringing new life to old wells and unlocking the potential of resources gas and oil from reservoirs with low permeability.

This completion technique involves injecting high volumes of fracturing fluids, or "fracking fluids", consisting primarily of water and sand under high pressure into the producing formation, allowing the creation or even restoration of conductive fractures paths that connects the reservoir to the well These new paths increase the rate that fluids can be produced from the reservoir formation, in some cases by many hundreds of percent. While different well sites require different mixes of fracking fluids depending on the composition of the rock bed and other factors, almost all mixtures are comprised of more than 95 percent water. As the pressure builds within the well, rock beds begin to crack. More fluid is added while the pressure is increased until the rock beds finally fracture, creating channels for trapped oil and natural gas to flow into the well and up to the surface. The fractures are kept open with proppant made of small granular solids (generally sand) to ensure the continued flow of resources. (See Figures 2 & 3)

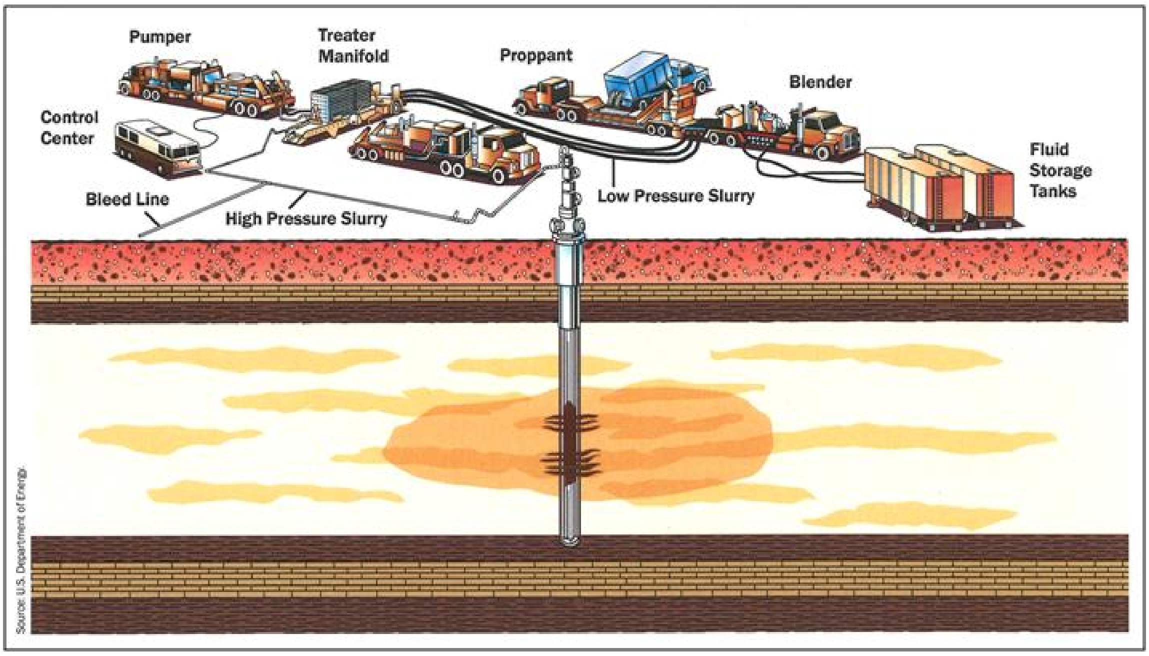

Figure 2: Representation of above surface equipment and facilities required for hydraulic fracturing jobs. *Source U.S. department of Energy*

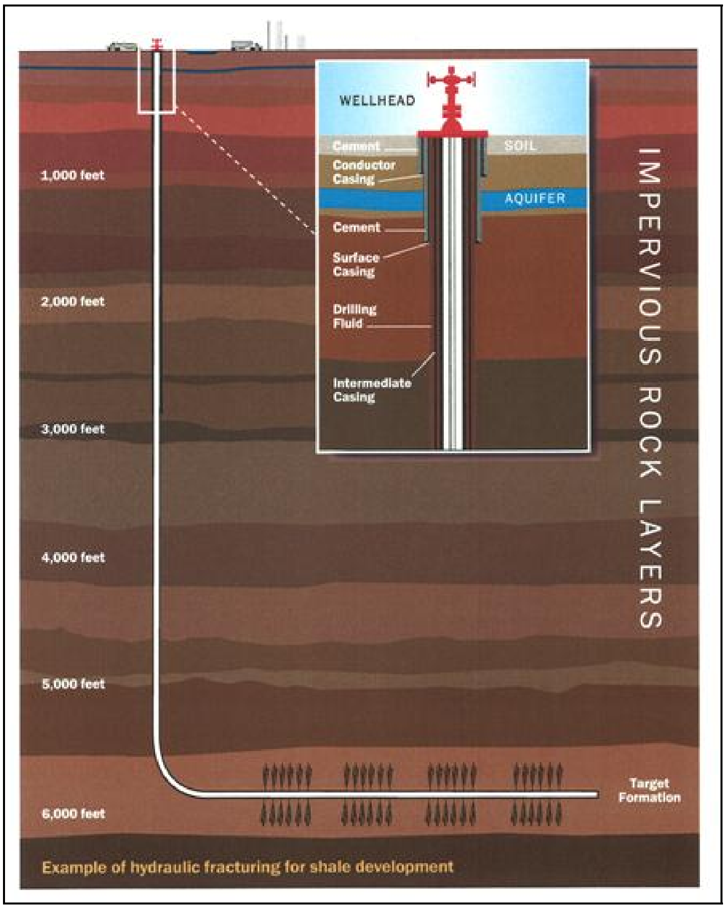

Figure 3: Example of proper well construction that provides groundwater protection during hydraulic fracturing jobs. *Source: API Report: Freeing Up Energy*

Historical Technology Development

Unconventional gas technology development has evolved significantly over the last forty years. The trend has moved from one of high horsepower approaches to one of precision in all aspects of development. During the 1960's nuclear detonations were being tested with the goal of fracturing or stimulating a large volume of low permeability rock allowing for the recovery of a significant volume of gas from a single wellbore. This technical approach failed for many reasons including the fusing of rock as opposed to fracturing of rock.

During the 1970's and 1980's the approach to unconventional gas formations evolved to massive hydraulic fracture treatments. Here the goal was to create very long hydraulic fractures reaching hundreds of feet into the pay zone allowing for the production of large volumes of gas. As research on the topic of hydraulic fracturing progressed, it was determined that extended length fractures were difficult, if not impossible, to create. The lack of formations to serve as fracture barriers to contain the upward growth of fractures and the complexity of multiple fractures being created limited the desired fracture length.

Today the evolution of lateral and horizontal drilling technology is beginning to allow the development of unconventional resources through the placement of smaller wellbores into exactly the area and location required for optimum production. Hydraulic fracturing remains an important and necessary well stimulation procedure, but is being done in a highly optimized manner, integrated with unique well completion procedures. Figure 4 illustrates the evolution of the technology over the past forty years.

The trend overall has been from large too small. Hydraulic fracture jobs pumped today are significantly smaller in size, but more effective than those in the 1970's. The evolution of "fishbone" well drilling patterns and the ability to identify, drill, and produce very thin pay zones all add to the "lighter and smaller" and more efficient approach.

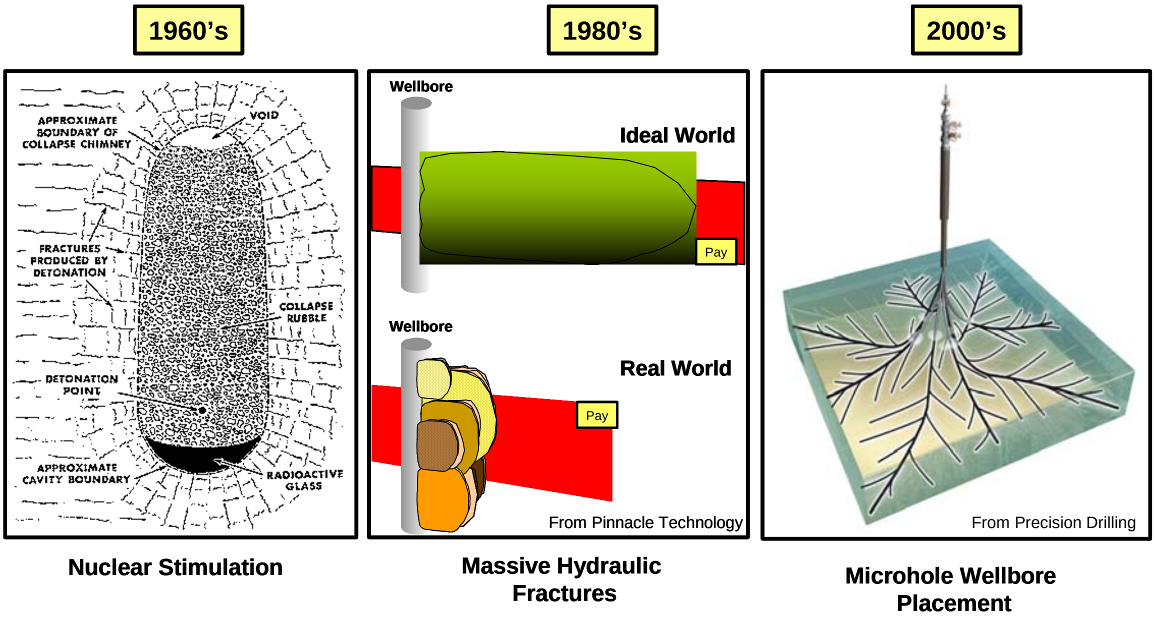

Figure 4: Technology Evolvement over Time (Source: Ref 3)

Current Technical State of the Art in Hydraulic Fracturing

Evolution from Vertical Wells to Long Horizontals

As conventional high permeability and high porosity reservoirs are produced and it becomes more difficult to find these types of reservoirs, the need for alternate sources of hydrocarbon production arises. It has been estimated by many that there is immense resource potential in unconventional low permeability and low porosity reservoirs such as tight sands, shale and coal beds across domestic and international boundaries. These reservoirs, for the most part, do not have the ability to produce hydrocarbons at an economical rate when previous drilling techniques are applied that utilize vertical wellbores and without induced permeability enhancement achieved through hydraulic fracturing.

In order to make an economical well in these unconventional reservoirs, a large portion of the formation containing the hydrocarbons has to be exposed to the wellbore. This can only be achieved if the wellbore follows the bedding plane of the formation for long distances, which requires long horizontal wells. Advancements in Measuring While Drilling (MWD) and Logging While Drilling (LWD) coupled with bit steering technologies have enabled drilling of wellbores that penetrate these tight hydrocarbon bearing formations for long distances. Long horizontal wells by themselves typically do not produce wells that are economical, however they do enable for multiple hydraulic stimulation treatments along the wellbore that increase the effective permeability of the reservoir by inducing hydraulic fractures and connecting and/or dilating existing natural fractures.

Fracturing Issues with Long Horizontal Wells

Fracturing challenges of long horizontal wellbores can be separated into two categories: surface footprint requirements and downhole operational constraints. In order to effectively stimulate the penetrated reservoir by the wellbore, multiple hydraulic treatments have to be pumped. While there is a wide range in the number of frac treatments executed in various unconventional plays that utilize horizontal wellbores, on average a five thousand foot horizontal section will require between 15 to 20 fracs. This many fracs requires about three million gallons of water in order to place about four million pounds of proppant. For this reason a relatively large surface footprint is required to house all of the fluid and proppant along with the equipment needed to pump the fracturing treatments. In many geographical locations it is not possible to secure enough land to store all the needed equipment and fracturing additives and this approach does not maximize efficiency. Therefore multiple wells are drilled from a single pad and the fracturing additives are reloaded for each well.

Downhole operational constraints arise from conveyance of tools, entry friction, and effective placement of fractures. In order to execute multiple fractures in a wellbore, isolation between frac stages is crucial. Isolation of frac stages can be achieved with either a ball or a bridge plug and in order to convey these to the right place in the horizontal, a clean wellbore has to be ensured. Otherwise there is a risk of sticking the ball or the plug and the entire operation comes to a halt, requiring expensive cleanout. High entry friction resulting from various sources can significantly increase the surface treating pressure to the point where it exceeds the limitation of the surface pumping equipment. In many cases hydrochloric acid is pumped at the leading stage of a hydraulic fracturing stimulation treatment to remediate entry friction issues. In most cases, all the fracs pumped in a single wellbore are identical. While this ensures operational efficiency it does not always provide an optimal fracture as the formation (bedding plane) can thin or thicken along the length of the horizontal section.

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Measuring Effectiveness

Effectiveness of horizontal wells can be directly measured by production performance which is dependent on well spacing, lateral length, and orientation of the lateral wellbore relative to the minimum in situ stress. Optimal spacing of horizontal wells will enable maximum recovery of hydrocarbons between two wells and reduce the hydrocarbons left behind to be recovered by future in fill wells. The spacing of horizontal wells has to be such that two wells are not competing for the same reservoir. Because directional drilling is much more expensive then vertical drilling, optimal lateral length has to be determined on the basis of economics and what is operationally feasible. The horizontal wellbore has to be positioned in such a way that when fracturing operations are performed the hydraulic fractures emanating from the wellbore create a network of hydraulic fractures coupled with natural fractures, thus enhancing production. A horizontal wellbore positioned normal to the maximum in-situ stress provides the most complex network of hydraulic fractures as shown in Figure 5 as it promotes a series of transverse fractures along the horizontal lateral. Complex fracture network increases the effective permeability of the reservoir thus enhancing production.

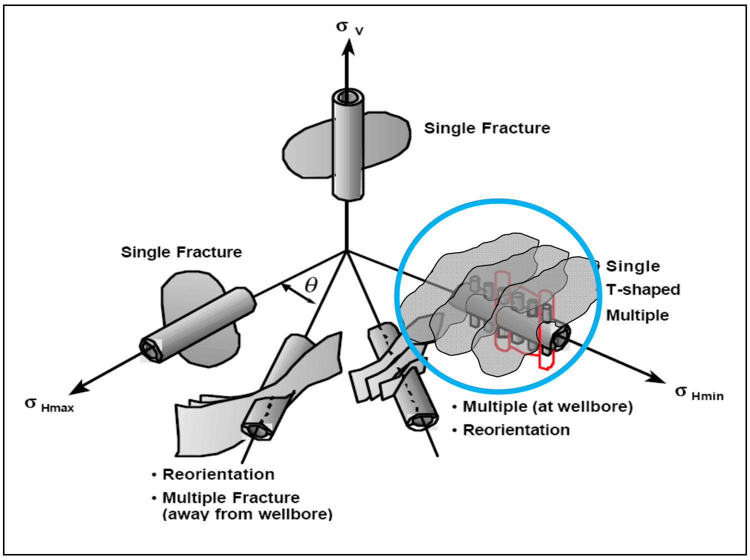


Figure 5: Hydraulic Fracture Geometry Based in Wellbore Position Relative to In-situ Stress Orientation

Hydraulic Fracturing Diagnostics

Current Techniques

Post fracture stimulation diagnostics are used to determine the overall position of induced hydraulic fractures and also the volume of the reservoir that was stimulated, also known as the Stimulated Reservoir Volume (SRV) shown in Figure 6. Current technologies that enable the determination of one or both of these parameters include net pressure matching, tilt-meter, borehole microseismic, temperature, chemical and radioactive tracer surveys. Net pressure matching was refined in vertical wellbores with single fracture treatments and provides insight into the geometry of the created fracture by matching the pressure response. In order for net pressure matching to be reliable, geomechanical reservoir properties have to be accurately modeled in a fracture simulator. Tilt-meter surveys utilize tilt-meters positioned either in the wellbore or on the surface and measure shift of the rock induced by hydraulic fractures. This technology is best for determining fracture azimuth. Additionally, depending on the location of the tools, fracture height and length can be inferred.

Borehole microseismic surveys utilize an array of geophones positioned in an offset well nearby the stimulated well. The geophones record microseismic signals (P and S wave arrivals) that are generated by the propagation of the hydraulic fractures. This technology can measure the spatial and temporal changes of hydraulic fractures. Determining the position of the microseismic source greatly depends on the accuracy of the velocity model used to describe the rock strata through which the signal propagated Various methods are used to generate the velocity model, including seismic profile surveys, acoustic logs, and check shots.

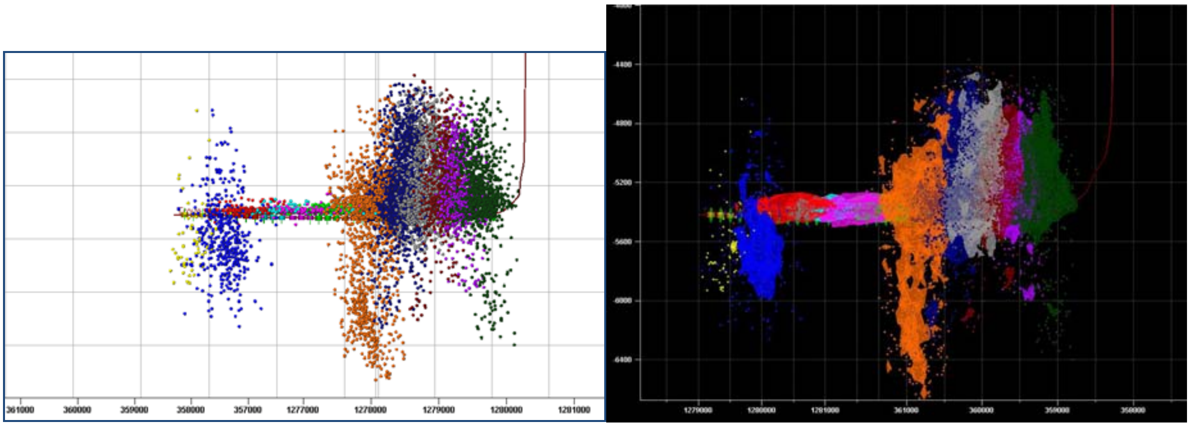


Figure 6: Microseismic Event Locations, left, and Estimated Stimulated Reservoir Volume (SRV)

Emerging Technologies

Emerging fracture diagnostic technologies include the use of geophones positioned on the surface and permanent fiber optic cables installed behind pipe. Because of environmental and efficiency considerations, many wells are drilled from a single pad and extend out as to cover the greatest amount of reservoir. Surface microseismic arrays are gaining in popularity because they do not require an observation well and a single surface radial array can be used to monitor fracture treatments on multiple wells such as the ones depicted in Figure 7. Although an observation well is not needed for a surface array, a large amount of land has to be available for setting up the array, in which case it may not always be an option. Additional surveying and permitting has to be performed prior to setting up the surface array and in some cases a large environmental footprint can be left if clearing of obstructions is required. Signal resolution of the surface array is reduced as compared to downhole arrays, as a result of attenuation of higher frequencies due a longer signal travel path.

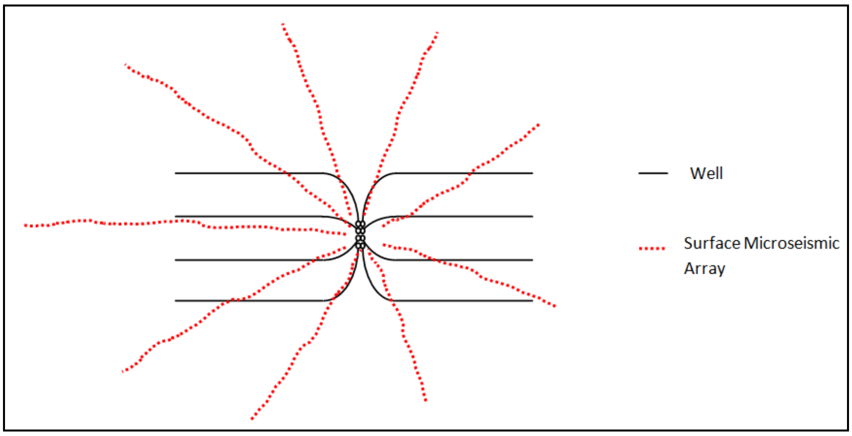


Figure 7: Example of a Surface Microseismic Array

Permanently installed fiber optic cables behind casing provide a real-time measurement of temperature variations during stimulation and production operations. During stimulation, the location of injected fluids can be determined; however fracture geometry can not be readily inferred

Environmental Challenges to Hydraulic Fracturing

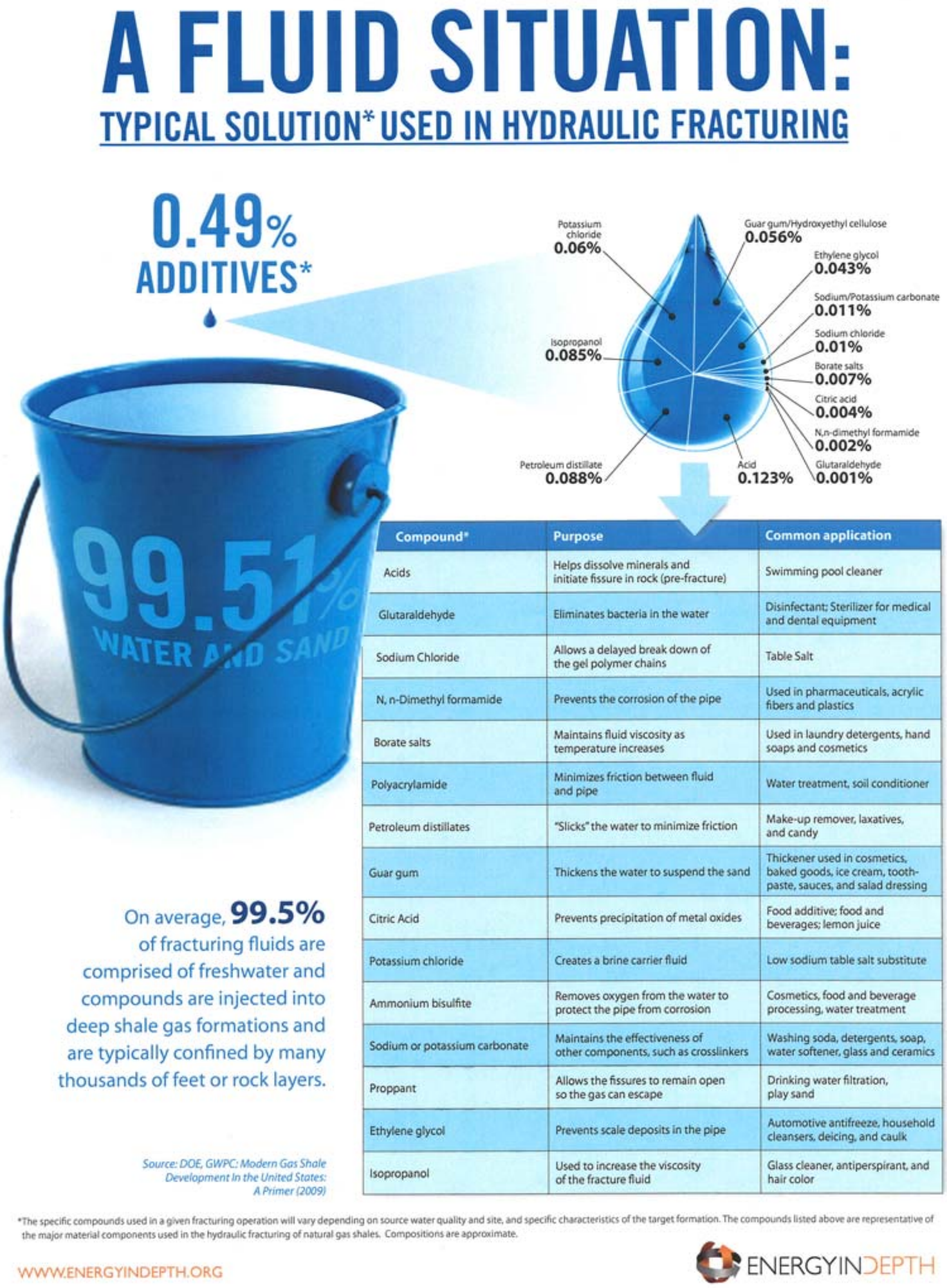
Operators continue to make great strides to manage the environmental challenges of sourcing fresh water for hydraulic fracturing and treating. One of the most important developments has been the practice of reusing the flow-back water from one well for part of the volume required for the next well's hydraulic fracturing effort. Typically, about 25% of the water injected flows back over the first few weeks after the hydraulic fracturing and, as a result, this reuse reduces the potential for environmental impact, reduces ton-miles required in water transportation, decreases air emissions, decreases carbon footprint, lowers truck traffic densities, reduces road wear and generally leads to greater stakeholder acceptance.

Even in the best case, fracturing support is still transportation-intensive with the one million gallons flowing back from one well requiring over 200 truckloads and four times that typically needed in total for the next well. In addition to reuse, operators sometimes dispose of flow-back and produced water by deep well injection at Class II wells, but this option is only available in regions where the geology is suitable for deep injection and the wells have been drilled. Re-introducing the water from hydraulic fracturing into surface or ground water can be environmentally safe if the water first is sufficiently treated but these treatment technologies can be very expensive. Developments continue within the industry to reduce the cost of these treatment technologies. In the meantime, some water treatment is important for re-use to protect equipment and the shale formation from damage. This portfolio of options allows operators to be flexible and allow for the freshwater requirements for shale gas development to be minimized.

Fracturing fluid migration into fresh water aquifers has not been observed. The fracturing takes place very far below fresh water supplies and when fractures are monitored with micro-seismic measuring they are found to not reach nearly far enough to cause water contamination. One source of confusion is that the majority of the water is not recovered back at the surface as flow-back water. This has led some to believe that this non-recovered water seeps back to the surface through the earth and contaminates fresh water aquifers. Although it is not demonstrated that fractures can reach fresh groundwater, there is the potential for spills at the surface and leaks and ruptures in surface casing if cementing jobs are not performed properly. As a result, it is important to understand what is put into fracturing fluids and promote sustainable operating practices that minimize the risk of surface contamination.

Public Perception and Concerns

There have been many concerns raised associated with the hydraulic fracturing process. Some of these concerns have been sensationalized in the documentary *Gasland*, in a series of articles in March 2011 published in the New York Times, and outlined in many internet blogs. There is no denying that there are impacts of energy development on the environment, but some of these media treatments neglect and distort facts. This would seem to be a lot of new attention to a process that has been used for over 1 million wells utilizing billions of gallons of fluid over a 60 year period. In part, this is due to significant activity taking place in populated areas that have little experience with natural gas production. There is a large amount of water required, chemicals are introduced into the water, and the processes used are generally invisible and below the surface (See Figure 8). The vast majority of applications are performed without incident, but in these cases good news is not news. The solution is doing good science and providing transparency to exploration and production activities. This can lead to a separation between fact and fiction and allow for the focus to be put on any risks to the environment that are real and the mitigations to further reduce impact over time.



Compound*	Purpose	Common application
Acids	Helps dissolve minerals and initiate fissure in rock (pre-fracture)	Swimming pool cleaner
Glutaraldehyde	Eliminates bacteria in the water	Disinfectant; Sterilizer for medical and dental equipment
Sodium Chloride	Allows a delayed break down of the gel polymer chains	Table Salt
N, n-Dimethyl formamide	Prevents the corrosion of the pipe	Used in pharmaceuticals, acrylic fibers and plastics
Borate salts	Maintains fluid viscosity as temperature increases	Used in laundry detergents, hand soaps and cosmetics
Polyacrylamide	Minimizes friction between fluid and pipe	Water treatment, soil conditioner
Petroleum distillates	"Slicks" the water to minimize friction	Make-up remover, laxatives, and candy
Guar gum	Thickens the water to suspend the sand	Thickener used in cosmetics, baked goods, ice cream, tooth-paste, sauces, and salad dressing
Citric Acid	Prevents precipitation of metal oxides	Food additive; food and beverages; lemon juice
Potassium chloride	Creates a brine carrier fluid	Low sodium table salt substitute
Ammonium bisulfite	Removes oxygen from the water to protect the pipe from corrosion	Cosmetics, food and beverage processing, water treatment
Sodium or potassium carbonate	Maintains the effectiveness of other components, such as crosslinkers	Washing soda, detergents, soap, water softener, glass and ceramics
Proppant	Allows the fissures to remain open so the gas can escape	Drinking water filtration, play sand
Ethylene glycol	Prevents scale deposits in the pipe	Automotive antifreeze, household cleansers, deicing, and caulk
Isopropanol	Used to increase the viscosity of the fracture fluid	Glass cleaner, antiperspirant, and hair color

Figure 8: Typical solution used in hydraulic fracturing (The specific compounds used in a given fracturing operation will vary depending on source water quality and site, and specific characteristics of the target formation. The compounds listed above are representative of the major material components in the hydraulic fracturing of natural gas shales) *Source: WWW.ENERGYINDEPTH.ORG*

The specific compounds used in a given fracturing operation will vary depending on source water quality and site, and specific characteristics of the target formation. The compounds listed in Figure 8 above are representative of the major material components in the hydraulic fracturing of natural gas shales.

The potential for environmental impact does exist and operators have not always been aggressive on reaching out to affected communities and explaining the process. As a result, there is often confusion and several potential concerns get combined under the heading of issues associated with hydraulic fracturing. These include the volume of water required, the potential for ground water contamination, the potential for spills of water at the surface, and the potential for seismic activity.

There have been some documented cases of localized surface releases of fluids at the surface caused by spills and casing ruptures. In these cases in the U.S., regulators have fined the operators and the operators have cleaned up the local spill and provided alternate sources of fresh water until monitoring provided assurance that the water quality was restored. These cases provide the strong case for voluntary release of information on fracture fluid constituents and identification and adoption of sustainable operating practices.

An additional allegation with the hydraulic fracturing process is that the process causes earthquakes. This concern has been raised in association with a small quake in Texas, a cluster of small quakes in Arkansas, and the most recent event in the UK in a region of shale gas development. Of course, the fracturing process does generate many small seismic events. Each small crack made in the rock can be measured. But these are not felt on the surface by people and there has not been any relationship proven or demonstrated between fracturing and seismic events of the magnitude measured in these specific instances.

Proposed Field Based Research to Address Today's HF Challenges

Hydraulic Fracturing has evolved from the performance of a single treatment in a vertical well to multiple treatments in a horizontal well (Figure 9).

The technology to adequately characterize and evaluate the hydraulic fracturing process has been eclipsed by the ability to drill the horizontal well and pump the fracture treatments.

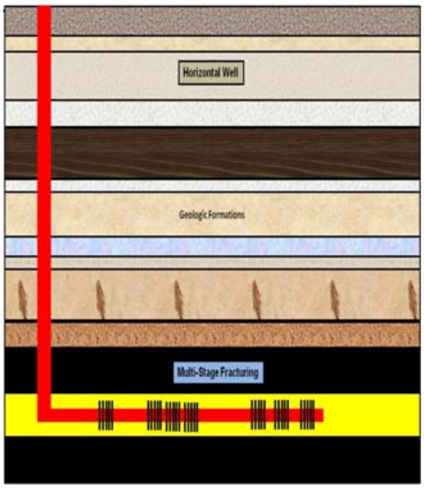


Figure 9: Multi-stage hydraulic fractured, horizontal well. (GTI)

GTI proposes a future collaborative industry project to conduct field research experiments on the hydraulic fracturing process. The objective of this project would be to enhance the understanding of the dimensions and productivity of hydraulically created fractures in long horizontal well completions aiming to develop improved procedures that will be reflected in better well productivity. Additional research to be performed will include novel ideas for creating permeability beyond the hydrualic fracturing process. Experiments with explosives, cryogenic fluids and novel heating techniques will be tested where feasible. Goals of future research should be to:

1. Develop Technology and Techniques to increase horizontal well performance by up to 100%.

2. Mitigate air, land and water environmental issues associated with well drilling and completion by improving the effectiveness of hydraulic fracturing enabling greater multi-pad drilling. Multi-pad drilling will minimize surface footprint and allow increased management of air and water issues.

A future multi-well test site would be conducted in several phases. An early phase would include site selection, experimental design and final goals and objectives. From this phase a detailed experimental plan and cost would be developed. If horizontal well performance can be improved by 100% the benefits could include adding 500 mmcf of reserves (across 1000 wells) and increased revenue of up to $2 billion even at current relatively low price in the U.S. of $4 gas.

Summary

Hydraulic fracturing is a 60 year old process that has been shown to be safe and effective for development of unconventional gas resources. With the development of gas shale resources in the U.S., development has spread to populated areas where the general public is not familiar with the process. A great deal of public concern has arisen in these areas over the safety of the process and the volume of water required. Public outreach is absolutely critical to separate fact from fiction.

The fracturing process initially was performed in vertical wellbores. As horizontal wellbore technology evolved more and more fracture treatments were designed and pumped in horizontal wellbores. Today, multiple treatments can be performed in a single wellbore. While the technology to perform these treatments from a physical perspective is in place, optimization of the process is still far from optimal. Production logs have shown that the overall process can be 50% effective or less.

The combination of environmental concerns and less than optimal performance has led industry to the point where additional research is required to resolve some of the effectiveness issues and add more science to the current art of fracturing. While theoretical and modeling efforts have advance significantly the needed next step is to conduct comprehensive and transparent field experiments to verify new theory explain the productivity responses from multiple and modified treatments in a horizontal wellbore geometry.

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