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COMPARISON OF PNEUMATIC AND HYDRAULIC FRACTURING FOR EMPLACEMENT OF TREATMENT MATERIALS IN LOW-PERMEABILITY FORMATIONS

Mark Strong (mstrong@ch2m.com), Craig Sprinkle, and Denis Ewing
(CH2M HILL, Atlanta, GA, USA)
Dan Owens (U.S. Navy, Southern Division, Charleston, SC, USA)
Capt. Brian Ventura and Leslie Smith (Marine Corps Logistics Base Albany, GA, USA)
John J. Liskowitz (ARS Technologies, Inc., New Brunswick, NJ, USA)

ABSTRACT: Pilot tests were performed at the Marine Corps Logistics Base (MCLB) located in Albany, Georgia to evaluate the performance of pneumatic and hydraulic fracturing for emplacement of in situ biological substrates/electron donors into low permeability alluvium and Ocala Limestone (part of the Floridan aquifer system). The performance of pneumatic fracturing for emplacement of in situ chemical oxidation reagents was also evaluated. Both pneumatic and hydraulic fracturing processes have been applied in the environmental industry to enhance the secondary permeability/ hydraulic conductivity of low-permeability formations composed of silt, clay, and fractured rock. In theory, primarily due to viscosity differences between the fluids, pneumatic fracturing offers the advantages of increased fracture density and improved uniformity, with corresponding improved efficiency of reagent/substrate distribution. Hydraulic fracturing offers the advantage of larger fracture apertures, which allow emplacement of proppant materials. Proppant materials in turn facilitate multiple injection events over time. Based on the pilot tests, pneumatic fracturing appears to be a superior method for single stage emplacement of treatment materials in low permeability formations.

INTRODUCTION

Four pilot studies involving both pneumatic and hydraulic fracturing were completed at the Marine Corps Logistics Base (MCLB) in Albany, GA. The studies were performed to evaluate fracture-assisted injection of chemical reagents, biological substrates, and electron donors for the purpose of groundwater remediation. This document summarizes key theoretical differences between fracturing methods, as well as practical implications of those differences, based on field observations at MCLB.

In general, soil fracturing enhances the permeability of geologic formations by injecting fluid into the subsurface at a pressure that exceeds the natural in situ stresses, and at a flow rate which exceeds the permeability of the formation. Fractures generally propagate perpendicular to the least principal stress of the formation (i.e. the path of least resistance). Since low permeability soils tend to be over-consolidated, the least principal stress is generally in the vertical direction, and fractures will tend to extend horizontally (at least initially) from the injection point (Schuring et al., 1999). As the fractures propagate away from the injection point, they tend to “bend” upward, depending on overburden stresses. The process results in the creation of a fracture or network of fractures, varying in aperture size, which can be used to efficiently distribute reagents or biological substrates in low permeability materials.

The target vertical interval for fracturing at MCLB, 60 to 80 feet below ground surface (bgs), was selected to coincide with the zone of highest impact immediately below the water table interface, which occurs at approximately 50 feet bgs. The geology of MCLB at the target depth consists primarily of overburden soil and alluvium, with Ocala Limestone (part of the Floridan aquifer system) present in localized zones near the bottom of the fracture interval. The overburden soil and alluvium at the depth of fractureing consists primarily of high-plasticity clay with some silt. The Ocala Limestone is composed primarily of fine (chalky), crystallized, dolomitic limestone. The horizontal hydraulic conductivity (h_x) of these two units varies from 0.002 to 0.2 ft/day.

FRACTURING METHODOLOGY

The primary differences between hydraulic and pneumatic fracturing, in terms of most environmental applications, are: 1) method of fluid injection, 2) fluid viscosity, and 3) flow rate. Injection pressure is a function of the formation, depth or overburden pressure, and the size of the borehole. These parameters were relatively consistent during the pilot studies at MCLB. Initiation pressures are higher during pneumatic fracturing because of fluid compressibility.

The ***method of injection*** for both fracturing techniques involves the use of pneumatic packers to isolate a target interval for fracturing. Hydraulic fracturing was completed inside six-inch diameter schedule 40 PVC casing, grouted in place within a 12-inch diameter borehole. To allow fluid to enter the formation, a fracture initiation "notch" (thin, disc shaped opening) was cut into the PVC casing and surrounding grout using a high pressure (10,000 psi) water jet. Pneumatic fracturing was completed inside four-inch diameter, open borings. Vertical distance between the packers, which averaged three feet, determined the interval of the borehole exposed to fracturing. Unlike hydraulic fracturing, where a single fracture is created per event, pneumatic fracturing can be used to create multiple fractures simultaneously.

Fluid viscosity ranges from 0.0178 to 0.0183 cp, for nitrogen and air (respectively), the common fluids used for pneumatic fracturing. Cross-linked guar gel used for hydraulic fracturing ranges from 150-200 cp (viscosity of water is 1 cp). For environmental fracturing applications, the lower viscosity of gas relative to water or guar gel can be a significant advantage. Research shows that pneumatically formed fractures consist of smaller, closely spaced apertures, which propagate faster and extend farther than fractures formed with higher viscosity fluids (Schuring et al, 1992). Observations during the pilot tests at MCLB appear to validate this research. Studies by Schuring also suggest that use of lower viscosity fluids may result in increased fluid loss to the formation ("leak-off").

Flow rates for each fracturing method were based on the field experience and expertise of the respective vendors. Pneumatic fracturing is particularly sensitive to injection flow rate. Low flow rates may result in significant leak-off or non-uniform/partial fracturing of the borehole wall isolated by packers. Since hydraulic fracturing is less sensitive to flow, it is possible to create single hydraulic fractures using a relatively low flow rate in some geologic materials. The guar gel employed in most environmental applications is useful for carrying solids and reducing leak-off.

PILOT TEST OVERVIEW

Four borings, one for each pilot test, were advanced using rotasonic methods. One of these borings was used for hydraulic fracturing and the remaining three were used for pneumatic fracturing. Each boring was advanced to a depth of approximately 85 feet, allowing clearance for mechanical equipment at the bottom of the 60 to 80 foot target interval.

Continuous data logging was employed for each test to record injection pressure vs. elapsed time. The resulting pressure-time history curve was used to determine both the fracture initiation pressure (pressure required to break the in situ stresses along the fracture plane) and the maintenance pressure (pressure required to propagate the fracture).

Hydraulic Fracturing Pilot Test. For this test, one boring, containing a grouted in place casing (designed "FR-A") was fractured at four depths: 76, 72, 66 and 60 feet below ground surface (bgs). The fluid used for hydraulic fracturing consists of biodegradable, water-soluble polysaccharide guar gum gel, mixed at approximately 4-4.5 g/L in water. In preparation for fracturing, the gel was mixed with sand proppant, as well as a cross linking agent (borax) and cellulase enzyme. Boron provided a useful tracer of fracture propagation. Guar gel flow rate averaged 10-15 gpm. Ethyl lactate (biological substrate) was metered into the gel stream at a rate of approximately 30 gph.

After "notching" of the PVC casing and surrounding grout to initiate the fracturing, injection of gel commenced. The deepest fracture interval (76 feet) was performed first, with an initiation pressure of 100 psi. Addition of sand proppant at 76 feet resulted in "bridging" of the sand inside the formation or the injection pipe. Subsequent fractures at higher elevation resulted in lower injection pressures than expected, indicating possible "merging" with a fracture(s) created at lower elevation. Vertical migration of hydraulic (and pneumatic) fractures is reported in the literature (Schuring, 2002).

Pneumatic Fracturing Pilot Tests. Three open hole borings, designated "FR-B, "FR-P, and "FR-Z" were fractured at continuous three-foot intervals; six to seven intervals per boring. Nitrogen gas was used to avoid introduction of oxygen to the subsurface. Gas flow rates averaged 800 to 1300 cfm. The gas was introduced using 1½ inch steel pipe connected to a cone type injection nozzle, lowered into position in sections using either a crane or drill rig,

A high flow burst of nitrogen gas was delivered to three-foot segments of each borehole to induce fracturing, working from the bottom up, for a duration of 10 to 30 seconds each. The short time frame required to complete fracturing improves efficiency in the field. The rate of pneumatic fracturing propagation reported by Schuring (2002) as greater than five feet per second, as opposed to less than ½ foot per second for hydraulic fracturing.

Fracture initiation pressure for the deepest fracture interval at borehole FR-A (77 to 80 feet bgs) exceeded 140 psi. Pressure history curves showed a characteristic "plateau" phase as fractures propagated, followed by a gradual reduction in pressure associated with leak-off into the formation. As in the case with hydraulic fracturing, subsequent fractures at higher elevation resulted in lower than expected injection pressures, indicating "merging" or interconnection with previously created apertures at greater depth, in addition to decreasing overburden pressure.

After the target 20 foot vertical span of each boring was fractured, injection of reactants and/or biological amendments was initiated. Hydrogen gas was delivered to "FR-B" once per week, for a period of six months. Nitrogen gas was used as a carrier fluid to deliver potassium permanganate and water (5% by weight) to "FR-P", and zero-valent iron powder and water (approximately 20% by weight in water) to "FR-Z". Potassium permanganate and zero-valent iron were both injected as a "one time" event.

FRACTURE PROPAGATION AND EFFECTIVENESS MONITORING

Hydraulic Fracturing. The following parameters were monitored during the hydraulic fracturing study:

- Hydraulic head pressure,
- Change in hydraulic conductivity of the formation,
- Ground surface deformation, and,
- Groundwater tracer concentration in groundwater.

Hydraulic head pressure changes, while significant, were not useful to determine the extent of fracture propagation. Groundwater displacement from the first fracture at 76 feet did not fully dissipate before the next fracture was created, because of the low permeability of the formation. The overall effect was cumulative and resulted in a staggered pressure curve.

Slug test data collected before and after fracturing showed negligible change. A 24 to 48 hour pump test may have resulted in better data, although the yield of the subject aquifer was extremely low prior fracturing. Because in situ treatment was planned, pumping experiments were not scheduled.

Review of surface deformation data indicated that the direction and extent of the fracture propagation was anomalous, although this effect was likely accentuated by heterogeneity of the formation itself. Although surface deformation was noted for the first fracture (76 feet), subsequent fractures failed to produce significant heave. The surface deformation profile was exaggerated significant distances from FR-A, which was unexpected. A maximum deformation of 0.70 centimeters was recorded 45 feet northwest of FR-A (the injection point). This result may indicate combined horizontal and vertical propagation of the fractures. Tiltmeter data was inconclusive; the data contained too much "noise" to be useful.

Boron tracer concentrations in monitoring wells surrounding the injection point also indicated irregular fracture propagation and guar gel distribution. Boron (associated with the borax cross linking agent) was detected in a monitoring well located 22 feet from FR-A at a concentration of 4,100 µg/L. The average concentration of boron in pure guar solution prior to injection is approximately 240,000 µg/L. Boron concentrations detected in other monitoring wells were considerably lower. Based on composite boron tracer and surface heave data, fracture propagation occurred both horizontally and vertically in an irregular "lobed" shaped pattern.

Significant changes in chlorinated solvent concentrations were not observed one year after lactate injection into hydraulic fractures. This result is attributable to low organic carbon content of the aquifer and/or nutrient limiting conditions (contributing to slow biological growth), rather than poor distribution of the substrate.

Pneumatic Fracturing. The following parameters were monitored during the pneumatic fracturing study:

- Ground surface deformation,
- Gas pressure in monitoring wells,
- Groundwater tracer concentration (as applicable),
- Geochemical parameters, and,
- Chlorinated solvent concentrations in groundwater.

Surface heave was negligible, as expected. Pneumatic fractures are considerably smaller than hydraulic fractures, in the range of several hundred microns, as opposed to 0.1 to 2 cm for hydraulic fractures.

Gas pressure measurements were collected from top of casing at monitoring wells surrounding the pneumatic fracture borings. These measurements are considered qualitative, used in the field as an initial gauge of fracture propagation.

Sodium hexafluoride was injected as a tracer with hydrogen gas in “FR-B” at a volumetric ratio of 0.1%. Sodium hexaflouride is highly soluble, with a low detection limit in groundwater. Dissolved hydrogen and sodium hexaflouride were detected in all monitoring wells (up to 30 feet from FR-B) at concentrations ranging from 50 to 380 nM. Chlorinated solvent concentrations decreased marginally over the six-month evaluation period, likely because of low organic carbon and/or nutrient limiting conditions in the aquifer.

Permanganate injected into pneumatic fractures at “FR-P” proved to be a useful tracer of fracture propagation. Within two weeks of injection of permanganate, discolored groundwater was observed at various radial distances and directions from FR-P, including one monitoring well positioned at a radial distance of 70 feet. Strongly oxidizing conditions (ORP > +500 mV) were also observed in all wells. Concentrations of chlorinated solvents decreased to less than detection limits within two weeks, from pre-oxidation concentrations of approximately 1 ppm total VOCs.

THEORETCIAL AND EXPERIMENTAL COMPARISON

Use of Proppants. Hydraulic fracturing offers the advantage of larger fracture apertures, which allow emplacement of proppant materials. Proppant materials in turn facilitate multiple injection events over time using low pressure pumping equipment. For this reason, proppant filled fractures may be advantageous in the context of long term in situ groundwater treatment, where an extended period of reactant injections, groundwater purging, or soil vapor extraction is required.

Use of proppants in pneumatic fracturing applications is an experimental process. Based on research by Gottschling (1985) proppants in pneumatic fractures are subject to “banking” near to point of injection, limiting the radial distance of distribution, or, in the case of excessively high gas velocity, the proppant may be non-uniformly distributed away from the injection point. Small-scale application of proppants in pneumatic fractures was conducted at McGuire AFB by the New Jersey Institute of Technology (Galbraith, 1999). The test involved pneumatic fracture assisted injection of ceramic beads into fine sand and silt.

Although most applications of pneumatic fracturing rely upon "self-propping" of the geologic formation, this may be a temporary condition. In accordance with the Cubic Law, fluid flow through open fractures can be significant, even fractures with relatively small dimensions. Brittle geologic materials such as stiff clays and bedrock tend to exhibit good self-propping characteristics, since irregularities along the fracture surface and shifting of the geologic medium prevent fracture closure (Schuring 2002). Research involving plastic clays has demonstrated fracture constriction due to swelling or overburden pressure is reversible.

Reversibility of fracture constriction was not demonstrated at MCLB. During weekly hydrogen gas sparging into pneumatic fractures for a continuous period of six months, sparge pressure was observed to increase progressively, while flow rate decreased. Eventually, near zero flow conditions were observed. The initial flow rate of hydrogen sparging was approximately 60 cfm; significantly lower than the nitrogen flow rate used to create the fractures (800 to 1300 cfm), and apparently insufficient to maintain fracture dilation. Constriction of fractures may have been caused by overburden pressure, clay swelling, and/or silting. The fracture interval at FR-B was positioned in a transition zone which included clay, silty sand, and limestone materials.

Reactant Distribution. In fine-grained soils, diffusive transport dominates (Domenico, 1990). The time frame for diffusive transport between fractures is reduced by maximizing fracture density. Hydraulic fracturing in vertical soil borings involves creation of discrete apertures at two to five foot intervals, while pneumatic fracturing involves creation of multiple fractures within a single three foot interval.

A direct comparison between chemical reagent emplacements within hydraulic and pneumatic fractures was not performed at MCLB. Emplacement of potassium permanganate and zero valent iron within hydraulic fractures was described by Siegrist (Siegrist, 2000). In terms of permanganate distribution, Siegrist notes, "Fractures filled with [$KMnO_4$ crystals] yield MnO_4^- ions that migrate away from their original location, dominantly by diffusion in a low permeability material….will produce a zone, at least several dm wide, where resident TCE will be rapidly degraded."

Based on field geochemical and laboratory analytical data collected during the permanganate study at MCLB involving pneumatic fracturing, strongly oxidizing conditions (i.e. in excess of 500 mV) and greater than 99% oxidation of TCE was observed in monitoring wells located at distances of 20, 25, 35, and 70 feet. Discolored groundwater (indicating MnO_4^- ion activity) was also observed in all of these wells within two weeks, and the groundwater remained discolored for more than one year following injection. Some "rebound" of TCE occurred in the monitoring well located at 70 feet (final reduction of TCE was about 65%).

Zero valent iron injection in pneumatic fractures resulted in greater than 99% reduction of TCE and strongly reducing conditions up to 25 feet from the point of injection. At a distance of 30 feet, reagent (permanganate) commingling was suspected.

Pilot test results indicate that the relatively low viscosity/density permanganate solution (approximately 5% by weight in water) was distributed over a larger area than the zero valent iron suspension (approximately 20% by weight in water).

Field Implementation. Pneumatic fracturing was more cost effective than hydraulic fracturing during the pilot tests at MCLB. Five days were required to complete four proppant filled hydraulic fractures in a single borehole, excluding drilling. One day was required to complete seven non-amended pneumatic fracture intervals. Two to three days were required to complete seven amended (reactant filled) pneumatic fracture intervals. Set-up time for hydraulic fracturing, including guar gum mixing tanks, injection paraphernalia, "notching" of the PVC casing, etc. was greater than that associated with pneumatic fracturing. Hydraulic fracture propagation is also relatively slow, increasing field time.

New techniques for combining rotasonic drilling and pneumatic fracturing are expected to further enhance application efficiency and reduce the time to complete injections (including drilling) to 1 or 1½ days during full-scale implementation, assuming a 20 to 30 foot vertical span of fracturing per boring. Techniques to improve the efficiency of hydraulic fracturing are also available, including completion of single fractures in smaller, closely spaced, grouted casings.

Borehole collapse and sealing issues can be problematic with pneumatic fracturing. Soil collapse and packer bypassing was encountered during the open hole pilot tests, which, in extreme cases, resulted in daylighting of reagent at the surface. Combined sonic drilling and pneumatic fracturing may partially mitigate these issues, since the borehole could be reamed out if collapse occurs and/or over-drilled if the annular seal is lost. Sonic drilling with water injection has been used successfully at other sites to create an annular seal, in lieu of packers. Because hydraulic fracturing uses a grouted-in-place casing, borehole collapse is not an issue.

Significantly higher injection pressures and storage of large nitrogen gas reservoirs on-site during pneumatic fracturing presents health and safety challenges which are lessened or eliminated using hydraulic fracturing.

The cost of hydraulic fracturing and substrate injection at MCLB was approximately $50,000.00 for one boring with four fractures, excluding drilling, and inclusive of mobilization, materials, demobilization, reporting, etc. The cost for pneumatic fracturing and chemical reagent injection into one boring with six to seven fracture intervals was approximately $36,000.00 (also excluding drilling, but otherwise inclusive). Some economy of scale associated with multiple pneumatic fracture borings was achieved.

CONCLUSION

Based on the pilot tests at MCLB, pneumatic fracturing appears to be superior to hydraulic fracturing for single stage emplacement of treatment materials in low permeability formations. However, the effectiveness of pneumatic fracturing for the purpose of long-term, recurring emplacement of treatment materials in situ at these depths requires further evaluation.

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