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Field Experiences With Oilfield Waste Disposal Through Slurry Fracture Injection

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Abstract

More than 100 years of extensive oil production in the U.S. and Canada has resulted in the generation of large volumes of oilfield waste, including produced oily sands and tank bottoms, drilling muds and cuttings, and crude contaminated surface soils. Much of this oilfield waste is the result of previous practices in which drilling muds and even produced oil were impounded in unlined storage pits. Many areas have also been contaminated due to spillage around well cellars, tank farms, and pipe yards. The Los Angeles Basin alone contains more than 10 giant oil fields (100MM bbls or larger) which together are estimated to have created more than 2 million cubic meters of crude contaminated soils. In addition to this pre-existing source of oilfield waste, ongoing production operations continue to produce large quantities of drilling muds, tank bottoms, and produced oily sands. A significant portion of the pre-existing and annually generated oilfield waste material is currently being stored on-site until operators are forced to deal with the wastes whether due to regulatory pressure or in order to convert the property to other uses.

An economic and environmentally sound technique to dispose of these produced oilfield wastes is to re-inject them back into the subsurface. The Slurry Fracture Injection (SFI) process involves slurrification of oilfield wastes with produced water and re-injection at fracture pressures into appropriate formations at the oil field where the waste was generated. On-site disposal of oilfield wastes provides four major advantages to the oilfield operator. These are:

1) An environmentally attractive permanent disposal solution.
2) Little impairment of surface land use.
3) Reduction of long-term liability to waste generator.
4) Reduced transportation and disposal costs.

Terralog Technologies is currently managing slurry fracture injection projects at several sites in the US and Canada, disposing of produced sands, pit sludges, tank bottoms, and crude contaminated surface soils. Typical disposal volumes are on the order of 4,000 to 8000 bbls of slurry waste per day, per well. This paper presents a summary of slurry fracture injection facilities, technical design considerations and monitoring techniques, and regulatory issues in the US and Canada. Two field examples are presented and described in detail.

Introduction

Permanent, low-risk disposal of Non-hazardous Oilfield Waste (NOW) can be achieved through injection of a slurry comprised of waste material and produced water into deep permeable geologic formations. Waste generated at an oilfield location can often be re-injected at fracture pressure through existing wells into the same subsurface formations from which the wastes originated.

The process of Slurry Fracture Injection (SFI) is a means to dispose of accumulated oilfield wastes by deep well injection. This process yields considerable advantages to the operator over conventional disposal methods. SFI provides an environmentally attractive and permanent disposal solution for considerable volumes of NOW waste, and has minimal impact on surface land use. In addition, it affords a significant reduction of long-term liability to the operator while reducing transportation and disposal costs.

Traditional alternatives to SFI disposal include road spreading, surface disposal or landfills, incineration, soil washing, and disposal into salt caverns. These methods are generally more costly and leave the operator susceptible to future environmental and other liability concerns.

Other potential solid waste streams can also be considered for disposal using this technique. Naturally Occurring Radioactive Materials (NORM) present in produced water, scale, and sand from oilfields in many regions such as the Gulf Coast of the U.S. are a good candidate for disposal in this manner. Because deep disposal carries such minimal environmental risk and the isolation is so complete, the approach also has a strong potential for permanent disposal of toxic solid wastes under the right geologic conditions. Waste materials not suited to the SFI process include materials which would react with the geologic formation or which might generate gas under the pressure and temperature regimes at depth.

This paper presents an overview of SFI operations and discusses the technical considerations of the process, including system design and monitoring elements. Field examples are presented to illustrate various operating conditions and waste streams.

The Slurry Fracture Injection Process

The process of Slurry Fracture Injection (SFI) was developed using existing and new technologies in order to isolate NOW waste at depth. The method is essentially a variation of hydraulic fracturing with modifications to contend with requirements for episodic, large-volume injection at moderate rates for periods of months to years in the same well. An existing production or Class II injection well can be recompleted for high pressure injection and perforated to accommodate the slurry properties.

The ideal geologic sequence for successful waste injection is a thick (>10m), laterally extensive, highly porous (>25%), and permeable (>1 darcy) zone of horizontally stratified unconsolidated sandstones and shales at moderate depths (400m to 1500m). These criteria ensure the following key conditions;

1. Fluid bleed-off is rapid, allowing reservoir pressure decay and strain relaxation between injection episodes;
2. A laterally extensive target stratum assures the necessary reservoir storativity to accommodate fluids;
3. Low permeability overburden such as a ductile shale provides hydrologic isolation from overlying groundwater zones;
4. Solid wastes remain close to the injection point because of the high permeability induced fracture bleed-off.
5. Stress barriers to minimize potential of vertical migration[1].

There are several factors critical to the success of SFI field projects. Appropriate operating parameters (injected slurry volumes, injection rates and pressures, and sustainable slurry concentrations) to accommodate sustained injection of material into an unconsolidated sand formation and containment of the injected material within the formation are crucial. In addition, the operating strategy (in terms of injection cycle duration, shut-in durations, injection rates and pressures, and daily injection volumes of sand) must also ensure containment within the target formation, and ideally provide a long term disposal solution for the operator. Finally, thorough monitoring of all injection operations allows continuous assessment of formation response to the injection process in terms of formation pressurization, fracture orientation, and fracture containment.

SFI Operations and Technical Design Issues

SFI field equipment are positioned onsite within 60 meters of the injection well. The field equipment for a typical SFI project is a Slurry Disposal Unit (SDU) including feed hopper and conveyance system for the waste material, grinding and slurry mixing components, a water supply pump, and a high pressure downhole pump (Figure 1). Other critical field elements include a pad with appropriate over-spill containment features and an impermeable liner for the SDU, sufficient storage area (tanks or pits) for the solid and liquid waste, and tanks for the water supply. In addition, appropriate monitoring equipment to optimize operations, electrical power, and adequate infrastructure to access the field location are required.

A typical well profile for slurry waste injection is presented in Figure 2. The target formation must be hydraulically isolated during SFI operations. Packers are placed above and below the target interval to facilitate formation isolation. Before injection commences, pressure fall-off and step rate tests are performed in order to evaluate flow behavior and injectivity in the target formation. The well casing is perforated begining at the bottom of the injection interval. The perforaton interval should not exceed 10 meters in length in order to sustain high injection pressures and rates. The perforation density is typically 20 shots/meter and covers between 90° and 120° phasing to ensure good radial distribution around the well. The packer/tubing assembly is installed close to the top of the perforation interval and should not extend into the perforation interval.

The waste material is processed through the SDU which is connected to a supply of fresh or produced water. The resulting slurry is introduced into a slurry pump capable of achieving high pressures and high rates. The slurry is then pumped down the well where it exits through the perforations and enters the formation. The injection pressure of the slurry is sufficient to overcome parting pressures in the formation. The natural pressure in the porous strata is far less than the water pressure in the slurry, providing a strong natural gradient that draws the water away, leaving the solids component behind.

The SFI operations strategy is formulated based on the specific geology of the field location and on the characteristics of the waste stream. The primary geologic considerations are thickness of the target formation, porosity, and permeability of the rock matrix. The viscosity and composition of the liquid waste stream (slops), and the grain size and composition of the solid wastes (sand) must be well characterized in order to develop appropriate parameters for successful injection. Optimal grain-size for successful injection ranges from 2μm to 350μm. Finer grain material tends to clog the pore space in the disposal formation while coarser grain material settles in the wellbore and interferes with the injection process. The solids concentration in the slurry can be as high as 30 to 40 percent by volume for fine grained material (<150 μm) and on the order of 20 percent by volume for coarser materials.

SFI is typically accomplished in periodic stages, generally lasting for 8 to 14 hours of injection with shut-in periods lasting from 10 to 72 hours. This allows the stress and pressure fields generated within the formation to redistribute and dissipate between injection episodes. Local (near wellbore) changes in stress and flow behavior are carefully monitored by surface and wellbore sensors to optimize injectivity and to track formation response to the injected solids. The injected fluid bleeds off and pressure returns to normal. Injection then resumes for another cycle. The long-term formation effects of sustained injection are not fully understood at this time. However, experience has shown that it should be possible to inject large volumes (>50,000m^3 [300,000 bbls]) of waste solids and liquids into the same formation over extended periods of time.

Field Monitoring Techniques

A significant amount of research and development has focused on monitoring technologies that will allow assessment of the insitu formation response to injected material during SFI operations. Proper evaluation and successful implementation of these monitoring technologies is key to optimizing the injection process and carefully tracking the reservoir state. There are three principal aspects of monitoring in SFI operations. These are:

1. Active monitoring of injection parameters to document and control the SFI process during injection,
2. Monitoring and testing formation response to determine formation flow parameters and potential impairment, and
3. Remote monitoring of formation response through adjacent observation wells, by the surface deformation field, and by other methods such as microseismic monitoring.

To date, the analysis of Bottom Hole Pressures (BHP) during injection and shut-in periods has provided the most accurate means of assessing the dynamic changes in formation flow and mechanical behavior during SFI operations. Through various BHP analyses, details of fracture propagation, stress state and formation flow parameters (such as permeability and transmissivity), assessment of fracture extension pressures, and fracture injection rates can be ascertained. Additional key injection parameters which are carefully monitored and regulated throughout the injection process include injection rate, injection pressure, injection volumes, and slurry rheology (density and viscosity).

When disposal formations are shallow (<800m depth) SFI operations can induce measurable surface displacements in the vicinity of the injection well. Tiltmeters are the most effective means of measuring ground movements associated with injection operations at these depths. Analyses of tiltmeter data provides reconstruction of the formation fracture behavior in terms of geometry (dip, orientation, aspect ratio), and deformation (volumetric and shear deformation).

Geophysical logging techniques are used to evaluate the hydraulic isolation of the disposal formation during SFI operations. Experience has shown that near-wellbore formation flow and stress state changes occur readily during SFI operations. As a result, assessment of the hydraulic isolation of the formation and near well containment of the injected material should be conducted periodically during injection operations. Radioactive tracer log and temperature log data collected concurrently provide a quantitative assessment of the hydraulic isolation of the formation and near well containment of the injected material during SFI.

Microseismic monitoring (MS) technologies are emerging as an effective monitoring tool capable of reconstructing the vertical and areal extent of fracture propagation during SFI operations. The advantages of MS technologies over conventional surface displacement monitoring techniques include real-time data recording, and the ability to monitor fracture development at depths greater than 800m with enhanced resolution.

A monitoring strategy is based on considerations used to optimize operating conditions and ensure that containment within the target interval is maintained. A typical monitoring strategy for field operations includes continuous recording of BHP, pressure fall-off analysis at the end of each injection period, periodic step-rate tests and analysis, and periodic tracer surveys and analysis.

The challenge in SFI operations is to fully understand the mechanics associated with the injection process. Large quantities (>30,000m^3 [200,000 bbls]) of oilfield waste material have been injected into disposal formations providing a substantial body of data on formation response. The monitoring data indicate that the formation flow and stress states do experience dynamic changes during SFI which directly influence the process injectivity and propagation of the injected waste material.

Regulatory Issues in the USA and Canada

When the Resource Conservation and Recovery Act (RCRA) was passed in 1976 to provide cradle-to-grave management of hazardous wastes in the U.S., it was recognized that wastes associated with oil and gas exploration and production (E&P) are generally lower in toxicity than other wastes regulated under RCRA. In 1988 the Environmental Protection Agency issued a regulatory determination stating that E&P wastes should be exempt from RCRA Subtitle C regulations.

For an oilfield waste to be exempt from federal RCRA regulations, it must have either come from downhole, or be intrinsically derived from primary field operations associated with exploration and production. Examples of RCRA exempt wastes include; produced water, drilling fluids, produced sand and tank bottom sludges, pit sludges, hydrocarbon bearing soils, and pipe scales.

Regulatory oversight for disposal of these materials is therefore primarily the responsibility of individual states. Several states, including California, Texas, and Louisiana allow these E&P wastes to be injected into Class II disposal wells on a case-by-case basis.

The designated nonhazardous oilfield waste material injected into Class II wells must originate downhole. Some states, including California, require sample analysis prior to injection of certain waste streams in order to verify that they are, indeed, nonhazardous. In other states, such as Texas and Louisiana, it is not required to analyze waste material prior to injection if it fits the criteria of designated nonhazardous Class II material.

In Canada SFI operations for oilfield wastes are regulated at the provincial jurisdiction level. In Alberta significant progress has been made in regulating SFI operations. The regulatory agency overseeing this work in Alberta is the Alberta Energy Utilities Board (AEUB). Produced sand, tank bottoms and oily sludges generated from oil production operations are generally classified as Non Dangerous Oilfield Wastes (non-DOW). Prior to 1997 SFI operations in Alberta were approved as Demonstration Projects, solely under the jurisdiction of the AEUB. The mandate of these projects was to evaluate the SFI process in order to show that large volumes of material could be successfully reinjected at high pressures and rates while maintaining containment within the disposal formation. Starting in 1997 SFI operations in Alberta will have to maintain compliance with AEUB regulations defined in the following guidelines:

1) G-51, Injection and Disposal Wells; Well Classifications, March 1994,
2) G-55, Storage Requirements for the Upstream Petroleum Industry, July 1995, and
3) G-58, Oilfield Waste Management Requirements for the Upstream Petroleum Industry, November 1996.

SFI wells will likely be classified as Class 1b wells with the following exemptions and restrictions:

1) Injection at above fracture pressure will be permissible (approximately 1.1 to 1.5 times fracture extension pressure),
2) Only waste material consisting of produced water, produced sand, and oily sludges from production operations may be injected.

SFI Field Examples

Slurry fracture injection for waste disposal has been applied to dispose of drilling muds and cuttings in Alaska, California, the Gulf of Mexico, and the North Sea[2-5]; it has been applied to dispose of NORM onshore and offshore in Texas and Louisiana[6-7]; and it has been applied to dispose of large quantities of produced sand and tank bottoms in Western Canada[8]. Table 1 presents a summary of several oilfield waste disposal projects currently being operated in Western Canada. Two of these projects, designated as case study A and case study B, are described in detail in the following sections.

Case Study A

Between July and November 1996, over 8,700m^3 [55,000 bbls] of produced sand and over 1,500m^3 [9,500 bbls] (of oily waste material has been injected into a subsurface formation in an extended high pressure injection operation at an oilfield location in southwestern Alberta, Canada. The overall objective of this operation is to dispose of large volumes of produced sand and oily waste from heavy oil production through deep injection into a former production well.

Oilfield wastes at this site are primarily composed of oily sand from heavy oil production operations in the area, with an additional quantity of oily tank bottoms (slops). The produced sand contains approximately 1 to 2% bitumen at 12 to 14 API gravity with trace heavy metals. The oily tank bottoms waste consists of a 24% oil, 19% water, and 57% solids emulsion. Figure 3 presents a photo of the disposal site. In the foreground a new containment pit for the solid wastes transported by vacuum truck from individual well sites can be seen. A stockpile of produced sand is visible in the background awaiting injection at the disposal well.

The oilfield waste is injected into the early Cretaceous Rex Formation of the Lower Grand Rapids Group which overlies the oil-bearing Manville Group. The Rex is a water sand with no identified economic oil reserves. Petroleum production in the underlying units is typically heavy oil and gas. The former production well chosen for this injection project was selected because of its close proximity to the waste stream, the fact that it had a pre-existing pad with road access, it had been completed for high pressure injection, and is located within 200m of other wells which can be used as pressure observation wells.

At this site the primary technical challenge of SFI was to successfully contain the oilfield waste materials within the disposal formation by minimizing vertical fracturing. Through careful monitoring of injection operations, formation response is evaluated in terms of formation pressurization, fracture orientation, and fracture containment on a continual basis, while at the same time maintaining the optimal operating parameters for injection cycle duration, slurry volumes, rates, pressures, and sand concentrations.

The monitoring strategy for this operation includes continual evaluation of multiple elements. Injection parameters including injection rates, BHP, well head pressure (WHP), slurry density, slurry volumes, and sand to fluid ratios are continuously monitored. Formation response is evaluated using daily fall-off and periodic step-rate tests. Surface displacement data are recorded using a tiltmeter array consisting of 12 tiltmeter devices arranged around the injection well in three concentric circles at 100m, 200m, and 400m radii respectively.

Figure 5 provides a summary of the SFI operations at this field through mid November 1996. A cumulative slurry volume of over 41,000m^3 [260,000 bbls] was injected through that time period. The injected slurry is composed of an average mix of 25% waste sand and slop and 75% produced or fresh water. To date over 1,800m^3 [11,000 bbls] of oily waste and over 10,000m^3 [63,000 bbls] of sand have been injected at this location, in a total slurry volume of 48,000m^3 [300,000 bbls]. Figure 6 summarizes the relative sand, slop, and slurry volumes injected through the reporting period. Typical daily operation parameters are as follows;

1) Slurry injection rate; 1.5m^3/min.
2) Slurry density; 1,150-1,200 kg/m^3
3) Daily sand volume injection; 150-200m^3/day
4) Daily slurry volume injection; 600-800m^3/day

Prior to SFI operations at this location, oilfield wastes were disposed of through use in road spreading operations, salt cavern disposal, treatment by crude separation techniques, and reprocessing at a cleaning plant facility. By disposing of these wastes using SFI, the operator was able to significantly reduce its produced sand disposal costs. Furthermore, local regulatory policy in the area requires that an environmentally sound oily sand disposal policy be implemented before expanding heavy oil production operations.

Case Study B

At this site the operator accumulates oily tank bottom sludges and produced sand from oil production operations in west-central Saskatchewan, Canada. The original technical objectives for the SFI project in this case were to dispose of approximately 12,000m^3 [75,000 bbls] of oilfield materials consisting of tank bottoms and produced sand from heavy oil operations over a two-year period. The produced sand consists of less than 5% bitumen at 12 API Gravity. The tank bottoms consist of a 80% oil-water emulsion and 20% fine sediment.

The sources of produced sand and tank bottoms at this site include well pad sites, skimmer tanks, and separators used in oil production operations. The sand and heavy oil production in this area comes primarily from Cretaceous oil-bearing formations. The produced sand is typically fine grained quartzose of 50-250μm diameter with silt and clay fines. The sand is generally disaggregated and free of any cementing agent.

The entire field operations for this project are contained in a large aluminum and steel enclosure measuring over 5400m^2 to accommodate harsh winter operations in this central Canadian location. A photo of the enclosed operations is presented in Figure 4.

Figure 7 provides a summary of the SFI operations at this field through early April 1997. Over the three month injection period from January through early April, about 9,000m^3 [57,000 bbls] of oily sand and tank bottoms was injected along with about 45,000m^3 [280,000 bbls] of produced water, for a total slurry of about 54,000m3 [340,000 bbls]. To date over 7,400m^3 [47,000 bbls] of oily waste and over 3,600m^3 [23,000 bbls] of sand have been injected at this location, in a total slurry volume of 64,000m^3 [403,000 bbls]. The injected slurry is composed of an average mix of 25% waste sand and slop and 75% produced water. Figure 8 summarizes the relative sand, slop, and slurry volumes injected daily through the reporting period. Typical daily operation parameters are as follows;

1) Slurry injection rate; 1.1-1.5m^3/min.
2) Slurry density; 1150-1210 kg/m^3
3) Daily sand and slop volume injection; 100m^3/day
4) Daily slurry volume injection; 600-700m^3/day

In the past these materials had been used in road spreading operations and trucked to sand-oil separation facilities. However, due to recent costs increases for these disposal options the operator chose to consider more cost-effective disposal techniques. A cost comparison of various disposal methods was recently made and the results are shown in Table 2. SFI was selected as the disposal method of choice due to the documented successes of other oil production operators, longer term environmental viability, and the cost-effectiveness of the technique.

Summary of Observations

Several insights have been gained after three years of injection operations and monitoring at a number of disposal sites in Western Canada. Some of these observations can be summarized as follows:

1. It is generally not possible to sustain long-term injection at below formation parting pressure, even with very fine grained and low density solids injection into high permeability (>1 darcy) and high porosity (>30%) sand intervals.
2. Surface tiltmeter analysis indicates that solids injection produces a complex and changing dilation zone around the wellbore, rather than a single discrete fracture plane.
3. The orientation of this dilation zone changes over time and with varying slurry properties.
4. Continuous waste injection leads to formation pressurization. It is necessary to inject in periodic episodes to allow excess pore pressure and formation stress to relax in order to sustain long-term injection within a single interval.
5. It is often necessary to continuously adjust slurry

concentrations and relative amounts of solids, oil, and water, in order to control reservoir pressurization and optimize long-term injection.

6. Individual high porosity sand intervals, on the order of 30m thick, have been shown capable of accepting relatively large volumes of solids and oily wastes (>10,000m^3 [63,000 bbls]).

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Conversion Table	
1 m	= 3.281 ft
1 m^3	= 6.29 bbl
1 MPa	= 145 psi
1 Kg	= 2.2 lb

Table 1. Current Waste Injection Projects Operating in Western Canada

	Primary Oilfield Waste	Approx. Yearly Slurry Injection (bbls)
Site A	Produced oily sand	250,000
Site B	Produced sand and tank bottoms	500,000
Site C	Tank bottoms	150,000
Site D	Produced sand and tank bottoms	510,000
Site E	Tank bottoms	100,000
Site F	Produced oily sand	760,000

Table 2. Cost Comparison For Selected Disposal Options at Site B

Year	Waste Volume Disposed	Technique	Estimated Cost (US$/bbl)
1994	3,800 bbls	Sand Cleaning	22.00
1995-present	1,600 bbls/month	Salt Caverns	22.00
1995-present	22,000 bbls	Road Spreading	13.00
1996-present	120,000 bbls	Slurry Fracture Injection	8.00

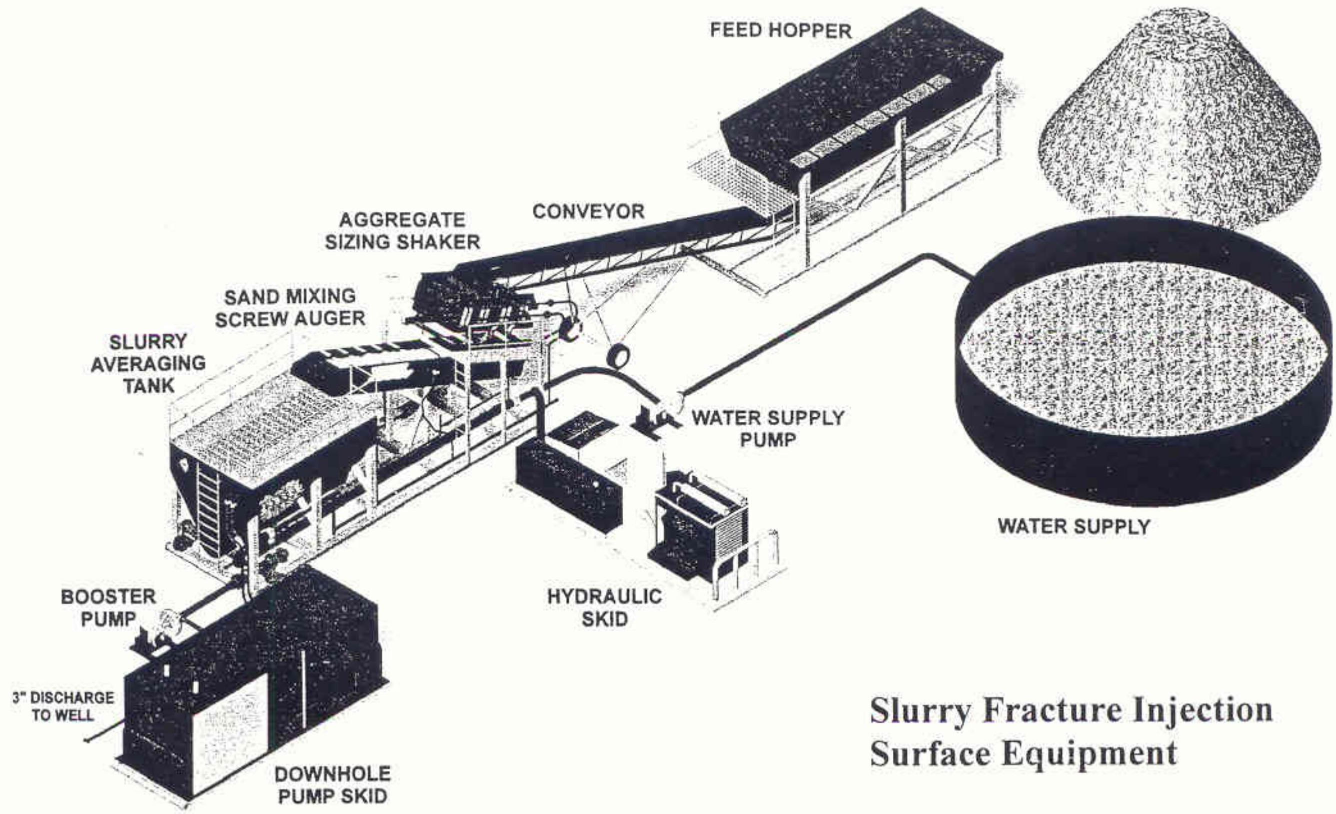

Figure 1. Slurry fracture injection field equipment

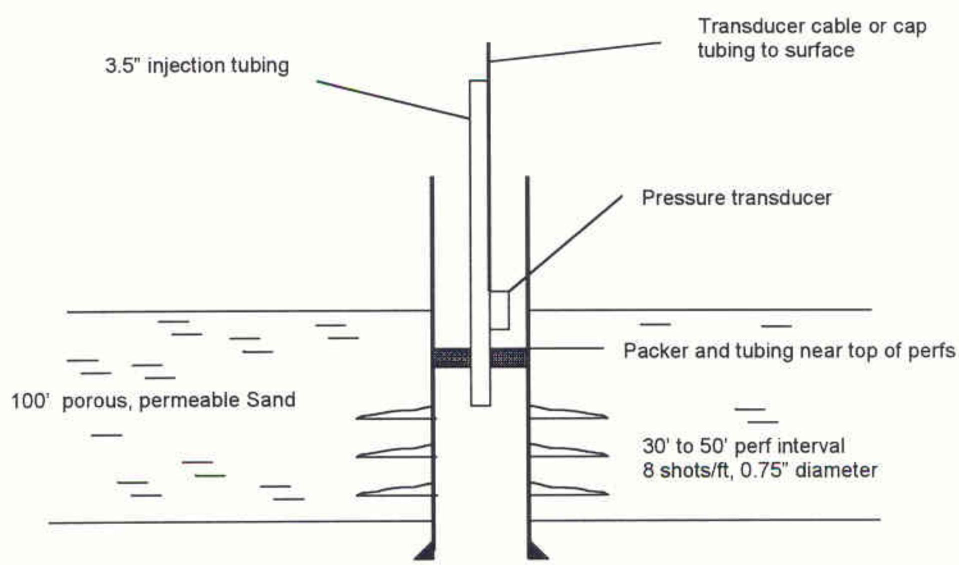

Figure 2. Schematic of typical well completion for slurry fracture injection

Figure 3. Site A surface layout. Produced sand stockpile to be injected is visible in background between water tank and well, which is being worked over. In foreground is new concrete and clay lined waste storage pit .

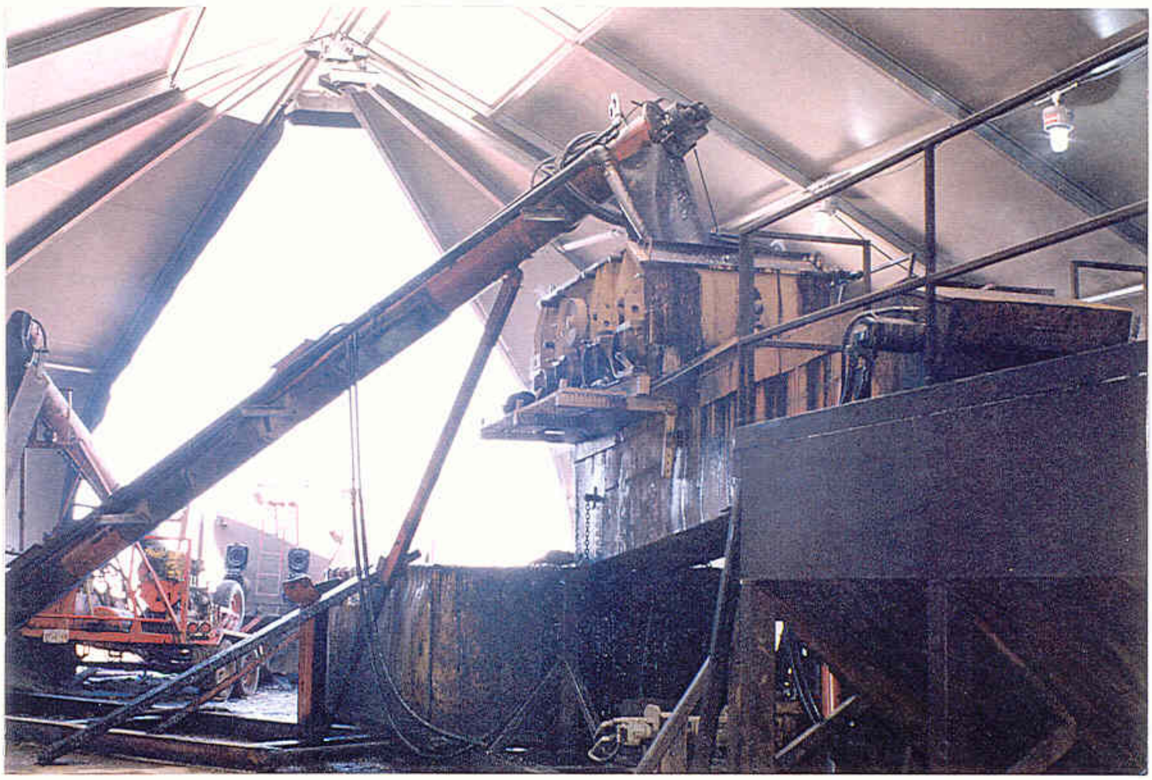

Figure 4. Site B injection equipment in operation. Enclosed SFI equipment at this site allows year-round operations during inclement weather.

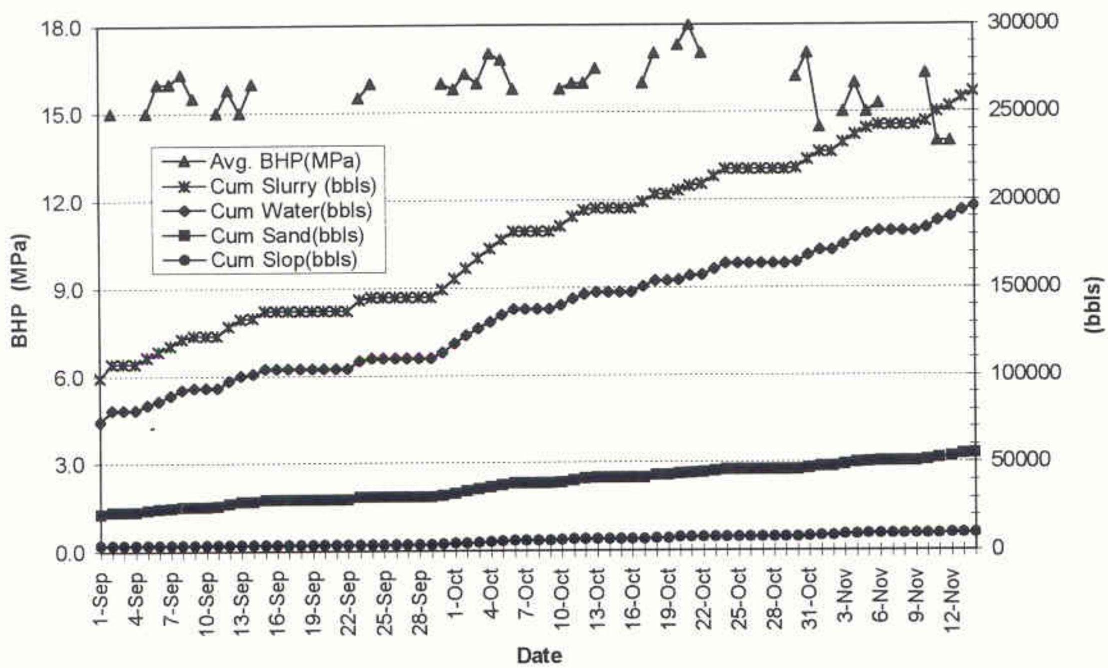

Figure 5. Case A cumulative waste injection summary

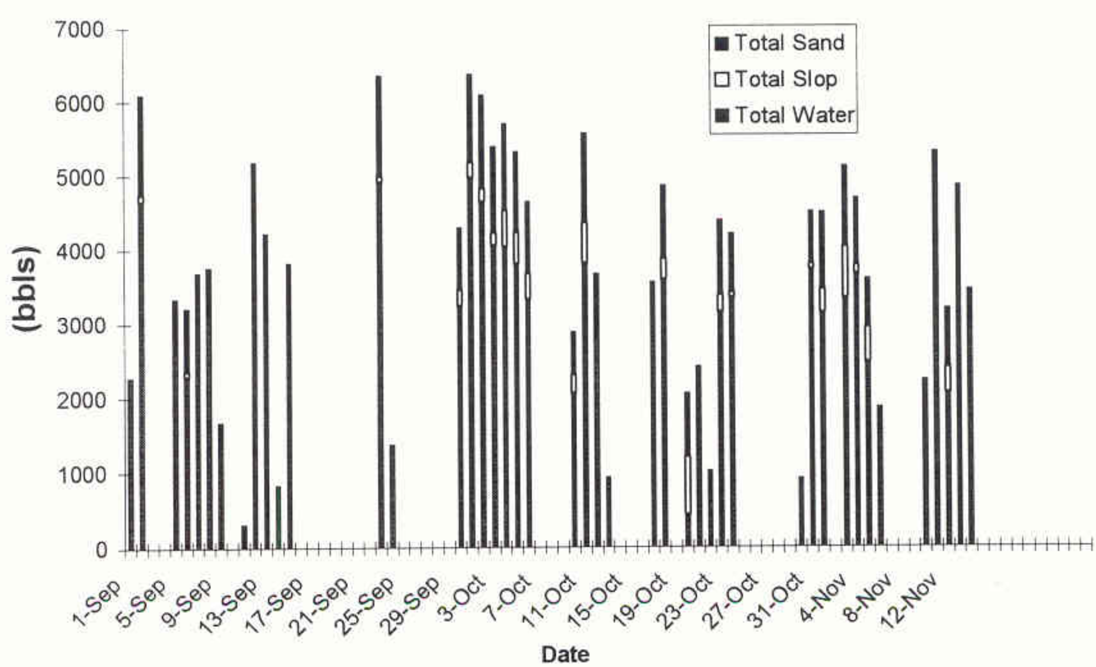

Figure 6. Case A daily waste injection summary.

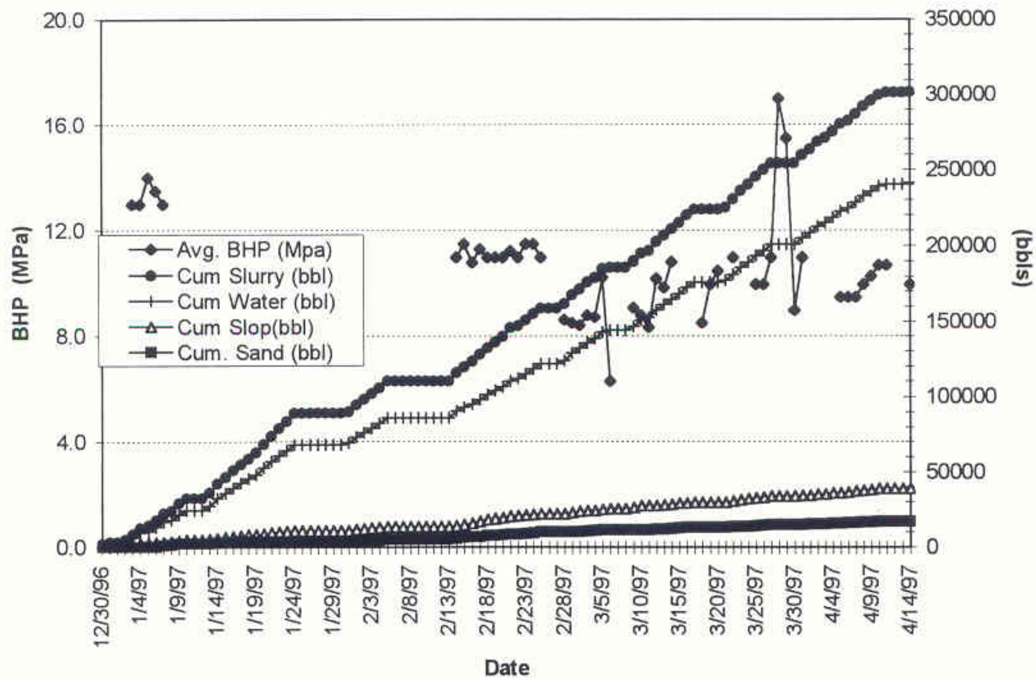

Figure 7. Case B cumulative waste injection summary

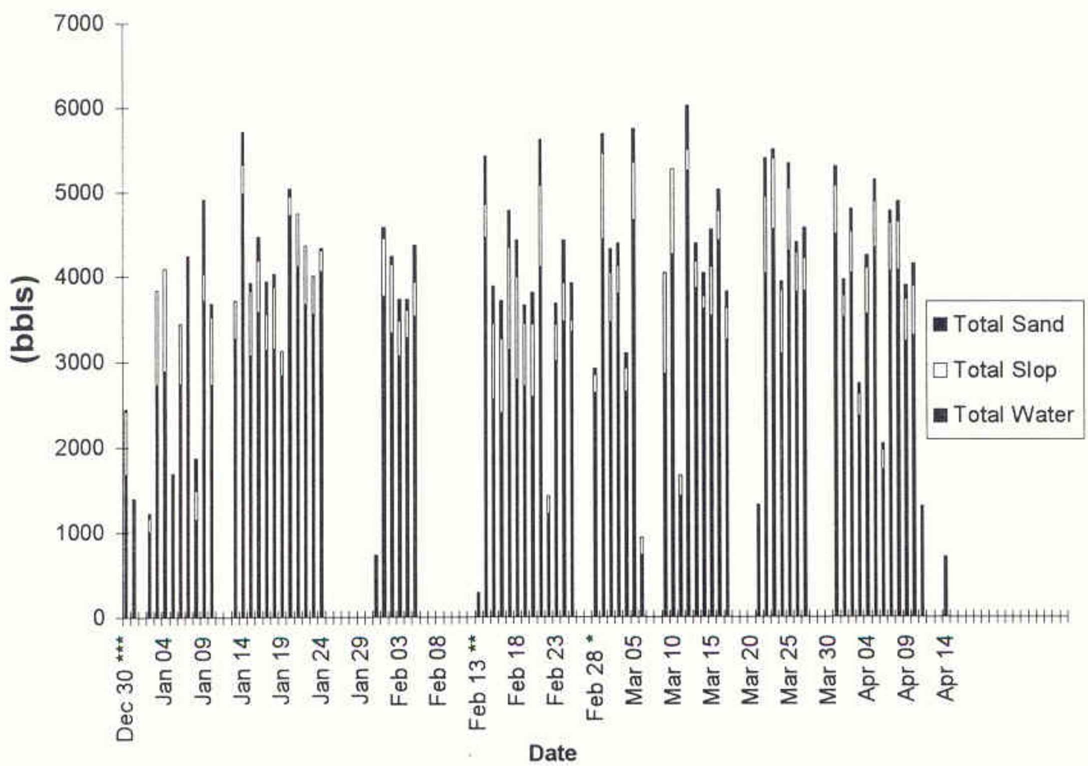

Figure 8. Case B daily waste injection summary.