TTI

Terralog Technologies

Development of Improved Oil Field Waste Injection Disposal Techniques

Topical Report # 4: Recommended Operating and Monitoring Guidelines

Prepared by:

Michael S. Bruno, Alex Reed, and Susanne Olmstead

Terralog Technologies USA, Inc.
332 E. Foothill Blvd, Arcadia, CA 91006

DOE Contract DE-AC26-99BC15222

Draft April 30,2001

Disclaimer

ABSTRACT

Slurry Fracture Injection (SFI) is a waste disposal technology in which petroleum exploration and production wastes, such as produced sand, drilling muds, tank bottoms, and pit sludge are mixed with water into a slurry and injected into deep unconsolidated sandstone formations above fracturing pressure. The mechanics governing the fracturing of unconsolidated sandstone formations remain poorly understood, and as a result there are few guidelines available to optimize the SFI process. The goals of this DOE sponsored project are to: 1) assemble and analyze a comprehensive database of past waste injection operations; 2) develop improved diagnostic techniques for monitoring fracture growth and formation changes; 3) develop operating guidelines to optimize daily operations and ultimate storage capacity of the target formation; and 4) to test these improved models and guidelines in the field. This Topical Report summarizes Terralog's efforts and results for project task 3: Operating and Monitoring Recommendations

A successful SFI project requires cooperation between regulatory agencies, the project operator and engineer, drilling and completions companies, and the site operators. Good communications need to be established between each of these groups. The success of an SFI project is sensitive to each party understanding and applying appropriate design, operating, and monitoring guidelines.

The SFI well for large-volume waste injection should be located in a formation and area that has sufficient capacity to contain the hydraulic fracture process in a suitable permeable zone. The formation properties should include high permeability (1 Darcy or more), high porosity (25% or more), moderate to large thickness (20m or more), and lateral continuity. Special care should be taken to evaluate the mechanical condition and cement coverage for any offset wells within about a kilometer of the proposed injection well. Ideally, the target formation should be overlain by multiple low permeability shale intervals (to provide flow barriers) and high permeability sand formations (to provide a flow sink, or buffer zone, in case of breach).

A typical SFI injection well should include surface casing and production casing cemented to surface. Injection should take place through a tubing and packer system. Good well drilling and cementing practices are critical in providing a good cement bond along the well for the SFI injection well. If a good cement bond exists, particularly in the 60 to 100 m above the target injection zone, the volume of slurry which infiltrates upwards is very small and the volume of waste which can be placed into the target formation can be very large relative to poorly cemented wells.

SFI is best performed as a cyclic injection process, with daily periods of injection and shut-in. This permits dissipation of pressures and stresses into the formation during shut-in periods. The pressure data collected during these cycles indicates the formation injectivity and stress conditions and can be used to predict future behaviour. Continuous slurry injection does not permit dissipation processes to occur and little information is available to determine injectivity and stress states.

Well logging, bottomhole pressure recording and other monitoring and analysis techniques are crucial in determining the behaviour of the SFI process. Monitoring and analysis provides information about the growth of hydraulic fractures and the waste pod, and confirms the containment of the injected wastes in the target formation. This feedback loop of information can then be used to direct future injection operations.

TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION AND PROJECT SUMMARY

Slurry Fracture Injection is a waste disposal technology developed by Terralog Technologies Inc. Oilfield produced wastes, such as produced sand, slop, and tank bottoms, are mixed with water into a slurry which is then injected into deep unconsolidated sandstone formations above fracturing pressure. The solids are permanently emplaced within hydraulic fractures generated during the pumping process, and the carrying fluid subsequently drains into the high permeability formation.

The mechanics governing the fracturing of unconsolidated sandstone formations remain poorly understood, and as a result there are few guidelines available to optimize the SFI process. The tasks for this research project have been to:

1. Organize a database of waste injection operations and formation response.
2. Evaluate correlations between waste types, injection pressure, pumping rate, etc.
3. Develop improved pressure analysis and fracture diagnostic techniques for solid waste injection in high permeability granular formations.
4. Develop operating guidelines to improve containment and optimize storage capacity.
5. Verify improved diagnostic tools and operating guidelines in the field.
6. Project documentation and presentations.

The results from Tasks 1, 2, and 3 have been described in detail in three previous Topical Reports by Terralog (2000a,b,c) and are briefly summarized herein.

Database Overview

Terralog Technologies assembled an SFI database template, and populated it with the monitoring data collected from eight oil field waste injection projects, comprising a total of more than 500 injection episodes (Topical Report #1). The measured data consists of slurry and material volumes, wellhead and bottomhole pressures, pumping rates, slurry densities, and other relevant information collected continuously at intervals from 5 seconds to 5 minutes. The database is created in Microsoft ACCESS format. It includes three tables: a Project Information Table, a Pressure and Rate Table, and a Daily Summary Table. Terralog has also created two plotting programs within Access in order to graphically view the data provided in the Pressure and Rate Table and Daily Summary Table. These can be used to rapidly view data for visual interpretation. The query tools built into Access can also be used to create custom datasets for specialized interpretation. The power of the Terralog database is that different variables can be plotted easily using the Microsoft Access program. Data from different projects can be compared directly. Cross plots of various injection parameters and observations can be made, with filtering on a third variable. For example, injectivity vs. viscosity can be plotted for all days in which sand percentage exceeds a certain value.

Empirical Correlations

This database has been used to evaluate influences of operational changes on injection and formation response in order to optimize operations and to provide insight into large-scale slurry injection in high porosity media (Topical Report #2). Some of the observed trends are consistent with expectations; however, some are not. For example, closure gradient does increase with accumulation, but is not particularly sensitive to daily changes in slurry composition. Injectivity appears to be more sensitive to sand concentration then to slop concentration. The following general observations can be made based on the correlations investigated:

- Closure pressure gradient tends to increase slightly as wastes accumulate in the target formation.
- On a daily basis for individual projects, however, there is little correlation between closure gradient and percent waste material.
- Injectivity has a distinctive maximum envelope that is highest for low percentages of waste material and sand. Mud and slop percentages appear to have no impact trend on injectivity.
- Near well permeability reflects the impact of accumulating materials and material injection strategy into a formation, but is not dependent on the daily changes in slurry composition.
- Injectivity appears to be more closely related to fracture growth than it is to formation permeability.

These types of observations are useful to guide future operations. In addition to providing insight on basic operating strategies, the database is also useful to evaluate existing and new fracture modeling and diagnostic techniques.

Fracture Modeling and Diagnostic Investigations

Our observations of fracturing and formation behavior during large-volume waste injection operations suggested a new physical model for episodic injection (Topical Report #3). When a vertical fracture is first induced in a virgin reservoir, its tendency will be to open against the least regional principal stress, $\sigma 3$, and extend in length parallel to this direction. During slurry fracture injection, the stream of waste slurry being pumped into the formation causes a fracture to open and material to dilate around the fracture, or within a "process zone". Much of the solid volume injected is accomodated by invading formation porosity, not simply within the fracture volume. The waste becomes trapped in the formation when pumping stops and the fracture and dilation zone closes.

This large amount of solids packing the fracture and dilation zone alters formation properties and behavior. The stresses within the process zone increase and the permeability within the process zone decreases. Subsequent injection episodes will then cause fractures to break through the waste pod, in a direction still parallel to $\sigma 3$, but with increasing difficulty. This is sometimes indicated by increased net pressure and less rapid pressure decline after shut-in. The minimum stress within the waste pod increases and, eventually, fracture re-orientation away from the $\sigma 3$ direction occurs. We propose a relatively simple analytic model to account for this "packing effect" as the waste pod grows with sequential injection, which allows prediction of fracture re-orientation as a function of injected volume. Model results are consistent with field observations, indicating that fracture re-orientation over a range of 30 to 60 degrees in azimuth can occur due to injection volumes on the order of 5000 cubic meters.

We also investigated the use of two dimensional analytical models (Perkins-Kern-Nordgren) and pseudo three dimensional models (FRACPRO) to simulate slurry fracture injection. These were modified to allow variations in shear modulus, leakoff coefficients, and closure stress with repeated injection episodes in order to capture observed formation behavior. Varying these parameters provides improvement over typical constant value assumptions, but it is difficult to recognize beforehand which parameters should be allowed to vary.

Finally we investigated the use of coupled fluid flow and particle flow models to simulate fracture and dilation processes during waste injection. These studies lead us to conclude that when formations are weakly cemented with limited shear strenght, there is a transition from brittle, discrete fracture extension, to more widescale dilation and inelastic parting. We were successful in developing a coupling process between a continuum flow model and a discrete particle model, allowing simulation of slurry particle injection and resulting fracture and dilation. These simulation results, although preliminary, appear to capture the physical processes involved in solids injection into weakly cemented media. This method shows good potential for better simulating waste injection, and warrants additional investigation and development effort.

Current Investigations

This Topical Report summarizes work completed towards Task 4, recommendations for operating and monitoring guidelines. A successful SFI project requires cooperation between regulatory agencies, the project operator and engineer, drilling and completions companies, and the site operators. Good communications need to be established between each of these groups. The success of an SFI project is sensitive to each party understanding and applying appropriate design, operating, and monitoring guidelines.

The following Section of this Topical Report presents recommended Geologic and Well Location Guidelines. The SFI well for large-volume waste injection should be located in a formation and area that has sufficient capacity to contain the hydraulic fracture process in a suitable permeable zone. The formation properties should include high permeability (1 Darcy or more), high porosity (25% or more), moderate to large thickness (20m or more), and lateral continuity. Special care should be taken to evaluate the mechanical condition and cement coverage for any offset wells within about a kilometer of the proposed injection well. Ideally, the target formation should be overlain by multiple low permeability shale intervals (to provide flow barriers) and high permeability sand formations (to provide a flow sink, or buffer zone, in case of breach).

Next we present recommended Well Completion Guidelines. A typical SFI injection well should include surface casing and production casing cemented to surface. Injection should take place through a tubing and packer system. Good well drilling and cementing practices are critical in providing a good cement bond along the well for the SFI injection well. If a good cement bond exists, particularly in the 60 to 100 m above the target injection zone, the volume of slurry which infiltrates upwards is very small and the volume of waste which can be placed into the target formation can be very large relative to poorly cemented wells.

Next we present recommended Operating Guidelines. SFI is best performed as a cyclic injection process, with daily periods of injection and shut-in. This permits dissipation of pressures and stresses into the formation during shut-in periods. The pressure data collected during these cycles indicates the formation injectivity and stress conditions and can be used to predict future behaviour. Continuous slurry injection does not permit dissipation processes to occur and little information is available to determine injectivity and stress states.

Finally we provide recommended Monitoring and Analysis Guidelines. Well logging, bottomhole pressure recording and other monitoring and analysis techniques are crucial in determining the behaviour of the SFI process. Monitoring and analysis provides information about the growth of hydraulic fractures and the waste pod, and confirms the containment of the injected wastes in the target formation. This feedback loop of information can then be used to direct future injection operations.

DESIGN AND OPERATIONS MANAGEMENT APPROACH

Our review and analysis of waste injection projects in Canada and the United States has led to a number of critical observations that distinguish large-volume fracture injection from typical short-term fracture stimulation. Some of these observations include:

1. Slurry injection into soft, high permeability formations creates a relatively thick fracture and dilation zone, providing greater storage capacity than traditional thin fractures generated in hard rock;
2. In contrast to normal stimulation operations in low permeability rock, during waste injection in high porosity formations fracture conductivity in the created process zone is often less than or equal to the native formation conductivity;
3. Stresses tend to increase within this fracture and dilation zone, as indicated by increasing shut-in pressure;
4. Reduced fracture conductivity, combined with increased stress within the waste pod, often results in new fractures being created with repeated injection episodes at orientations varying over a range of 30 to 60 degrees;
5. Formation response, fracture behavior, and injectivity can be controlled and optimized by varying injection material content (solids concentration, constituent ratio, density, etc…) and injection rates.

Recognizing some of these unique aspects to large-volume waste injection, and keeping in mind the critical project management requirements for environmental containment, operating cost reduction, and long-term injectivity and well life, we can begin to develop optimum design and operating strategies.

GEOLOGIC & WELL LOCATION RECOMMENDATIONS

The first requirement is to select an appropriate injection interval to accept the design waste volume, and to contain the material within the permitted zone. Well logs and core samples (if available) should be examined to locate a thick, high-permeability, *target injection formation* which is laterally extensive so as to dissipate pressures quickly after each injection episode. This should be overlain by a *containment zone* comprised of multiple shale and sand zones to act as alternating barriers to inhibit upward fracture growth and fluid migration. Fractures may grow slightly into these formations, but are carefully monitored. The final geologic barrier is a *confining zone* of relatively thick impermeable shale into which no fracturing is allowed. The composition of formation zones is illustrated schematically in Figure 1. Design guidelines for each of these intervals are summarized below.

Target Injection Formation

Granular wastes disposed by SFI are best placed into a *Target Injection Formation* which is composed of high permeability, high porosity, weakly consolidated sands. This formation should also be relatively thick (> 20 m) and laterally continuous.

High permeability formations allow slurry carrying fluid to be carried off rapidly into the formation. This limits hydraulic fracture growth and prevents buildup of formation fluid pressures. The design goal is to develop thick fracture and dilation zones and to allow quick dissipation of fluid pressures after shut-in. Excessive pore pressure buildup can lead to increasing formation stresses, increasing risks for induced bedding plane slip, faulting, and well damage.

Thick formations provide increased storage capacity for waste placement and increased transmissivity (permeability×height) available for fluid leakoff.

High porosity formations also provide additional storage capacity for waste placement. Field and laboratory observations indicate that storage capacity for injected solids comes not only from created fracture space, but most significantly from access to about 3% to 5% of nearby porespace due dilation, infiltration, and matrix grain movement.

Poorly consolidated sand formations are more easily displaced and deformed in the near wellbore and fracture process zone, again allowing for greater storage with less fracture extension. :

Formations with high porosity provide more void space volume into which solids can be placed than formations with low porosity. Furthermore, soft formations deform inelastically and do not transmit stresses to great distance. Soft formations are generally aseismic, so that even large scale deformation and shear is accomodated by general yielding, rather than brittle seismic events.

Laterally continuity of the target formation provide greater storage capacity, while lateral continuity of the containment zones promote lateral movement of the injected wastes (as opposed to vertical migration). The target formation should have uniform thickness and permeability over a large area (greater than 25 km^2).

Containment Zone

Above the target formation should be a *Containment Zone* which is composed of shales and sands which retard upward fracture growth and fluid flow. The shales should be relatively impermable, and the sands should of sufficient permeability to absorb any upward fluid motion. The combination of sands and shales will tend to blunt fracture growth.

A containment zone should be identified early in the planning process since it is possible that hydraulic fractures may grow above the initial taret injection zone, especially in long-term projects. Project TTI 11 illustrates an example of this process (Figure 2). The initial target sandstone lay between 1372.8 and 1386.2 m. The storage zone of the waste grew from 13.4 m height initially to about 33.5 m midway through the project. However, the fracturing height increased no further to the end of the project, during which time an additional 60,000 m^3 of soils were injected into the formation. The storage and fracture zone height was monitored using gamma ray and temperature logs. The logs showed the storage zone quite effectively since the soils contained naturally occurring radioactive material (NORM) and the slurry was cooler than the natural formation temperatures.

SFI fracture growth remained limited in height in this example because the containment zone was composed of a series of thin sands and shales. Shales tend to limit fracture growth since they have higher horizontal stresses than sands and have higher stiffness. Thin sands limit fracture growth because fracture fluid drains rapidly into them instead of remaining in the fracture. Mechanical slippage at the sand-shale interface may also halt the upward growth of a fracture tip.

Confining Zone

The *Confining Zone* overlies the containment zone and provides the final barrier between migrating injected fluids and overlying formations containing fresh water, oil, gas or other valuable formation materials. This zone should be an impermeable shale which is at least 30 to 50 m thick. The zone should also be extensive in area (>10 km^2) and relatively uniform in properties throughout the area.
When a shale layer is homogenous and continuous over sufficient area, it provides an effective flow barrier. Monitoring can be used to confirm that the shale also provides and effective fracture barrier.

Well Site Considerations

An SFI well should be located in an area that is most advantageous based on geological concerns and minimum intersection of the target and confining zones by nearby wells. The well should be located in an area where target, containment and confining geologic zones described above are laterally extensive.

When determining the site of an injection well, an Area of Review should be established in which all natural resources are assessed. This assessment should establish whether or not SFI will have any impact on them and corrective procedures if necessary. The radius of the area of review about the injection well should at a minimum extend to the radius of elevated pressures caused by waste injection.

Ideally, SFI wells should be placed in locations where few wells are present within the radius of influence. Analytical and pseudo-3D numerical fracture models indicate that fracturing half-length for large-volume projects can sometimes exceed 500 m. If there are wells within the radius of influence, they should be well cemented throughout the injection interval and confining zone. These wells should then be monitored periodically with temperature logs to verify that they are not providing a pathway for waste injection fluid migration out of the injection interval.

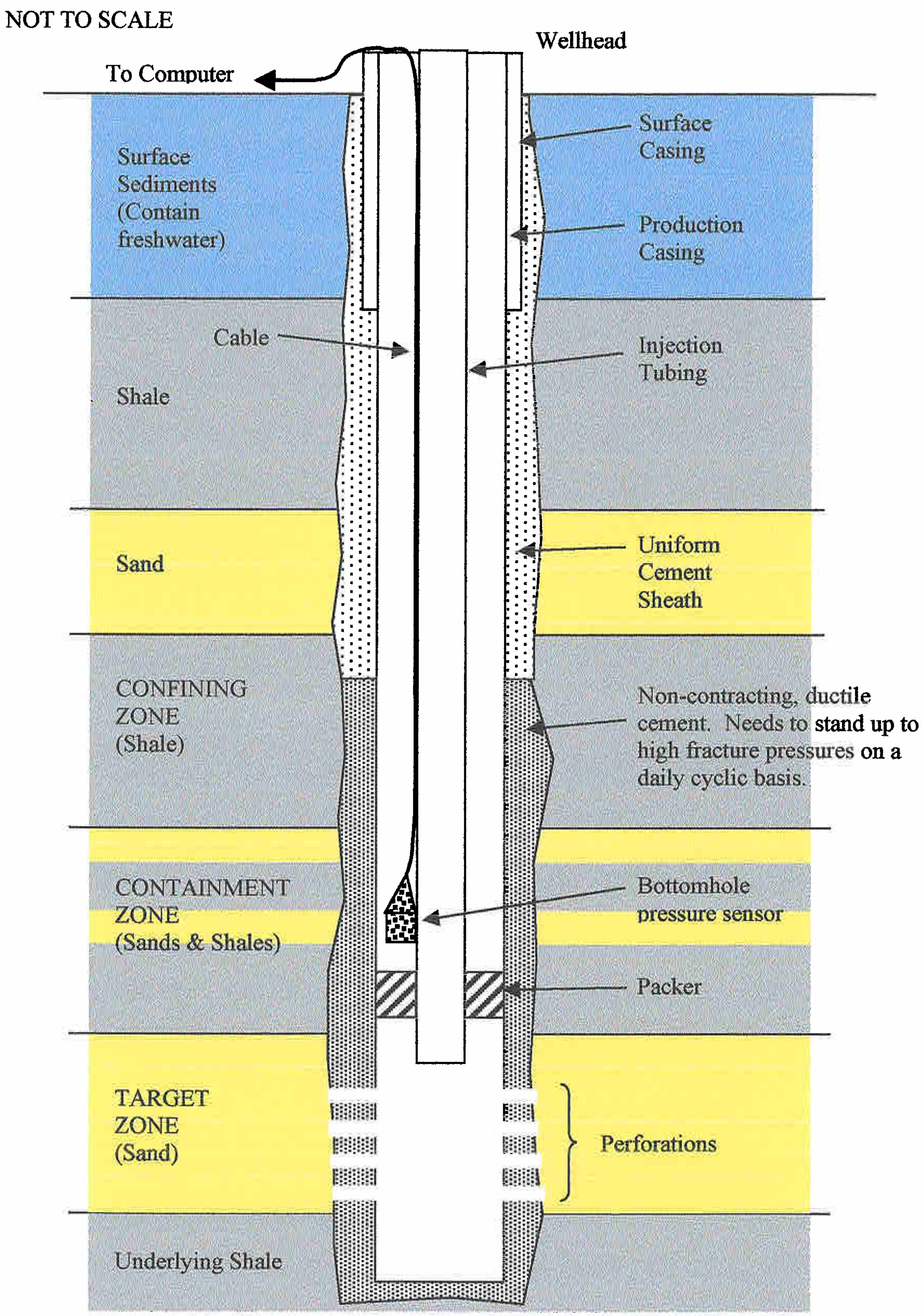

Figure 1: *Suggested well construction guidelines*

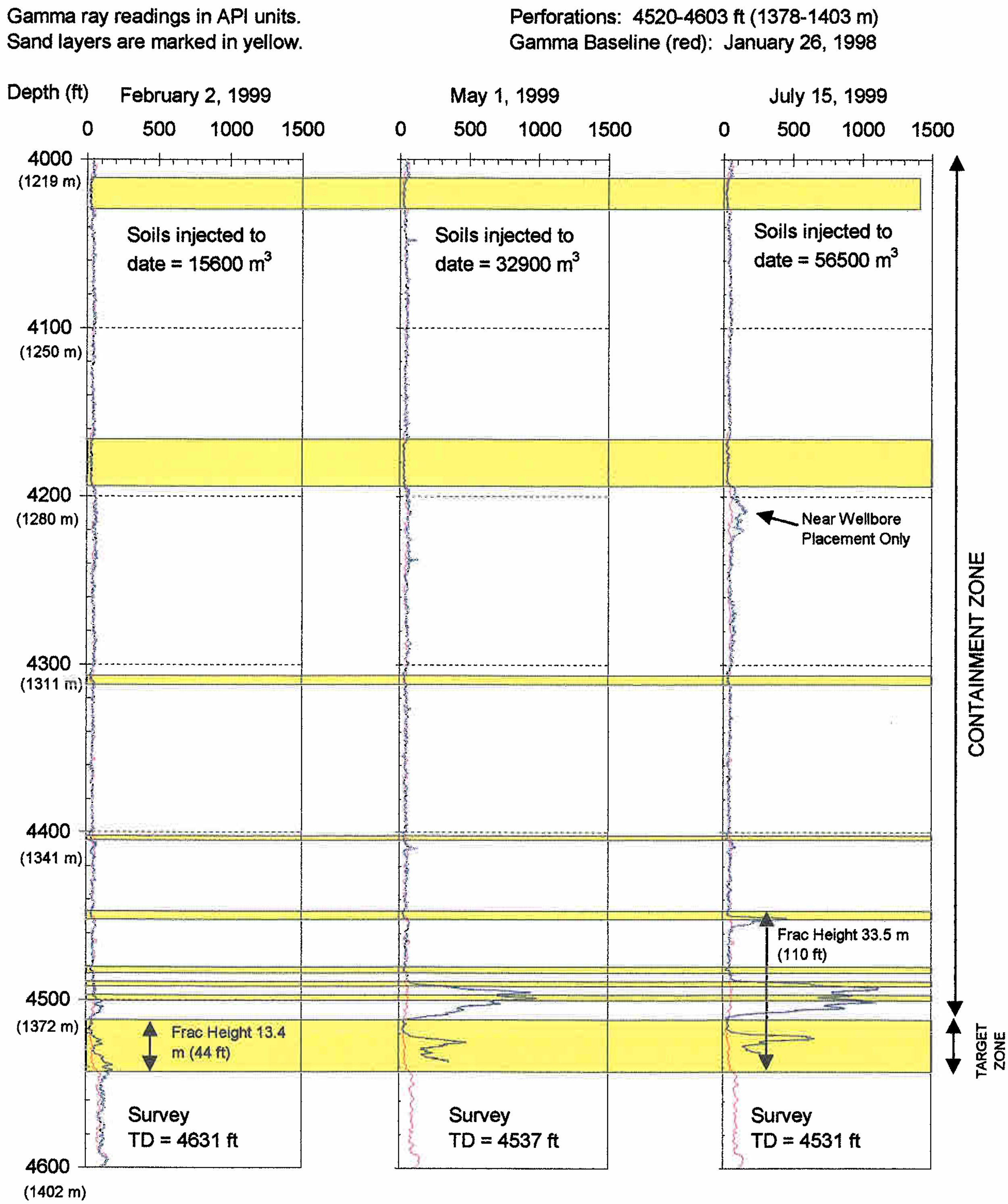

Figure 2: Example of fracture height growth into the Containment Zone.

WELL COMPLETION RECOMMENDATIONS

The injection well should be completed in a manner that prevents fluid and waste communication between different geologic zones. The completion should be robust enough to handle multiple hydraulic fracturing episodes. A typical construction design for an SFI well is shown in Figure 1.

Well Cementing

The cement between the well casing and the surrounding rock is the weakest link containing injected slurries in the target formation. The life expectancy of a well can be significantly increased if good or excellent cement bonds exist from 60 to 100 m above the target zone. This requires controlled drilling and cementing practices.

Drilling practices which can aid good cement placement are:

- Larger than normal hole should be drilled so a thicker cement sheath can be formed.
- A good mud circulation system should be used to keep the hole clean and minimize filter cake buildup.
- The hole should be cleaned of drill cuttings and filter cake prior to installing the casing using scrapers and conditioned mud.
- Varnish should be removed from the production casing prior to installation, to improve the cement bond to the steel.

Cementing practices which can aid in forming a good bond are:

- A final cleanout of the hole with the casing in place should be performed with a viscous mud flush. The normal preflush immediately prior to cementing should be doubled in size, and followed by 5 m^3 of scavenger slurry.
- The cement should be made up using a continuous batch mixing method, to create a cement with consistent weight and strength.
- The casing should be rotated and reciprocated throughout the cement job to aide cement placement throughout the annulus.
- Do not set weight on the casing until the cement has cured.

Since the wellbore in the target formation and the containment zone will experience the greatest changes in stress due to cyclic hydraulic fracturing, this part of the well should use cement with greater durability. The cement in this zone should be a low shrinkage, ductile/pliable cement, as opposed to a high strength, high shrinkage, brittle cement. The ductile cement need only be placed in the target zone and overlying containment zone as shown in Figure 1.

A cement bond log should be run once the cement has been cured. If extensive sections of poor cement bond exist in the containment or confining zones it may be necessary to perform remedial cement squeezes. Unfortunately, the success of squeeze jobs in improving the cement bond is not guarranteed, and may in fact weaken the integrity of the casing to cyclic hydraulic fracturing.

The necessity of a good cement bond around the injection well is demonstrated in the following example. In the gamma ray logs shown in Figure 2, it is possible to see that some slurry was placed in the vicinity of 1280 m by July 15, 1999. Temperature logs showed no significant slurry placement in this location, so fracturing into the formation did not occur. The location of this placement matched a stretch of poor cement bond shown in the cement bond log. The slurry probably reached this poorly bonded section through a microannulus up the wellbore from the perforations. The microannulus was sealed thereafter since no further activity was observed at 1280 m.

Well Completion

Figure 1 shows a standard SFI well completion. A production casing with tubing and packer has proven an adequate design to date. The purpose of the tubing and packer is to prevent pumping and shut-in pressure cycles from acting on the casing. Pressure cycling could cause the casing to expand and contract which would weaken the bond with the cement. Microannuli could form which would create a flow pathway to overlying formations for slurry from the injection zone.

The production casing should be about twice the diameter of the tubing. The casing should be of uniform diameter throughout to minimize workover problems. Tubing diameter should be chosen based on the expected slurry flow rate. The diameter can be increased to reduce slurry flow friction.

MONITORING AND ANALYSIS RECOMMENDATIONS

Since extensive hydraulic fracturing occurs during SFI, significant monitoring and analysis should occur to confirm that waste placement is contained within the correct zone and that injection behaviour and formation response is optimized. Typical monitoring systems used in SFI projects are shown in Figure 3 and summarized in Table 1.

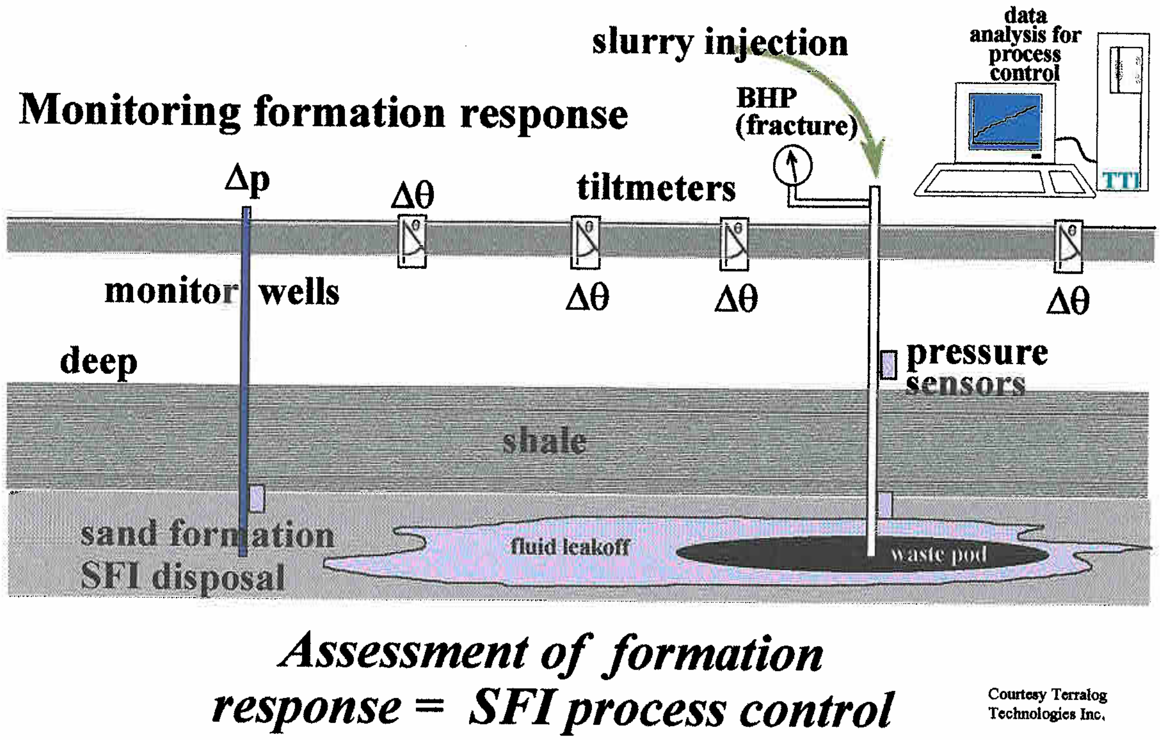

Figure 3: Some sample techniques used to monitor the SFI process

Table 1: Summary of recommended SFI monitoring tools

Tool	Project Description	Typical Application
Bottom-hole pressure at injection well with shut-in analysis	• All projects	• 24 hrs/day monitoring; • minimum scan rate every 5minutes; • 5-60 second scan rate for 60 minutes after shut-in of daily SFI operations (high resolution data needed for pressure fall off tests (PFOTs).
Step Rate Tests (SRT)	• All projects	• Baseline SRT prior to start of SFI; • SRT approximately every 5000m3 of waste; or, at end of project if <5000m3 of waste injected.
Injection Well Tracer logs	• All projects	• Baseline log prior to start of SFI; • log every 5000m3 of waste; or, at end of project if <5000m3 of waste injected.
Injection Well Temperature Logs	• All projects	• Baseline log prior to start of SFI; • log every 5000m3 of waste; or, at end of project if <5000m3 of waste injected.
Pressure within containment zone	• Projects with waste material injection >5000m3/month • Projects with waste material injection >10,000m3/yr	• Continuous or periodic monitoring.
Tiltmeters and/or microseismic surveys	• When formation properties are appropriate and given well availability	• Baseline prior to start of SFI; • Continuous or periodic monitoring
Injection Parameter Monitoring	• All projects	• Monitoring all injection parameters continuously during SFI operations; • minimum scan rate every 1 second; • record data to disk a minimum of every 5 minutes.
Regular and Frequent Material Sampling	• All projects	• Collect samples once a week; • conduct analyses on a minimum of one sample per month; • keep all samples from SFI project for at least 6months after project completion.

Well Logging

Well logging can be used to determine fracturing and flow behaviour as it is occurring near the wellbore. There two types of well logs: passive and active. Passive logging measures formation parameters around the injection well when no fluid injection is occurring. Active logging attempts to measure fluid flow and fracturing in the formation during pumping.

Passive logs can be used when the injected slurry has physical properties that are significantly different from the native formation. If the injected slurry contains radioactive materials, these will show up strongly in a gamma ray log. Temperature logs can be used when the injected slurry temperature is markedly warmer or colder than the natural formation temperatures.

Radioactive tracer logs are an active logging technique which can be used to determine if uphole migration of fluid is occurring. Water should be pumped through the injection well at the rate which causes hydraulic fracturing. As this occurs, a small amount of radioactive Iodine-131 is released into the stream. A gamma ray tool is moved up and down in the well to observe the path taken by the tracer once it is into the formation. Tracer logs can also be used to determine how much fluid is passing through each group of perforations.

Figure 4 shows before and after radioactive tracer logs run on the injection well in one SFI project. After a subtantial volume of material had been injected in this well, it appeared that slurry containment had been lost. Comparison of these two logs showed that the cement had failed around the injection well and fluids were working their way uphole along the casing.

Whether active or passive logs are run is determined by the type of slurry material being injected. Logs should be run every two months or 50,000 m^3 of slurry injected in order to develop a good history of behaviour lest odd fracturing events occur.

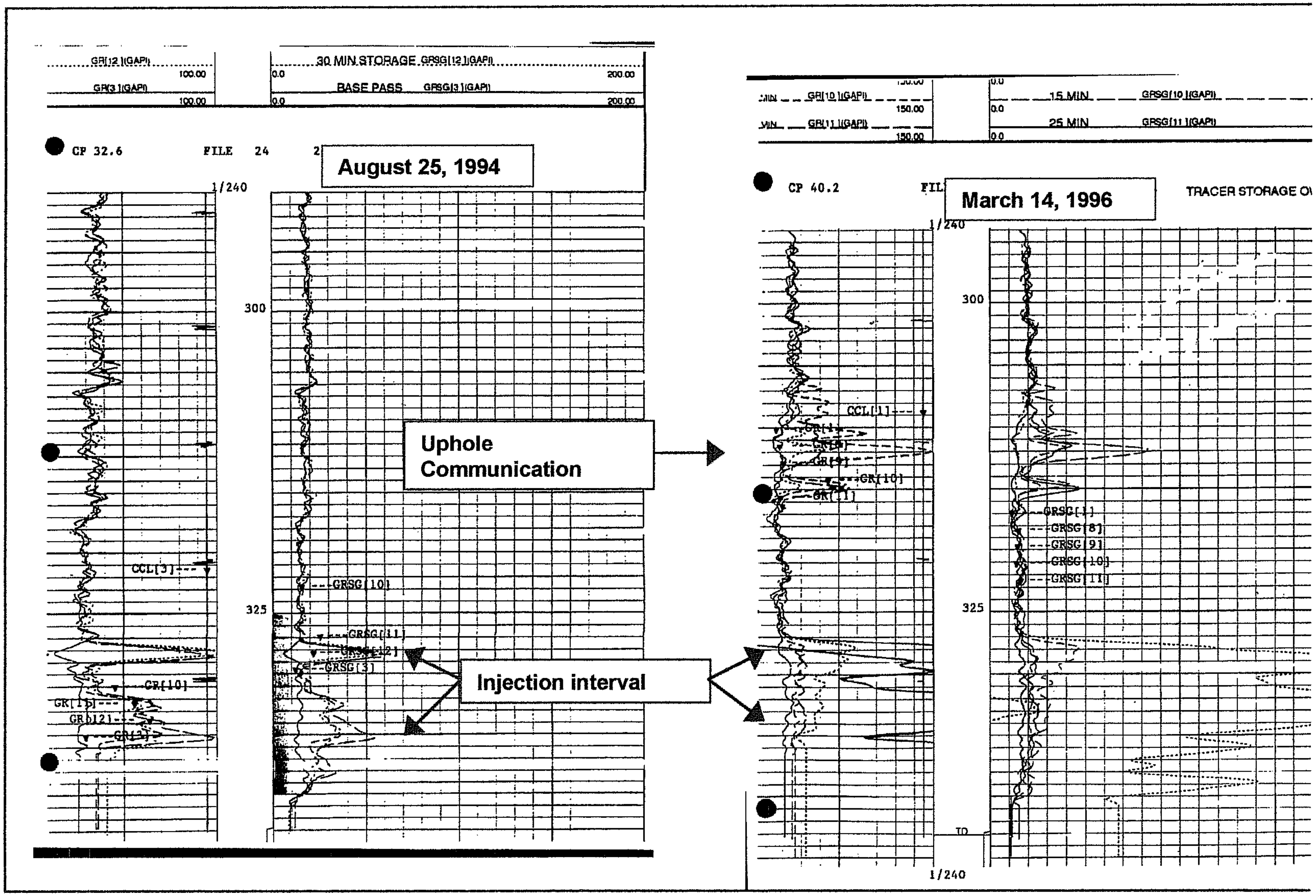

Figure 4: Tracer survey data illustrating uphole migration of injectate (Project TTI2)

Injection Parameters

Continuous monitoring of the injection process must be performed so that the injected slurry can be characterized and the formation response can be determined. The critical measurements include: bottomhole pressure, wellhead pressure, well annulus pressure, injection flow rate, slurry density, and slurry volumes. Data from these sensors should be recorded with an electronic device, such as a datalogger or computer, which has battery power backup. Recordings should be made once every five minutes.

Notes by the site operators often provide information about operations that dataloggers cannot describe. These should be recorded daily and placed in an accessible library to aid in future analyses.

Bottomhole Pressure

Bottomhole pressure is the most important single parameter to measure, since it is the only sensor which is continuously observing the behaviour of the formation. At minimum readings should be taken once every five minutes, and should be as frequent as once every 5 seconds during periods of rapid pressure change, as occurs at pump start-up and shut-down. A sensor with good accuracy is preferred (e.g. accurate to ±0.025% full scale), but this has to be balanced with the rapid readings and changes in pressure that can occur.

Analysis of bottomhole pressures can take the form of analysis of injection pressures and fall-off pressures.

Injection pressures can be summarized as an average injection pressure (BHP_{inj}) for each injection day. The BHP_{inj} can act as a gross indicator of fracture behaviour over time as shown in Figure 5. In this particular case BHP_{inj} tended to fall over time which probably indicates easier fracture initiation as the formation is broken up, and possibly reduced friction effects. In other project BHP_{inj} has been observed to rise over time which may indicate increased formation stiffness or stress.

Pressure behaviour during each injection period can be analysed using two-dimensional and pseudo-three-dimensional fracture models. This type of analysis is discussed in depth in Topical Report 3. These analyses can be used to estimate fracture dimensions (height, width and length), net pressure required to hold the fracture open, and friction pressure drops in the well and fracture.

Pressure fall-off analysis can detemine the following:

- Formation stress state (instantaneous shut-in pressure, fracture closure pressure)
- Minimum shut-in pressures
- Permeability and "skin" around the injection well
- Fracture length

SFI creates fractures which open against the minimum total stress (σ_3) in the formation. When pumping has stopped, the instantaneous shut-in pressure (ISIP) is equal to the sum of σ_3 and the net pressure required to hold open the fracture. Several minutes or hours later the fracture will close, at which time the bottomhole pressure is equal to σ_3. Changes in σ_3 are important since they can indicate whether fractures are vertical or horizontal, if waste placement is significantly compressing the formation, and if out-of-zone fracturing is occurring. Figure 5 shows the changes of injection and closure pressures through the course of Project TTI6.

Minimum shut-in pressures (SI_{min}) are used to estimate the leakoff characteristics of the waste pod and formation. These pressures are recorded at the end of each shut-in, immediately prior to the start of the next injection cycle. A variant of this is to measure the bottomhole pressure 12 hours after the start of shut-in (SI_{12hr}). Low values of SI_{min} indicate rapid pressure declines and good fluid communication with the far-field high permeability formation. Elevated values of SI_{min} indicate slow pressure decline and a flow regime dominated by the low permeability waste pod. Large variations in SI_{min} values were observed in Project TTI6 (Figure 5).

Pressure fall-off analysis can be used to estimate the permeabilities of the virgin target formation and of the waste pod. Often the analysis indicates the far-field permeability with a "skin" around the injection well. The "skin" is actually the low permeability waste pod which can have quite large dimensions. Typical virgin formation permeabilities are in the range of 400 – 4000 md. Typical waste pod permeabilities are in the range of 1 to 100 md. An example of permeability analysis using numerical matching on a Horner plot is shown in Figure 6.

Log-log plots can also be used to determine permeability in pressure fall-off data, but their greater strength is in determining changes in flow regime during shut-in. Figure 7 shows an example plot where changes in flow behaviour indicated that the hydraulic fracture had grown beyond the waste pod into the virgin formation. The flow regime patterns may remain similar in several weeks of pressure fall-offs, and distinct periods of these patterns were observed in Project TTI11.

Fracture length can be assessed if linear flow occurs during pressure fall-off. Linear flow occurs when the fluid flows at right angles to the fracture wings in the formation. This can be diagnosed with either the log-log or square-root plots and the fracture length estimated as shown in Figure 8.

Changes of indicator pressures (BHP_{inj}, ISIP, Closure, SI_{min}), permeability, skin, and fracture length over the course of an SFI project indicate the behaviour and growth of hydraulic fractures and the waste pod. Having a good picture of what the fractures and waste pod are doing allows for anticipation and diagnosis of well and formation problems as they occur.

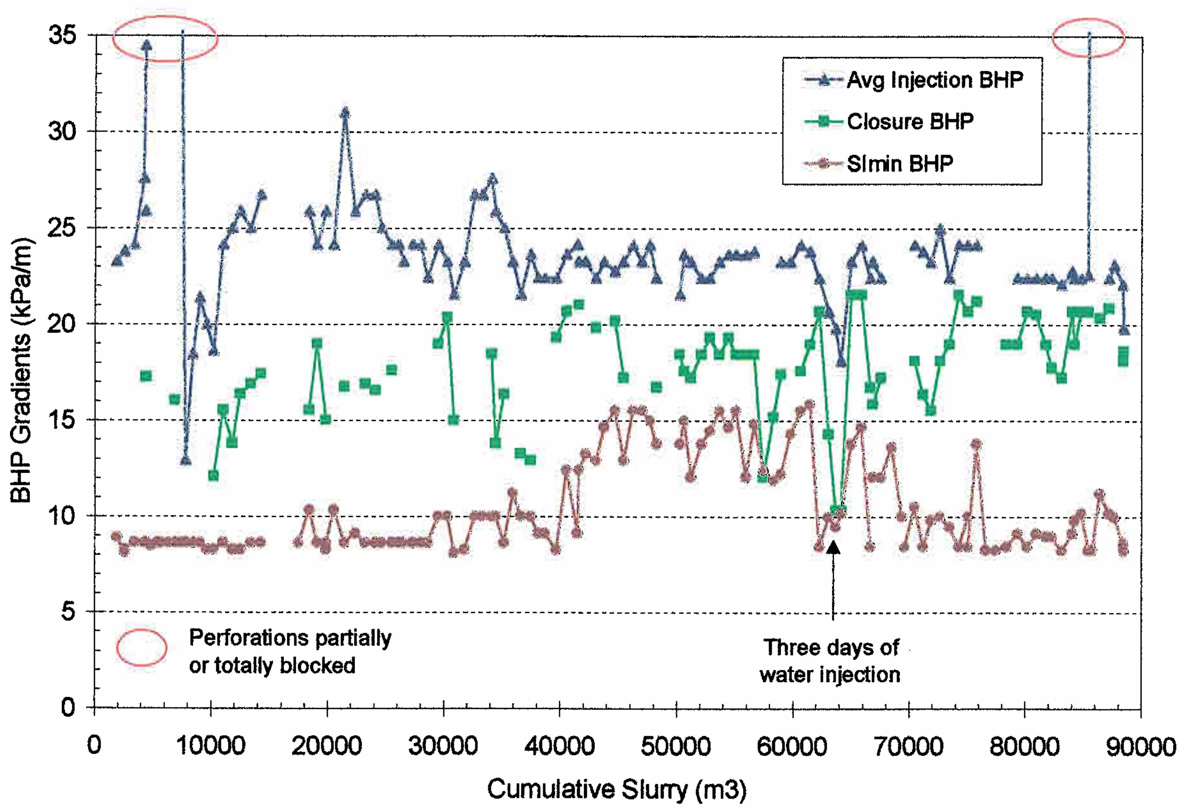

Figure 5: Development of indicator pressures during Project TTI6

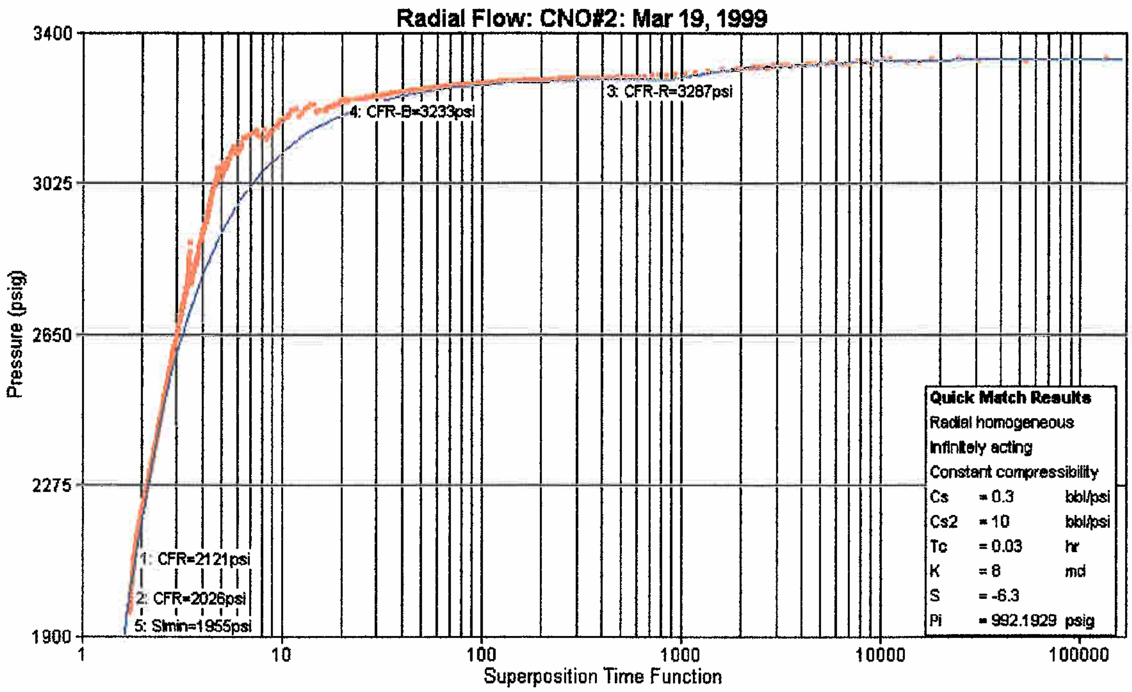

Figure 6: Example of permeability analysis on Horner plot (Project TTI11)

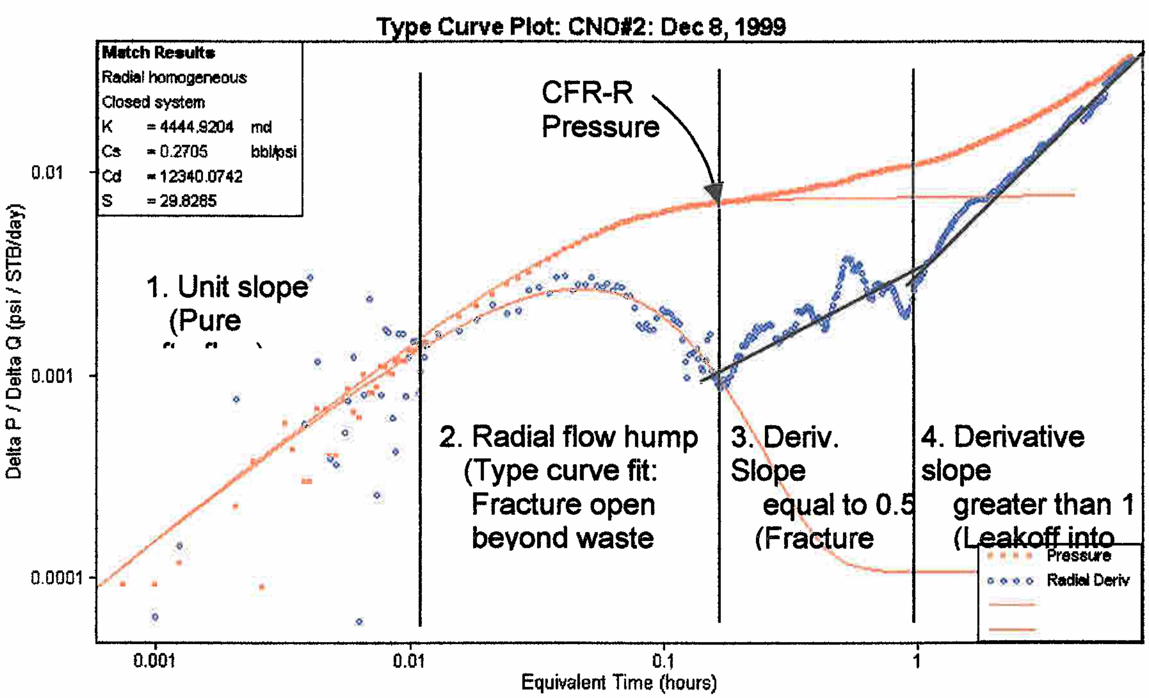

Figure 7: Log-log plot showing distinct flow regimes during shut-in (Figure TTI11)

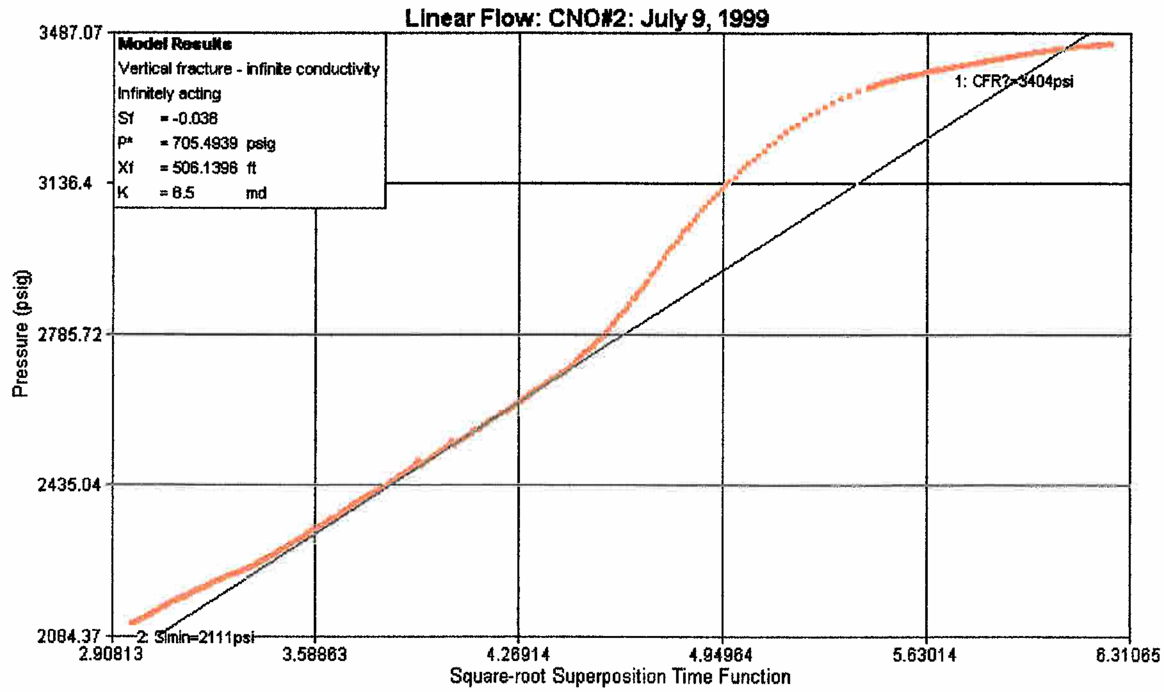

Figure 8: Square-root plot showing linear formation flow and fracture length (Xf) (TTI11)

Formation Tests

Formation tests should be performed prior to the start of a SFI project and at regular intervals thereafter. These tests are used to determine the state of injectivity and stress in the formation and waste pod.

Step rate tests are performed to determine formation parting pressure and changes of in situ stresses. A step rate test is performed by injecting water at rates that step up every thirty minutes. Step rate tests should be run at regular intervals, at least once per month, to determine fracturing pressure and fracture extension rate. The step rate test program must use consistent injection rates and durations of each rate.

A typical test program is:

Duration (min)	Water Injection Rate (m^3/min)
30	0.25
30	0.50
30	0.75
30	1.00

30	1.25
30	1.50

The step rate test is analysed by plotting the final bottomhole pressure (BHP) of each rate period on a pressure vs. rate plot as shown in Figure 9. The initial steep slope of points indicates radial formation flow, and the flat or slightly positive slope indicates fracture flow. The point where these two lines intersect is the formation parting pressure, which is a good indicator of in situ stress. If a negative slope is observed, fracture height growth into overlying formations is occurring (Figure 10).

Injectivity tests are performed by injecting water into the formation at a rate below the fracture extension rate. This test is intended to determine the radial flow characteristics of the formation. A typical test would inject water at a rate of 0.25 m^3/min for 4 hours. The injection rate must be held absolutely constant to obtain good bottomhole pressure data. The BHP data is analysed using semi-log and log-log plots, and if the data quality is good, can provide acceptable estimates of permeability and skin.

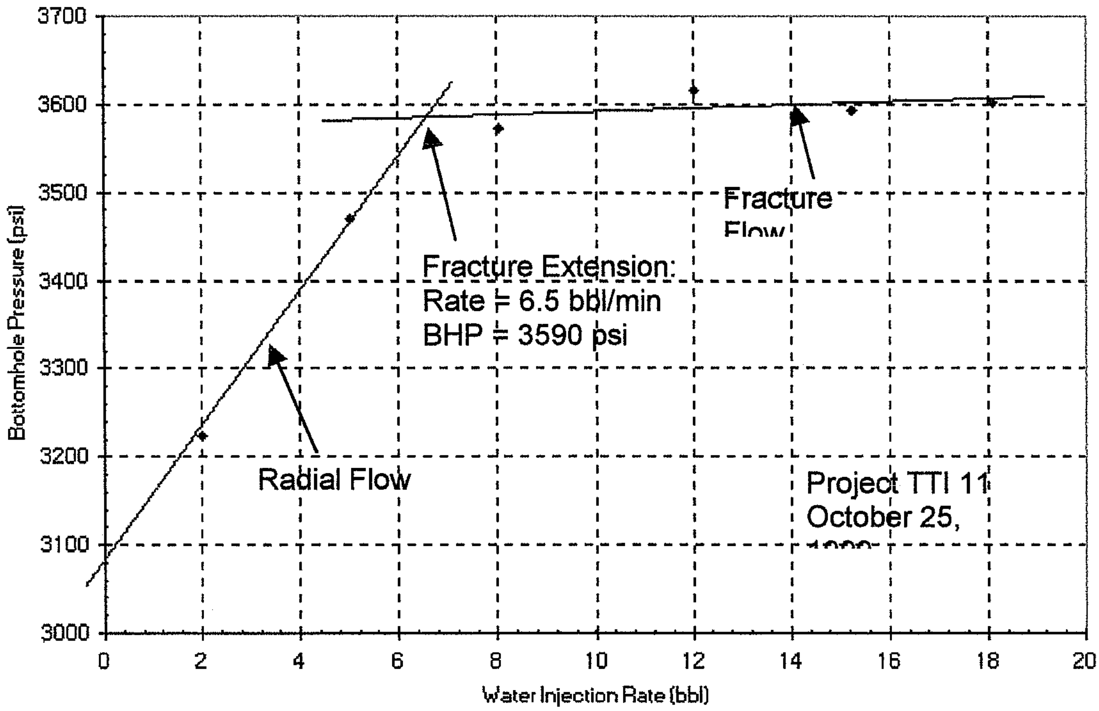

Figure 9: Example of a typical step rate test

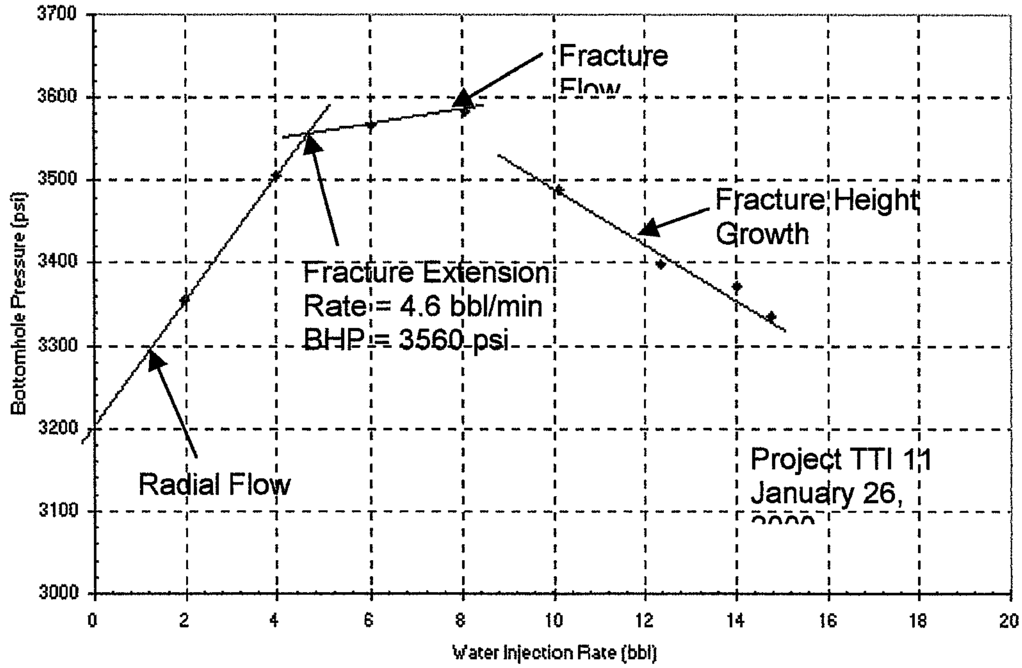

Figure 10: Example of a step rate test where fracture height growth is occurring

Pressure fall-off tests are performed by analysing the bottomhole pressure data recorded during any shut-in period immediately following slurry or water injection into the well. Pressure data should recorded at least every five minutes, and during the initial fall-off period the recording frequency should be every five seconds to capture the rapid pressure changes that occur. The data is analysed using Horner semi-log and log-log plots, which provides estimates of permeability, skin, and fracture length if linear flow is present.

Observation Wells

Observation wells can be useful to determine formation behaviour at some distance from the injection well. The typical use of an injection well is to have a bottomhole pressure sensor to monitor the change in formation pressure over the course of a project. The observation well can also be used for mechanical monitoring systems such as downhole tiltmeter and microseismic arrays as discussed below. The observation well must be placed a sufficient distance away from the injection well that will not be intersected by hydraulic fractures, and must also have cement in good condition so that no upward fluid migration will occur.

Tiltmeter Systems

As a hydraulic fracture grows in a formation, it deforms the formation and slightly lifts the overlying earth. The pattern of deformation at the surface is characteristically unique enough that the fracture dip and azimuth can be easily determined. Other fracture characteristics such as location, depth, volume and length can also be determined, although with less numerical confidence. To measure the deformation at the surface of the earth an array of 12 to 16 tiltmeters should be placed around the injection well. The tiltmeter is analogous to a sensitive electronic carpenter's level which takes readings every 5 minutes. Data from each tiltmeter is taken to determine the earth deformation during each injection episode and calculate the fracture parameters listed above.

The greatest strength of tiltmeter analysis is in determining the orientation of hydraulic fractures. Tiltmeter analysis in Project TTI4 showed that vertical fractures were created, with an additional component of vertical uplift due to formation dilation. Once hydraulic fractures had initiated, they remained in the same orientation throughout an 8 to 10 hour injection period. Only 10% of the injection periods showed fracture orientation changing midway through the day. New fracture orientations were observed with each injection, even if the intervening shut-in was only an hour long (Figure 11). This type of behaviour was also observed with tiltmeters at the Mounds Drill Cutting Project and confirmed with formation coring afterwards, as illustrated in Figure 12 (Moschovidis et al, 1999).

Downhole tiltmeters are a recent development which allow much better resolution of the depths of the top and bottom of the fracture. This method requires an array of tiltmeters to be present in an adjacent observation well. Unfortunately, the observation well needs to be quite close to the injection well: for a vertical resolution of ±10 ft, the observation well needs to be 100 ft from the injection well (Davis, 2001). Since the observation well could act as a conduit for slurry materials to break into overlying zones, it does not seem advisable to place an observation well at such close proximity. Work is currently progressing on downhole tiltmeters installed inside the injection well annulus, but the tools are not commercially available as of this writing. If installed in the injection well they could define quite well where fracture tops are located.

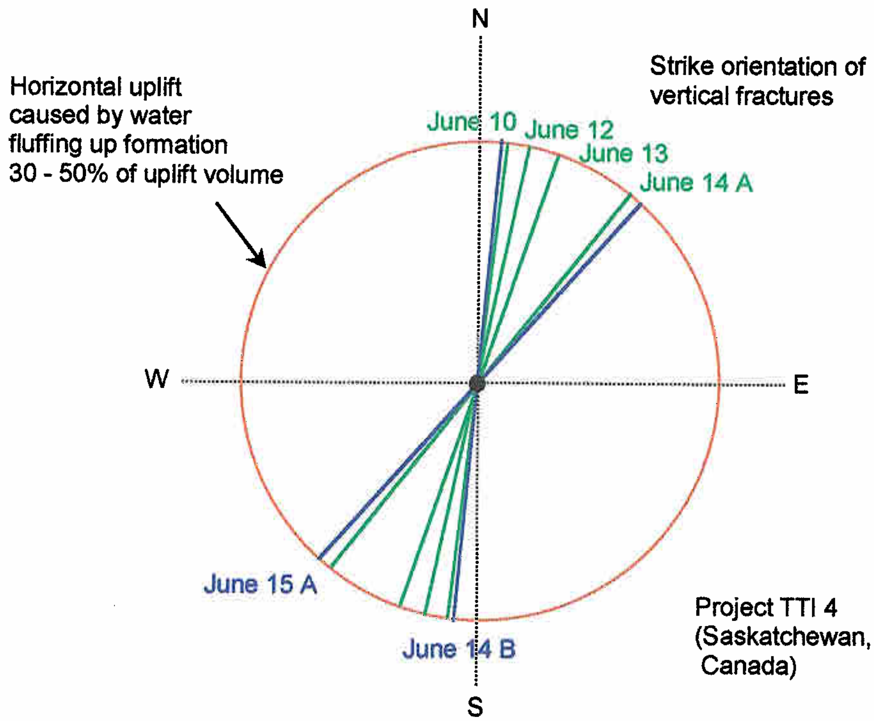

Figure 11: *Fracture orientations for successive slurry injections*

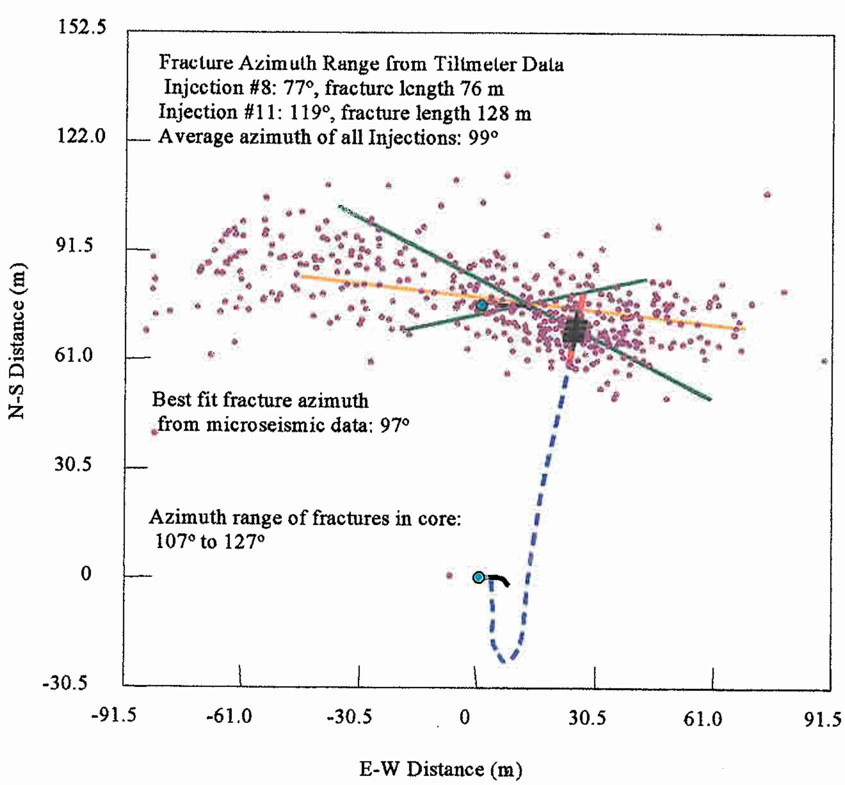

Figure 12: *Mounds Project fracture orientations (Moschovidis et al, 1999)*

Microseismic Systems

Hydraulic fracturing causes tensile and shear failure of the sandstone fabric around the fracture to occur. These failure events are called microseismic events, and can be recorded with an array of accelerometers or geophones in nearby observation wells. The recorded microseismic events are processed to locate the source of each event and an image of the fracture geometry can be created. This technology is somewhat expensive and to date has not been used in long term SFI projects, although the costs may drop enough in the near future to make this a valuable tool.

They have been demonstrated to be successful in short-term tests in relatively hard rock (see for example Figure 12). It is not clear, however, if microseismic monitoring can capture fluid migration in relatively soft, highly porous, and highly permeable sand zones. These formation are often aseismic. For example, microseismic monitoring of steam fracturing operations at Cold Lake (Boone, et al 1999) identified slip and fracturing in the overlying shales, but not fracturing within the injection zone.

OPERATING RECOMMENDATIONS

During an SFI project, the injected solids will be placed around the injection well in a succession of hydraulic fractures. Waste injections over time will create a waste pod of immobile solids (e.g. sands, clays) and low viscosity fluids (e.g. drilling muds, slop oil emulsions) around the injection well. The goal while performing SFI is to maximize the use of the formation space around the injection well and to have controlled fracturing behaviour.

Terralog has established a number of operating guidelines based on experience and also by analysing the database of SFI projects. The following commentary should be relevant to any future slurry fracture injection project or other similar projects.

Continuous Versus Cyclic Injection

There are two possible injection strategies: continuous low-rate injection versus cyclic injection, where a fixed period of slurry injection is followed by a shut-in period. The advantages of cyclic injection relative to continuous injection are:

- New fracture orientations are initiated each time pumping is started. The rotation of fractures about the injection well increases the volume of formation that is used for waste placement.
- Formation pressures and stresses are dissipated during shut-ins which minimizes the possibility of out-of-zone fracturing.
- Information on formation and waste pod behaviour can be collected during shut-in by analysing the pressure fall-off behaviour.

The rotation of fractures about the injection well was shown using tiltmeter analysis in the TTI4 project. Each time pumping started, fracture azimuth was found to be in a different plane from previous fractures (Figure 11). Once initiated, most fractures remained in the same orientation throughout the 8 to 10 hour pumping period. In only 10% of the injection periods did fracture orientation change midway through. Similar observations have been made with much smaller injections at the Mounds project (Moschovidis et al, 1999).

The disadvantage of cyclic injections relative to continous injection is:

- In order to get full 24-hour utilization of the pumping equipment, two injection wells are required by cyclic injection projects as opposed to one well by a continuous injection project. This is only an issue when very large volumes of waste are to be disposed (>400 m^3/d).

Slurry injection should be performed in daily cycles of pumping followed by well shut-in. The injection period should be 8 to 12 hours in duration, followed by at least 12 to 16 hours of shut-in. The shut-in periods permit pressures and stresses to dissipate into the formation from the fractured zone. Pressure fall-off data collected during this time can also provide good indications of the state of fracturing and dissipation processes.

Cyclic injection is preferred to continuous slurry injection over the course of weeks and months since more information is gathered about the formation state. Dangerous fracturing conditions can be predicted and averted more easily than when continuous operations are used.

Scheduling of Injection Periods

A cyclic injection strategy requires that the injection periods be broken into several stages:

1. Preflush of clean water to clean out the well and initiate hydraulic fracturing.
2. Injection of slurry containing the granular wastes.
3. Postflush of clean water to clean any remaining solids out of the well.

The preflush is usually 10 to 20 minutes in duration. The injection rate should be increased slowly during the first couple of minutes up to the normal slurry injection rate. The slow increase minimizes pressure shocks that may damage the well or formation.

Slurry injection should be performed at a rate equal to or greater than the hydraulic fracturing rate determined for the formation. The hydraulic fracturing rate is determined from the step-rate test described in the Monitoring and Analysis Guidelines section. On past projects slurry injection rates have been between 1 and 3 times the fracturing rate. The higher injection rates are typically chosen when larger volumes of material need to be disposed each day.

The water postflush is intended to clean the well of solids. The total volume of the postflush should be at least 5 well volumes in size, and is usually 10 minutes in duration. When the postflush is complete the pumps should be shut down all at once and the wellhead valve closed quickly to get consistent measurements of the instantaneous shut-in pressure (ISIP). A rate step-down test may also be performed to assess the magnitudes of perforation and near-wellbore friction (Pinnacle, 2000). The shut-in period which follows should be at least 12 hours in length.

Formation response should be monitored to confirm that pressures are declining back to baseline reservoir conditions at the end of each shut-in. Injection pressures should also not increase or decrease signficantly from "normal" behavior. That is, maximum injection pressures should stay consistent to within about 10% of their average values. The minimum shut-in pressure should be within about 10% of the initial formation pressure prior to starting the next injection episode.

Slurry Composition

To date, four types of materials have been handled by slurry fracture injection: produced sand, slop oil emulsions, drilling mud, and contaminated soils. The proportion of these materials and water in the slurry is not critical, but should remain within reasonable bounds to promote good fracture growth, good water leakoff, and minimize plugging of the injection well.

The total proportion of all wastes in the slurry are best maintained between 10% and 40% by volume. With slurries dominated by sand the proportion should be lower to prevent tip screenout from occurring (high leakoff rates prevent fracture growth). Slurries containing clayey materials (e.g. soils) can be injected with higher concentrations since the leakoff rate from the fracture is much lower. This allows for greater fracture volume and growth. Figure 13 shows percentage of total waste material in each day's slurry plotted against the daily slurry volumes for projects TTI1 to TTI9 (420 injection episodes). The plot shows that injections were performed with waste proportions anywhere between 0% and 60%.

Sand concentrations in SFI slurries should reach at most 35%. This is a relatively low value since we do not want to initiate tip screenouts. Sand concentrations in hydraulic fractures intended for oil or gas production stimulation can be much higher than 35% but the design of sand placement in those fractures differs from SFI. With SFI we want the waste materials placed some distance from the well, whereas stimulation fractures want to create a continuous sand flowpath between the well and the formation. Figure 14 shows the daily sand concentrations used in previous SFI episodes.

Slop oil is a product which has been disposed on several SFI projects. Slop is an emulsion of crude oil and water which cannot be economically processed to separate the oil from the water. It can have great variations in composition and properties, especially of viscosity. It is typically limited to 20% to 30% proportion of injected slurries since the viscosity effects are varible and the impact on fracturing and the waste pod not well defined (Figure 15).

Drilling mud is another product which can be highly variable in composition and properties. It's presence in slurry does not appear to affect injection pressures greatly, but it has significant impact on waste pod permeability and shut-in pressures. Drilling mud is designed to minimize leakoff of fluids into formations. Unfortunately, it also does this in the SFI waste pod, which is a problem since rapid leakoff from the waste pod is desired to minimize the possibility of shear failure. It has been handled in slurry proportions up to 20% (Figure 16) but this requires close monitoring.

Soils contaminated by oil production were injected in projects TTI9, TTI10 and TTI11. The high clay and silt content of these soils meant they could be pumped in slurry proportions up to 60%. This is possible since they reduce leakoff from hydraulic fractures enough to permit good fracturing, but do not have as severe impact on waste pod leakoff as drilling muds. On any new SFI project the soil percentage should be tested at various levels (e.g. 20%, 30%, 40%) to determine impact on fracturing and shut-in behaviour.

In most projects all forms of waste products are combined to form one slurry. However, it may be necessary to separate the wastes so they are injected at different times throughout the day. This staging of wastes was performed at a later stage of Project TTI6 when injected drilling muds were significantly degrading the leakoff ability of the waste pod. The injection period was broken into drilling mud slurry stages followed by sand slurry stages which created high conductivity channels through the waste pod. The improvement in shut-in pressure declines was immediate (Figure 17).

Changing the proportion of sand in the slurry may itself not improve waste pod leakoff. Figure 18 shows that no distinct patterns of injectivity or shut-in pressures were present in Project TTI11 despite large variations in sand content. The high clay content of the soils in this project masked any effects the sand might have made.

The next two sections look at specific modifications of waste or slurry material that have been performed on some underground waste injection projects: addition of viscosifiers, and grinding of the granular wastes. These are processes that do not add value to the disposal process.

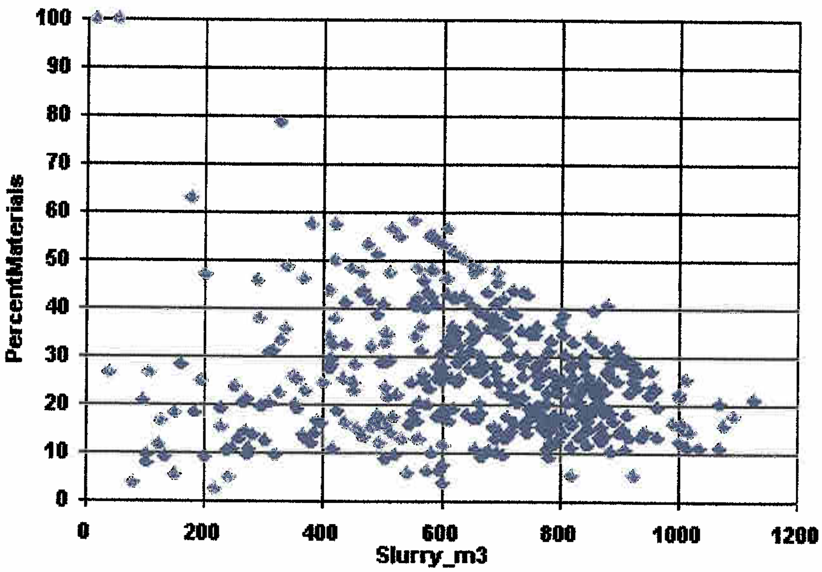

Figure 13: Percent waste materials in slurry per day (Projects TTI1 – TTI9)

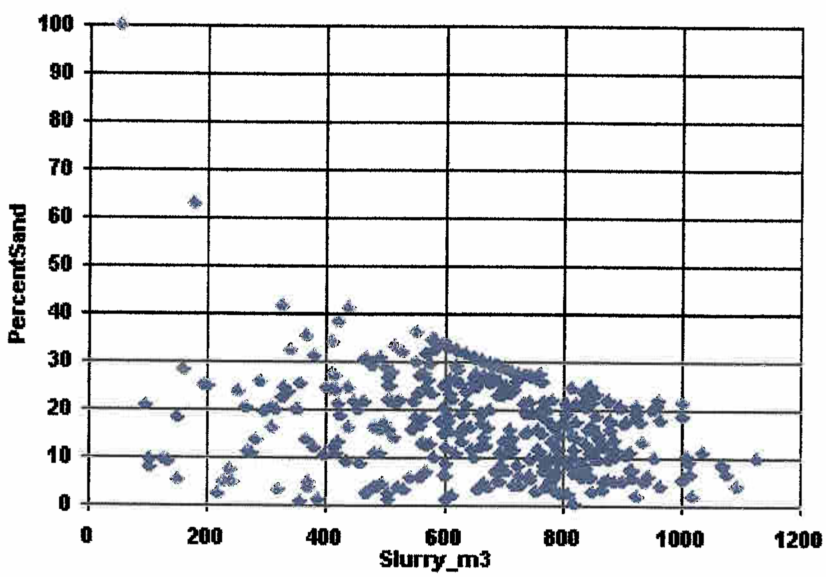

Figure 14: Percent sand in slurry per day (Projects TTI1 – TTI9)

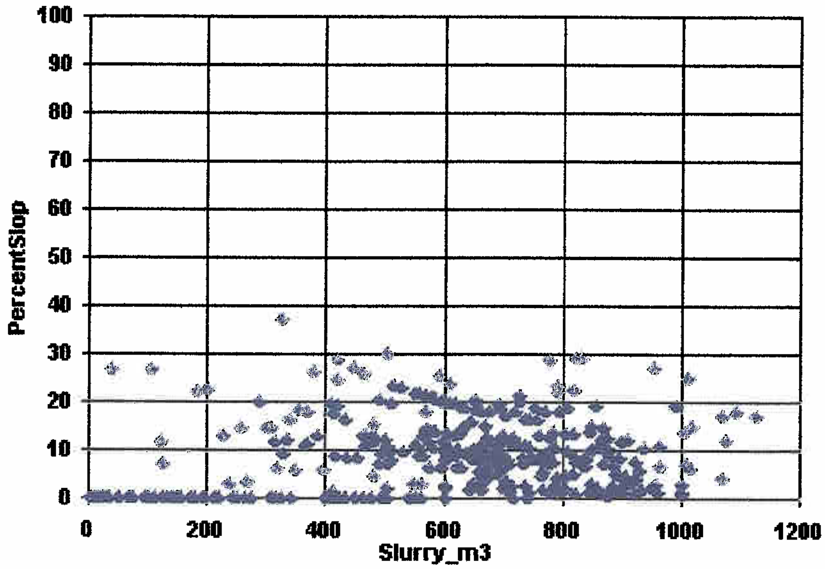

Figure 15: *Percent slop oil in slurry per day (Projects TTI1 – TTI9)*

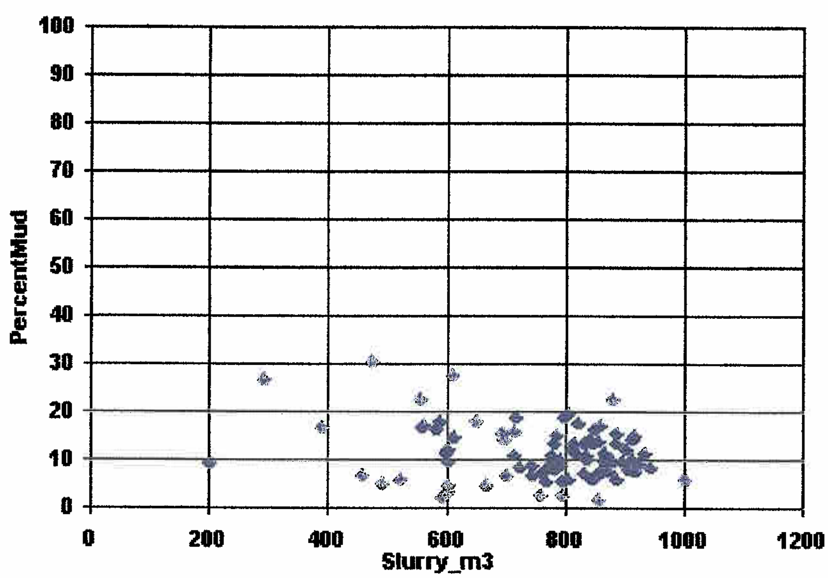

Figure 16: *Percent drilling mud in slurry per day (Projects TTI6 and TTI9)*

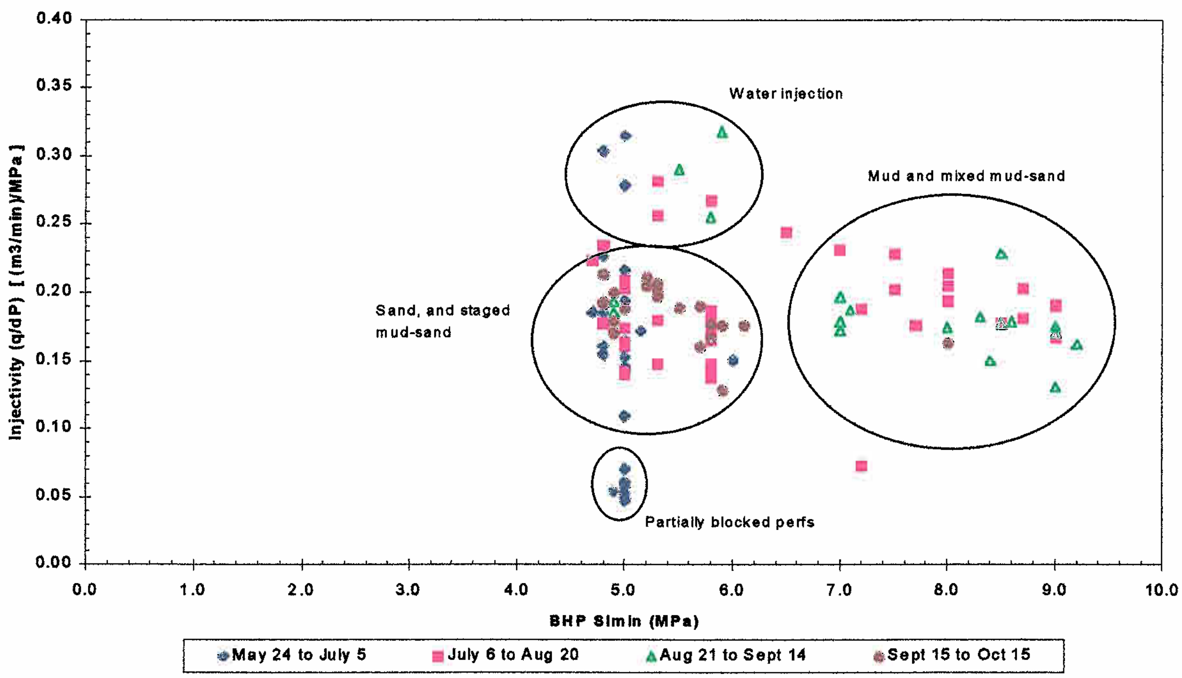

Figure 17: Injection scheme can be modified to maintain injectivity and improve pressure decline after shut-in

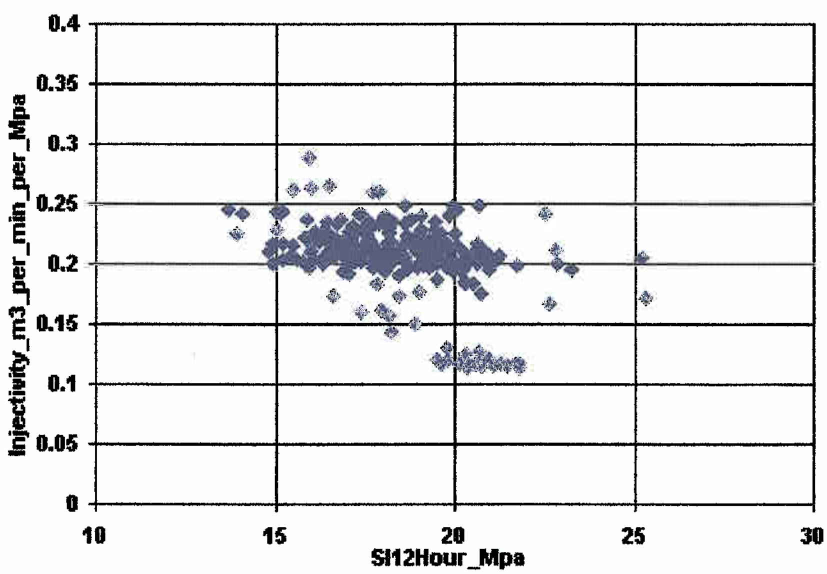

Figure 18: Example of where changing strategies do not have major impact (Project TTI11)

Viscosifiers

Stimulation hydraulic fracture operations typically use viscosifiers such as gels and cross-linked fluids to optimize fracture growth. Increasing the viscosity of fracturing fluids creates greater fracture volume and also suspends proppants so they can be placed more deeply in the fracture. However, in a waste disposal situation, viscosifiers are not typically necessary for fracturing purposes and are costly to use.

In most sandstone formations, water has sufficient viscosity to create hydraulic fractures. Depending on how high the formation permeability is, high fluid leakoff from the fracture may keep the dimensions of the fracture very small. If sand is the only waste component in the slurry this can be a problem since it can cause screen-outs and very high injection pressures. Figure 19 shows an example where the injection was very sensitive to the percent sand: screen-outs occurred when sand concentration reached 12%. At this level, very large water volumes would be needed to dispose the produced sands.

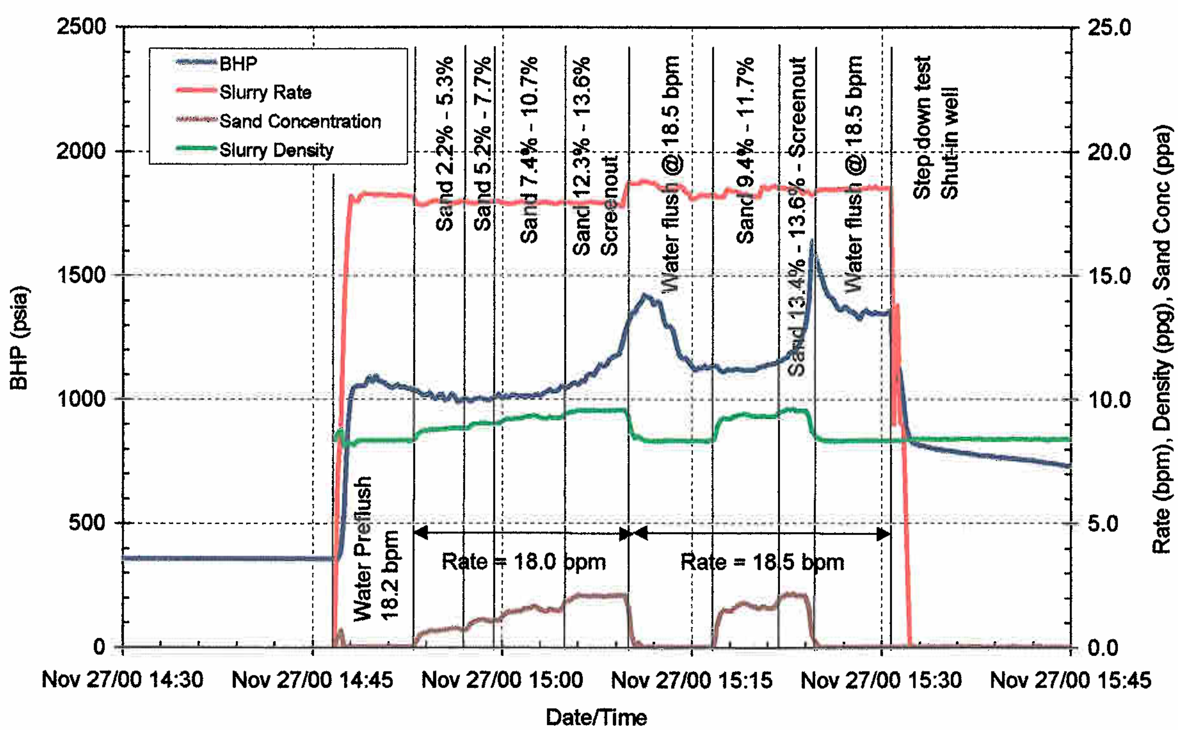

Figure 19: Stable and screen-out conditions with changing sand rates (Project TTI12)

Requirements for large water volumes and precise control of sand concentration can be lessened by the use of viscosifiers. However, gels and cross-linkers are expensive products to use on disposal projects. Other options are typically available in oilfield waste handling processes.

Two types of oilfield waste products are used in many SFI projects that can mimic viscosifier behaviour: clayey materials (tank bottoms, soils, drilling muds) and viscous oily fluids (slop oil emulsions, tank sludges). Figure 20 shows an injection period following Figure 19 where slop oil was added to the slurry. The maximum stable sand concentration increased to 16% from 12%, and screenouts had smaller pressure magnitudes. This is the behaviour often sought in using typical viscosifiers.

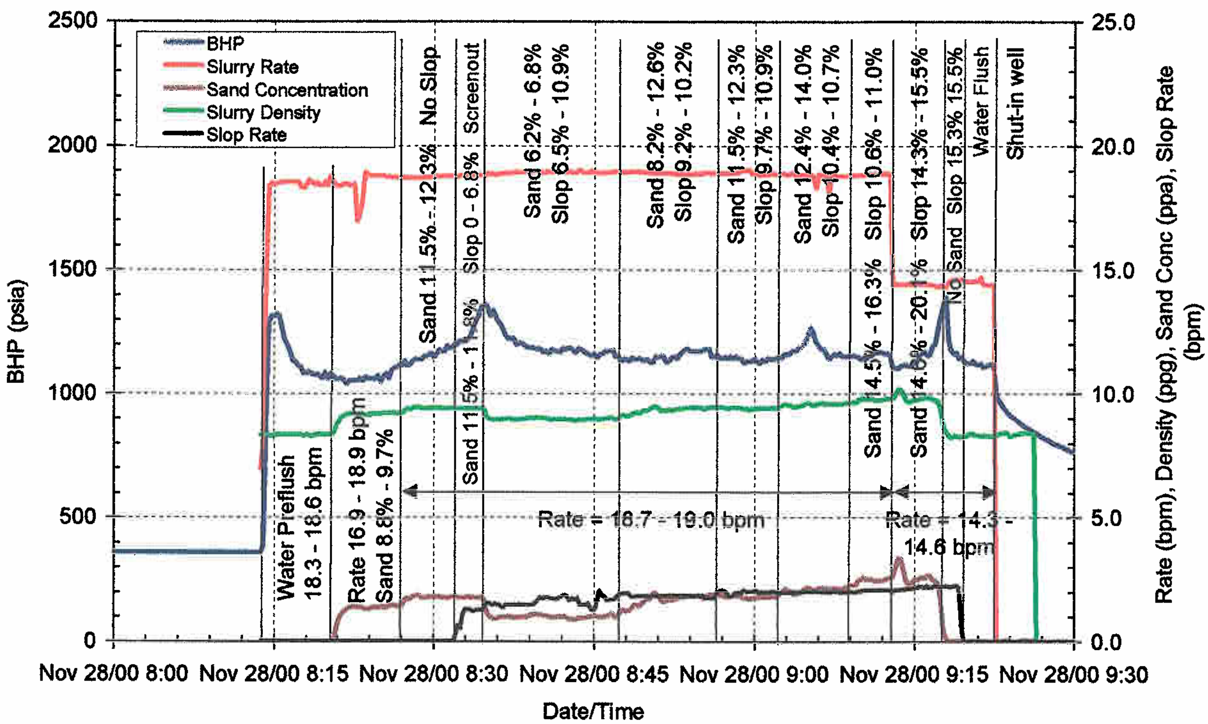

Figure 20: Effect of slop oil on sand concentration and screenout behaviour (Project TTI12)

Soils, clays and drilling muds also create similar injection behaviour as the slop oil example shown here. Slop oil appears to increase the overall viscosity of the slurry fluid. Clays and muds tend to form filter cake on the fracture walls which significantly reduces fluid leakoff, and increases fracture volume and growth. If these materials are available, and need to be disposed anyway, they can be just as effective physically and are far cheaper than commercial viscosifiers.

Grinding of Granular Materials

A number of operators who inject drill cuttings into the ground typically grind the solid components into fine particles. Fine particles are preferred since they can be pumped in slurries more easily, and it is believed they will remain suspended in the well and hydraulic fractures better.

Terralog's experience has shown that granular wastes with grain sizes up to 2 mm diameter can be handled for months or years without significant damage to the pumping equipment. This being said, the pumps should be sized sufficiently to minimize erosion and wear surfaces. Very fine grinding of granular wastes can further reduce erosion of pumping equipment, but will be offset by the higher operating costs of grinding equipment.

Grinding should only be necessary when a significant portion of the incoming granular waste is over 2 mm in grain size. In many cases the oversize material is of very small quantity and can be disposed of in landfills more cheaply than run through a grinder. However, there are cases (e.g. offshore drilling platforms) where grinding of oversize material is cost effective.

Suspension of particles in the well is not a great concern. Whether particles are large or small, the bottom of the injection well fills up with settled solids and sometimes a large number of perforations are covered. The velocity of the slurry through the remaining open perforations is high enough to carry all additional slurry particles into the hydraulic fracture.

Suspension of particles in hydraulic fractures should not be a concern in SFI projects. Over the course of multiple injection cycles, many fractures are created with different lengths and locations of particle placement. It does not seem critical in this sense whether waste particles remain suspended or not.

There is only one case where grinding of granular waste is necessary to benefit fracturing processes. Hydraulic fractures need to have large enough volume to contain the slurry solids. Fracture growth occurs when fluid leakoff from the fracture into the formation remains low. In very high permeability formations (>2 darcy) this condition cannot be met with slurries of sand and water, and waste components such as oil emulsons, clays or drilling muds are required to reduce the fluid leakoff factor. If none of these wastes are available at the injection site it would then make sense to grind a portion (up to 30%) of the granular waste to create a fine-grained material. The fine-grained material will create a filter cake on the fracture walls which reduces leakoff from the fracture.

In summary, the majority of SFI projects do not require grinding of the granular wastes. Fine grinding of the solids does not have any benefit to pumping or fracturing processes, and requires significant operating expense. Grinding should only be used in two cases: where oversize material cannot be handled economically in any other manner, and where formation permeability is so high that some form of fine-grained additive is required but no other waste is available.

SUMMARY OF RECOMMENDATIONS

The SFI well for large-volume waste injection should be located in a formation and area that has sufficient capacity to contain the hydraulic fracture process in a suitable permeable zone. The formation properties should include high permeability (1 Darcy or more), high porosity (25% or more), moderate to large thickness (20m or more), and lateral continuity. Special care should be taken to evaluate the mechanical condition and cement coverage for any offset wells within about a kilometer of the proposed injection well. Ideally, the target formation should be overlain by multiple low permeability shale intervals (to provide flow barriers) and high permeability sand formations (to provide a flow sink, or buffer zone, in case of breach).

A typical SFI injection well should include surface casing and production casing cemented to surface. Injection should take place through a tubing and packer system. Good well drilling and cementing practices are critical in providing a good cement bond along the well for the SFI injection well. If a good cement bond exists, particularly in the 60 to 100 m above the target injection zone, the volume of slurry which infiltrates upwards is very small and the volume of waste which can be placed into the target formation can be very large relative to poorly cemented wells.

Well logging, bottomhole pressure recording and other monitoring and analysis techniques are crucial in determining the behaviour of the SFI process. Monitoring and analysis provides information about the growth of hydraulic fractures and the waste pod, and confirms the containment of the injected wastes in the target formation. This feedback loop of information can then be used to direct future injection operations.

SFI is best performed as a cyclic injection process, with daily periods of injection and shut-in. This permits dissipation of pressures and stresses into the formation during shut-in periods. The pressure data collected during these cycles indicates the formation injectivity and stress conditions and can be used to predict future behaviour. Continuous slurry injection does not permit dissipation processes to occur and little information is available to determine injectivity and stress states. The use of viscosifiers and gels is generally not needed during waste injection. Grinding of solids is also generally not needed.

REFERENCES

Boone et al, (1999): Microseismic monitoring for fracturing in Colorado Shales above a thermal oil recovery operation, Proc. 37th US Rock Mech. Symp., Vail Colorado, 6-9 June, 1999, pp 1017-1024

Moschovidis et al, (1999): The Mounds Drill Cuttings Injection Field Experiment, Proc. 37th US Rock Mech. Symp., Vail Colorado, 6-9 June, 1999, pp 1017-1024

Terralog Technologies Inc. (2000a): Development of Improved Oil Field Waste Injection Disposal Techniques, Topical Report #1: Database Assembly, January 1, 2000. DOE Contract DE-AC26-99BC15222

Terralog Technologies Inc. (2000b): Development of Improved Oil Field Waste Injection Disposal Techniques: Topical Report #2: Empirical Correlationss, June 15, 2000. DOE Contract DE-AC26-99BC15222

Terralog Technologies Inc. (2000c): Development of Improved Oil Field Waste Injection Disposal Techniques: Topical Report #3: Fracture Modelling and Diagnostic Investigations, October 31, 2000. DOE Contract DE-AC26-99BC15222