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Terralog Technologies USA, Inc.

# *Development of Improved Oil Field Waste Injection Disposal Techniques*

## Topical Report # 2: Empirical Correlations

Submitted by:

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# 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 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 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 provides a brief review of the database assembled during project Task 1, and summarizes in greater detail the efforts and results of task 2: Empirical Correlations.

Terralog Technologies has assembled an SFI database template, and has populated it with the monitoring data collected from eight oil field waste injection projects, comprising a total of more than 500 injection episodes. 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.

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. Some of the observed trends are consistent with expectations; however, some are not. For example, closure gradient does increase with cumulative materials over time, but is not particularly sensitive to daily changes in slurry composition. Injectivity appears to be more sensitive to sand concentration then to slop concentration. 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. In the current work, for example, we have modeled fracture propagation with a traditional Perkins-Kern-Nordgren analytic approach. With this model neither fracture growth nor shear modulus appear to correlate well with cumulative waste injection or slurry concentration. Closure gradient seems to actually decrease with shear modulus. These observations are not consistent with physical expectations, suggesting that linear elastic fracture models cannot adequately explain the behavior of large-scale waste injection in very soft, porous media. Improved model and diagnostic techniques are required and will be the focus of the next phase of investigation in this project.

# TABLE OF CONTENTS

## LIST OF FIGURES



## LIST OF TABLES

# INTRODUCTION

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 still remain poorly understood, and as a result there are few guidelines available to optimize the SFI process. The goals of this project are to improve diagnostic techniques for monitoring fracture growth and formation changes, and to develop operating guidelines to optimize daily operations and ultimate storage capacity of the target formation.

Each waste disposal project performed by Terralog is monitored extensively. Data is collected in intervals of 5 seconds to 5 minutes throughout the course of each project. The measured data consists of slurry and material volumes, wellhead and bottomhole pressures, pumping rates, slurry densities, and other relevant information. Pressure and rate data is analyzed using fracture models and well test analysis to determine the characteristics of fractures and the permeability of the surrounding formation.

These measurements and analyses provide information on a daily basis, but an overall picture of SFI operations and formation management has been difficult to achieve. A database containing all of this information and suitable querying and plotting tools will provide a good diagnostic tool to determine operational and formation parameters on both an empirical level and an analytical level.

The tasks for this research project are:

1. Organize the 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. Project documentation and presentations.

This current status report summarizes work completed towards Task 1 (database assembly) and Task 2 (correlation evaluation).

# DATABASE SUMMARY

Terralog Technologies Inc. has assembled an SFI database template, and has populated it with the monitoring data collected from eight oilfield waste injection projects, comprising a total of more than 500 injection episodes. Each waste disposal project performed by Terralog is monitored extensively. 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. Pressure and rate data is analyzed using fracture models and well test analysis to determine the characteristics of fractures, the permeability of the surrounding formation, and the changing in-situ stress conditions.

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. The Project Information Table contains basic information on the injection formation and well completion. The Pressure and Rate Table contains key injection parameters (pressure, rate, density) which were recorded continuously at high frequency (from 5 second to 5 minute sampling frequency) at each of the projects. The Daily Summary Table provides a "snapshot" of information for each day of slurry fracture injection, summarizing information such as the total volumes of the slurry components, average injection rates and pressures, and the associated values of injectivity and pressure gradients. Also included in the database are the analyses of injection pressure and pressure fall-off which are used to determine the state of the formation. Examples of each of these three database components are provided in the following sections.

## Project Information Table

To properly assess the data from each project, formation and well parameters are required. The information in this table are summarized below.

- Project Code
- Well Completion
- Well Direction
- Perforation Top (tvd)
- Perforation Bottom (tvd)
- Formation Name
- Geological Formation Top
- Geological Formation Bottom
- Formation Description
- Initial Permeability
- Initial Pressure (MPa)
- Overlying confining geological formation
- Underlying confining geological formation

## Pressure and Rate Table

The Pressure and Rate Table contains the variables which were monitored continuously at each injection site. At each Terralog project the well pressures, slurry flow rate and density were measured every five minutes throughout the life of the project. In addition, bottomhole pressures were measured at high resolution sample rates of 5 s to 30 s in the period immediately following shut-in for improved well-test analysis. Table 1 lists the parameters which have been stored in the Pressure and Rate Table. Table 2 shows an example of actual data. For each injection episode, this raw data is analyzed and summarized in the Daily Summary Table.

Table 1: Description of Pressure and Rate Table Parameters

| Value Description | Variable Name and Units |
|---|---|
| Project Code | Project_Code |
| Date and Time | Date_Time |
| Bottomhole Pressure | BHP_kPa |
| Wellhead Pressure | WHP_kPa |
| Slurry Flow Rate | Qslurry_m3_per_min |
| Density | Density_kg_per_m3 |

Table 2: Sample of Pressure and Rate Data from Project TTI6

| Date_Time | BHP_kPa | WHP_kPa | Density_SGU | Qslurry_m3_per_min |
|---|---|---|---|---|
| 06/07/97 7:20:00 AM | 5049 | 57 | 0.6998 | 0 |
| 06/07/97 7:25:00 AM | 5035 | 28 | 0.6998 | 0 |
| 06/07/97 7:30:00 AM | 5035 | 69 | 0.6998 | 0 |
| 06/07/97 7:35:00 AM | 5035 | 75 | 0.6998 | 0 |
| 06/07/97 7:40:00 AM | 6017 | 161 | 1.0966 | 0 |
| 06/07/97 7:45:00 AM | 11768 | 6235 | 1.1000 | 0.5348 |
| 06/07/97 7:50:01 AM | 15886 | 11726 | 1.0255 | 1.5934 |
| 06/07/97 7:55:00 AM | 14275 | 10154 | 1.1018 | 1.5928 |
| 06/07/97 8:00:01 AM | 13870 | 9570 | 1.1082 | 1.5934 |
| 06/07/97 8:05:01 AM | 13682 | 9385 | 1.1073 | 1.5947 |
| 06/07/97 8:10:01 AM | 13502 | 9177 | 1.1061 | 1.5934 |
| 06/07/97 8:15:01 AM | 13459 | 8981 | 1.1781 | 1.5921 |
| 06/07/97 8:20:01 AM | 13611 | 8779 | 1.2289 | 1.5941 |

## Daily Summary Table

The Daily Summary Table is the key repository of information and most useful component of the database. This contains a summary of critical injection parameters and interpreted formation response for all injection episodes for all projects. Table 3 presents a summary of the Daily Summary Table parameters. Each row of data in the Daily Summary Table consists of one injection episode, showing all data collected for that time period. In total, there are 68 variables contained in the columns of the Daily Summary Table. Most of these parameters are numeric values, but some are descriptive text variables. The parameters in the database have been chosen to best represent the characteristics of the injection period operations and formation response.

There are 790 daily entries in the database, of which 518 are injection episodes, and 272 are days that operations were suspended due to days off, well workovers, or maintenance issues. The variables can be grouped into those parameters that were directly measured (independent measurements), dependent values calculated directly from the measurements, and interpreted values determined from data analysis. A sample portion of this database Table for one project is presented in Table 4.

Table 3: Description of Daily Summary Table Parameters

| Value Description | Variable Name and Units |
|---|---|
| *General Project Information:* | |
| Project Code | Project_Code |
| Project Name | Project_Name |
| Well Name | Well Name |
| Formation Name | Formation Name |
| Perforation Top (tvd) | Perf Top_tvd |
| Perforation Bottom (tvd) | Perf Bottom tvd |
| Formation Top (tvd) | Fmn Top tvd |
| Formation Bottom (tvd) | Fmn Bottom tvd |
| Date | Date |
| Operational Status | Operational_Status |
| Operational Status Code | Operational_Status_Code |
| Monitoring Status | Monitoring_Status |
| Monitoring Status Code | Monitoring_Status_Code |
| Shut-in Analysis(type of analysis performed) | Shut-in Analysis |
| Flow Regime | Flow_Regime |
| Shut-in Analysis Confidence | Shut_In_Analysis_Confidence |
| Injection Behavior | Injection_Behaviour |
| | |
| *Independent Measurements:* | |
| Pumping Time | Pumping_Time_hr |
| Shut-in Time | Shut_in_Time_hr |
| Water Volume | Water_m3 |
| Total Materials Volume | Material_m3 |
| Sand | Sand_m3 |
| Drilling Mud | Drilling_Mud_m3 |

| | |
|---|---|
| Slop | Slop_m3 |
| Soil/Pit Material | Soil_Pit_material_m3 |
| Total Slurry Volume | Slurry_m3 |
| Cumulative Water Volume | Cum_Water_m3 |
| Cumulative Materials Volume | Cum_Material_m3 |
| Cumulative Sand Volume | Cum_Sand_m3 |
| Cumulative Slop Volume | Cum_Slop_m3 |
| Cumulative Mud Volume | Cum_Mud_m3 |
| Cumulative Soil/Pit Material Volume | Cum_Soil_Pit_Material |
| Cumulative Slurry Volume | Cum_Slurry_m3 |
| Average Injection Rate | Avg_Inj_Rate_m3_per_d |
| Average Slurry Density | Density_kg_m3 |
| Average Injection Bottomhole Pressure | Avg_Inj_BHP_MPa |
| Average Injection Wellhead Pressure | Avg_Inj_WHP_MPa |
| Minimum Shut-in Pressure | Simin_BHP_MPa |
| | |
| *Dependent Values:* | |
| Injectivity | Injectivity_m3_per_d_per_MPa |
| Estimated Slurry Viscosity | Est_Slurry_Viscosity_cP |
| Average Injection BHP Gradient | BHPinj_Grad_kPa_per_m |
| Minimum Shut-in Pressure Gradient | Simin_Grad_kPa_per_m |
| % Total Materials in Slurry | PercentMaterials |
| % Sand | PercentSand |
| % Mud | PercentMud |
| % Slop | PercentSlop |
| % Soil/Pit Material | PercentSoil_Pit_Material |
| | |
| *Interpreted Values:* | |
| Instantaneous Shut-in Pressure | ISIP_MPa |
| Closure Bottomhole Pressure | BHP_Closure_MPa |
| Closure Bottomhole Pressure Gradient | Closure_Grad_kPa_per_m |
| Permeability (Zone 1) | Zone_1_Perm_mD |
| Skin (Zone 1) | Zone_1_Skin |
| Permeability (Zone 2) | Zone_2_Perm_mD |
| Skin (Zone 2) | Zone_2_Skin |
| Wellbore Storage | Wellbore_Storage_m3_per_Kpa |
| P* (Estimated Reservoir Pressure) | P_Est_Res_Pressure_MPa |
| Fracture ½ length | Linear_xf_m |
| PKN_LL Closure (kPa) | PKN_LL_Closure_MPa |
| PKN_LL Length Growth | PKN_LL_Length_Growth_m_s_e05 |
| PKN_LL Shear Modulus | PKN_LL_Shear_Modulus_GPa |
| PKN_LL $r^2$ Value | PKN_LL_R_Squared |
| PKN_LL % Volume Difference | PKN_PercentVolume_Diff |
| PKN Injection Time (hrs) | PKN_Injection_Time_hrs |
| GDK Closure | GDK_Closure_MPa |
| GDK $R^2$ | GDK_R_Squared |
| GDK Length Growth | GDK_Length_Growth_m_s_e05 |
| GDK Shear Modulus | GDK_Shear_Modulus_GPa |
| GDK Injection Time | GDK_Injection_Time_hrs |

Table 4: A Portion of the Daily Summary Table

| Project Code | Date | Pumping Time (hr) | Water Volume ($m^3$) | Slop Volume ($m^3$) | Sand Volume ($m^3$) | Avg. Inj. Rate ($m^3$/min) | Avg. Inj. BHP (kPa) |
|---|---|---|---|---|---|---|---|
| TTI 6 | 10-Aug-97 | 6.3 | 641 | 8 | 47 | 1.99 | 13.5 |
| TTI 6 | 11-Aug-97 | 8.7 | 503 | 9 | 135 | 1.54 | 14.0 |
| TTI 6 | 12-Aug-97 | 8.0 | 614 | 17 | 117 | 1.65 | 13.5 |
| TTI 6 | 13-Aug-97 | 6.5 | 445 | 20 | 65 | 1.66 | 14.0 |
| TTI 6 | 14-Aug-97 | 5.9 | 446 | 17 | 0 | 1.58 | 13.0 |
| TTI 6 | 15-Aug-97 | 3.0 | 301 | 0 | 0 | 1.67 | 13.6 |
| TTI 6 | 16-Aug-97 | 9.3 | 518 | 164 | 159 | 1.54 | 12.5 |
| TTI 6 | 17-Aug-97 | 8.8 | 653 | 8 | 104 | 1.65 | 12.5 |
| TTI 6 | 18-Aug-97 | 3.5 | 380 | 0 | 0 | 1.81 | 13.7 |
| TTI 6 | 19-Aug-97 | 4.5 | 543 | 0 | 0 | 2.01 | 13.5 |
| TTI 6 | 20-Aug-97 | 9.3 | 685 | 16 | 124 | 1.68 | 13.0 |
| TTI 6 | 21-Aug-97 | 9.8 | 499 | 0 | 83 | 1.23 | 13.0 |
| TTI 6 | 22-Aug-97 | 9.0 | 553 | 8 | 116 | 1.52 | 13.5 |
| TTI 6 | 23-Aug-97 | 8.5 | 495 | 0 | 154 | 1.58 | 13.7 |
| TTI 6 | 24-Aug-97 | 8.8 | 347 | 0 | 94 | 1.16 | 13.7 |
| TTI 6 | 25-Aug-97 | 9.0 | 669 | 0 | 127 | 1.59 | 13.7 |
| TTI 6 | 26-Aug-97 | 7.3 | 526 | 0 | 72 | 1.60 | 13.8 |
| TTI 6 | 27-Aug-97 | 7.3 | 724 | 0 | 0 | 1.88 | |
| TTI 6 | 28-Aug-97 | 8.3 | 735 | 0 | 45 | 1.76 | |
| TTI 6 | 29-Aug-97 | 6.3 | 508 | 0 | 13 | 1.63 | 13.5 |
| TTI 6 | 30-Aug-97 | 9.0 | 654 | 0 | 81 | 1.58 | 13.5 |
| TTI 6 | 31-Aug-97 | 9.0 | 642 | 0 | 91 | 1.57 | 14.0 |
| TTI 6 | 01-Sep-97 | 9.5 | 656 | 0 | 65 | 1.46 | 13.8 |

**General Project Information**

This area provides the basic information about each project. The Operational Status column represents the pumping status of the injection period. Each Operational Status has a numerical code that has been assigned to it (Table 5). The Operational Status Codes are grouped as follows: 10 to 17 are injection days, 20 to 26 indicate well testing operations, 30 and above are for suspended operations and the associated reasons. The status code can be used with the SFI database plotter to screen out specific data points such as injection episodes in which only water was injected.

The Monitoring Status column reflects the status of the monitoring equipment for each injection period. Again, a code has been assigned to each type of status (Table 6). These codes are grouped as follows: 110 to 112 for fully operational data collection system, 120 to 124 for broad monitoring system failures, and 130 and above for specific sensor failures. These codes can be used to assess the quality of specific data in the Daily Summary Table.

Table 5: SFI Operational Status Codes

| Operational_Status_Code | Operational_Status |
|---|---|
| 10 | Slurry Injection |
| 11 | Water Injection by TTI |
| 12 | Water Injection by Client |
| 13 | Wellbore Failure during injection |
| 14 | Communication with offset wells during injection |
| 15 | Step Rate Test and Slurry Injection |
| 16 | Waste Injection by Client |
| 17 | Communication with injection well annulus |
| 20 | Step Rate Test |
| 21 | Pressure Fall-off Test |
| 22 | Step Rate Test and Pressure Fall-off tests |
| 23 | Tracer Log Test |
| 24 | Tracer Log and Step Rate Tests |
| 25 | Dye Injection Tests |
| 26 | Testing Well Integrity |
| 30 | Operations Suspended - Days off |
| 31 | Operations Suspended - Extended Pressure Fall-off Test |
| 32 | Operations Suspended - no water/waste available |
| 33 | Operations Suspended - no service equipment available |
| 34 | Operations Suspended - awaiting client/TTI decision |
| 35 | Operations Suspended - blocked well perforations |
| 36 | Operations Suspended - well cleanout |
| 37 | Operations Suspended - pumping equipment repairs |
| 38 | Operations Suspended - well repairs/workover |
| 39 | Operations Suspended - Well Clean out and Tracer Log |
| 40 | Operations Suspended - frozen equipment or water line |
| 41 | Operations Suspended - Rig in/Rig out |
| 42 | Well Cleanout and Step Rate Test |

Table 6: SFI Monitoring Status Codes

| Monitoring_Status_Code | Monitoring_Status |
|---|---|
| 110 | Fully Operational |
| 111 | Fully Operational, density measured by mud scales |
| 112 | Fully Operational, behavior too erratic to obtain averages |
| 120 | No data collected - Download Failure |
| 121 | No data collected - Power Failure |
| 122 | Injection data collected but no fall-off data -Power Supply |
| 123 | BHP Data okay, WHP,Density and Rate calculated from pump |
| 124 | WHP, Flow Rate and Density okay, BHP calculated from pump |
| 130 | BHP Sensor Failure, all other sensors ok |
| 131 | WHP, Flow Rate and Density Unit Failure, BHP sensor ok |
| 132 | Density Sensor Failure, all other sensors ok |
| 133 | Slurry Volumes not correct, all other sensors ok |
| 134 | WHP Sensor failure, all other sensors ok |
| 135 | BHP Sensor out of well, all other sensors ok |
| 140 | Cannot Access Archive |

**Independent Measurements**

Time measurements and material volumes are taken from the daily pump reports. All volumes are reported in units of $m^3$. As each project dealt with different waste streams, some entries will be blank (for example, some projects did not inject Mud as part of the slurry; therefore, these cells will be blank).

Cumulative values are the running totals for each project to the end of the pumping day in question; values reported in $m^3$.

The injection rate, Average BHP, Average WHP, Density and Min. Shut-in pressure are measured with a bottomhole sensor (except wellhead pressure) and collected by dataloggers at each project.

**Dependent Values**

Injectivity is equal to the average pumping rate divided by net pressure (average injection pressure – virgin reservoir pressure), and gives an indication of how well the formation is accepting fluid during a given injection episode.

Viscosity was calculated using an equation based on the turbulent flow equations. This equation is a rearrangement of work developed by Swamee and Jain (1976). Viscosity (μ) is calculated as follows:

$$\mu = 560\sqrt{\frac{1000\rho\, p_f D^3}{L}}\left[\exp\left(-1.0365\frac{Q}{60D^2}\sqrt{\frac{\rho L}{p_f D}}\right)-\frac{\varepsilon}{3.7D}\right] \qquad [1]$$

Where $\mu$ is fluid viscosity (cP), $\rho$ is fluid density (kg/m$^3$), $p_f$ is pressure drop due to friction (kPa), D is pipe diameter (m), L is pipe length (m), Q is flow rate (m$^3$/min), $\varepsilon$ is pipe roughness (m).

Gradients: as each project was conducted in different formations, pressure values are divided by bottomhole sensor depth to provide easy comparison between projects. By doing this, the pressure data can be readily compared across a project by project basis. All values are in reported in kPa/m.

% Total Materials in Slurry: For each injection period, the volume of each component is divided by total slurry volume to obtain volumetric composition of the slurry.

Consistency of the slurry was not the same each day due to different volumes of slop, sand, mud and water. The different flow characteristics of each component contained in the slurry can be best described in terms of viscosity. Direct measurements of slurry viscosity with a viscosity meter were never attempted, so viscosity had to be calculated based on the pressure drop in the pipeline leading to the wellhead and in the well tubing.

**Interpreted Values: Determining ISIP and Closure**

Instantaneous shut-in pressure (ISIP) corresponds to the bottom hole wellbore pressure just as shut-in occurs (i.e., just when the fracture begins to close). Closure pressure refers to the bottom hole wellbore pressure just as the fracture closes completely; this is identical to the pressure required to open the fracture, and is theoretically equal to the minimum principal stress of the formation (known as $\sigma_3$). ISIP is especially important for the purposes of well test analysis; closure is necessary to perform PKN analysis, as $\Delta p$ in equation [7] is equal to bottom hole wellbore pressure – closure pressure (described in a later section).

Two methods have been used to determine ISIP and closure pressure: the derivative plot method and well test analysis. In the derivative plot method the rate of pressure decline (dP/dt) is plotted against bottomhole pressure (Figure 1). In this plot ISIP occurs at the pressure where the most negative dP/dt occurs. Closure is determined at the point where the dP/dt points deviate from a straight line as shown.

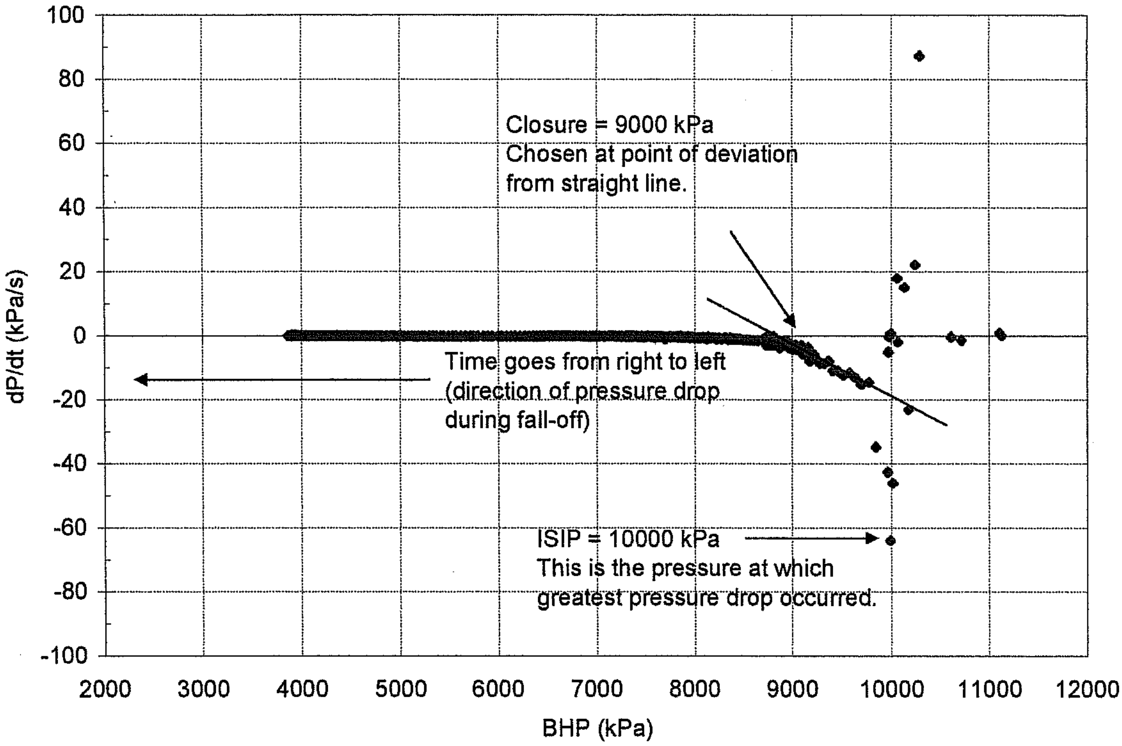


Figure 1: Determining ISIP and Closure Pressure from pressure derivative plot

The other technique for determining ISIP and Closure pressure is from well test analysis. ISIP in this case is defined as the first point at which wellbore storage is observed, as shown in Figure 2 (Horne, 1995). Closure pressure is determined from the point at which linear flow from the fracture into the formation ceases (Figure 3).

The data shown in Figures1, 2 and 3 comes from project TTI5, May 17, 1997. It can be seen that there is some discrepancy in the values returned by both techniques (300 to 500 kPa). The ISIP and closure values in the database were determined by both methods, with probably two-thirds of the values determined by the derivative plot technique. However, the well-test methods are more reliable with complicated fall-off behaviours and will be used primarily in the future.

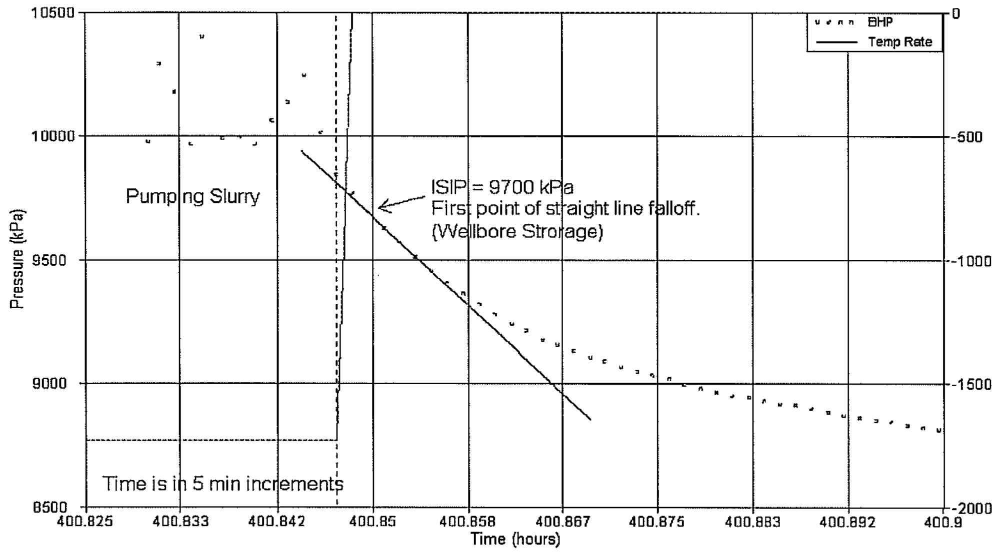


Figure 2: Determining ISIP from well test analysis

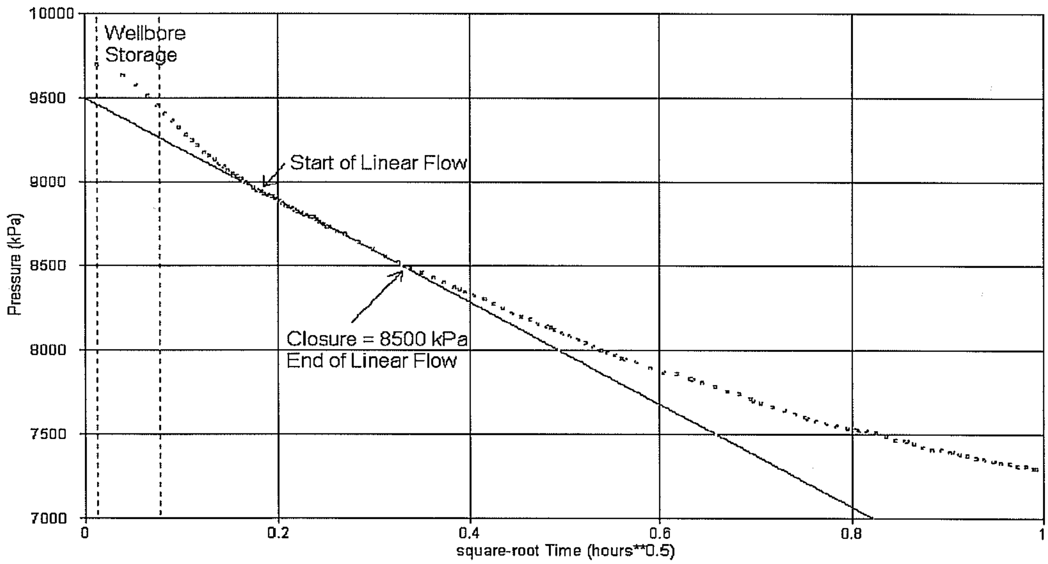


Figure 3: Determining Closure from well test analysis

# DATABASE QUERY TOOLS

Terralog has 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.

## BHP Plotter

The BHP Plotter is used to view data within the Pressure and Rate Table. The data from any time period can be viewed and then exported to an Excel or ASCII text file if desired.

The BHP Plotter interface is shown in Figure 4. Bottomhole pressures (BHP) and slurry injection rates (Qslurry) are plotted, each with its own axis. The tabs in the upper right corner are used to pick the start and finish times of the data to be plotted. The BHP axes settings are available to zoom in on the pressure data. The name of the source data table can also be entered.

The bottom section of the plotter interface contains the options for exporting data. The displayed range of data as set by the start and finish times can be exported to either Excel or ASCII text formats. The file name and directory are entered in the two text boxes provided.

The only limitation of this plotter is that it can display no more than 4096 points, which is an internal Access setting. This does not affect the number of records which can be exported, which can be up to 65535 records.

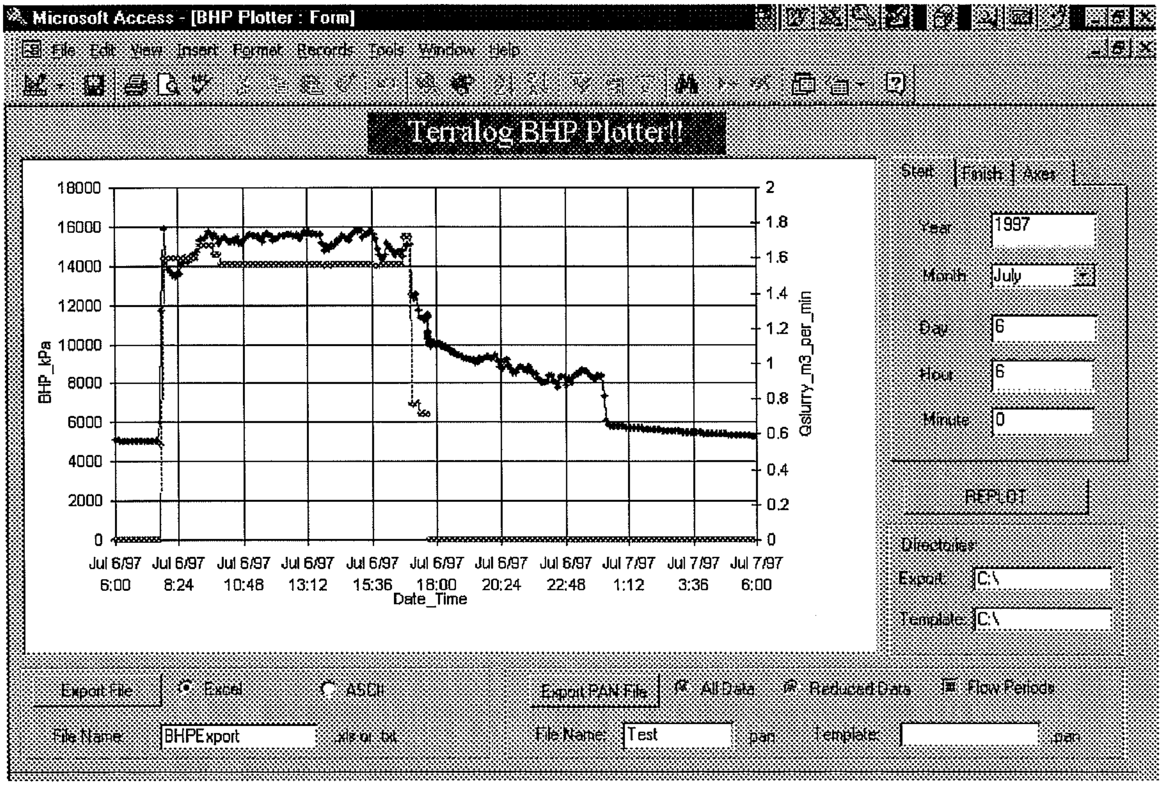


Figure 4: BHP Plotter Interface

## SFI Daily Plotter

The SFI Daily Plotter is used to view data in the Daily Summary Table. This plotter can be used for two purposes: to observe the development of a parameter over the course of a project, and to create cross-plots to determine the correlation between two separate parameters.

Figure 5 shows the user interface of the SFI Daily Plotter. The drop-down boxes in the upper right are used to pick the two parameters to be plotted on the horizontal and vertical axes. Each box contains a list of all the parameters in the Daily Summary Table. The section in the lower right is used to filter the plotted data based on any parameter, such as Project Code or %Sand. The filter is governed by the "=", "<" and ">" operators. The buttons at the left side of the screen are used to zoom in on the plotted data.

An example of a correlation plot of two parameters is shown in Figure 6. This plot shows the initial shut-in pressure (ISIP_MPa) versus average injection pressure (Avg_Inj_BHP_Mpa), filtered to display all injection episodes in which the percent of injected sand (PercentSand) is less than 20%. Such a plot for example, could be used to compare the influence of injectate on injectivity and shut-in pressure across a range of projects.

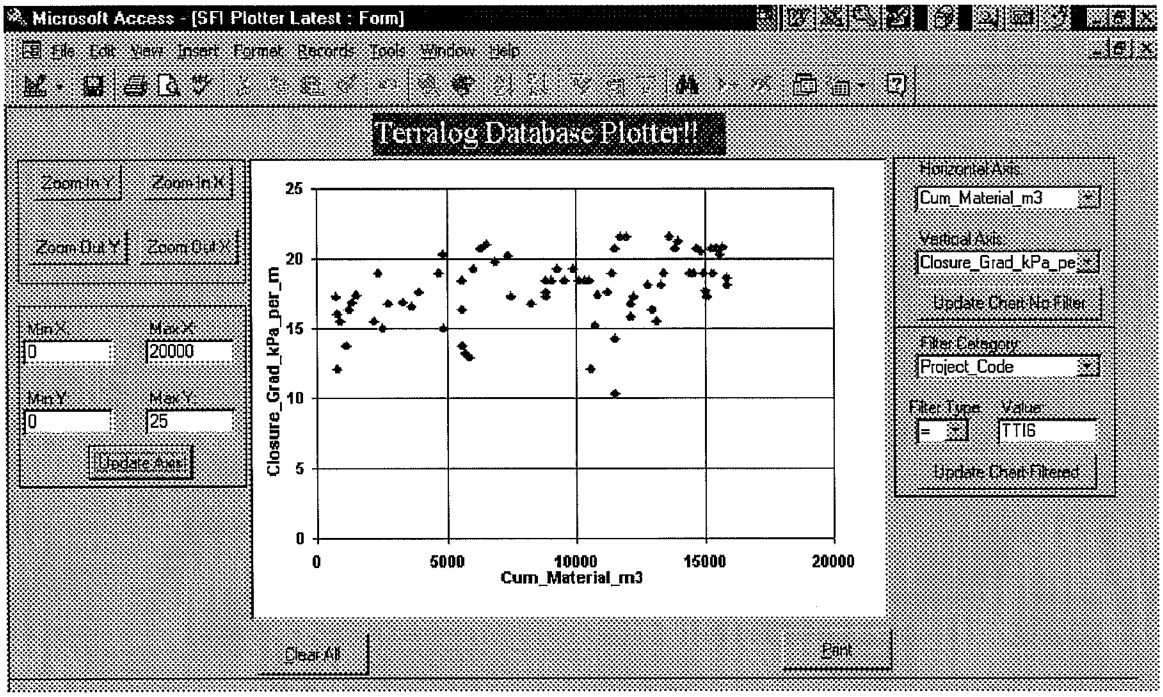


Figure 5: User interface of the SFI Daily Plotter.

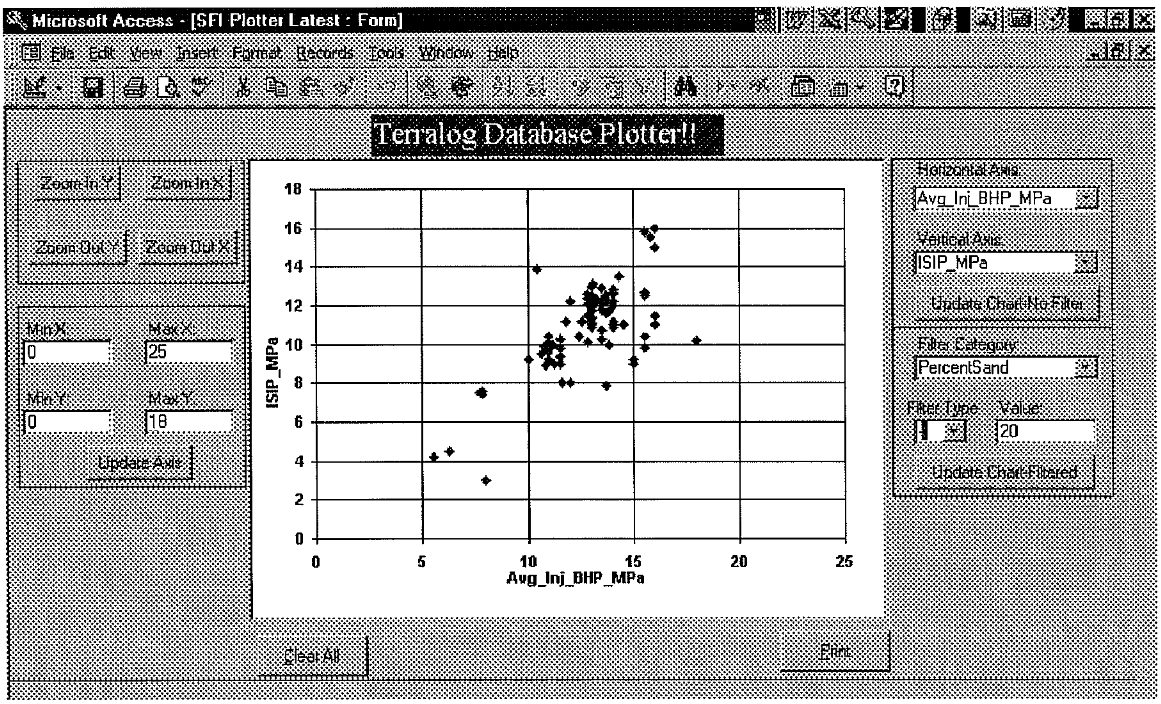


Figure 6: Example of correlation plot

## Access Query Tools

In addition to the plotters created by Terralog, Microsoft Access also provides the ability to perform specialized queries of the database. An example query is shown in Figure 7, which then produces a table as shown in Figure 8. Such tables can then be printed or exported to any spreadsheet.

An example use of this tool is generate the list of days injection well tests were performed, such as step rate tests or radioactive tracer tests (as shown in Figures 7 and 8). Another example is creating a list of reservoir permeabilities (generated from well test analysis) when the slurry was composed of certain types of material (e.g., >10% Mud).

Ultimately, other users of the SFI database do not have to rely on Terralog's interpretations; they can develop their own using the plotter and query tools.

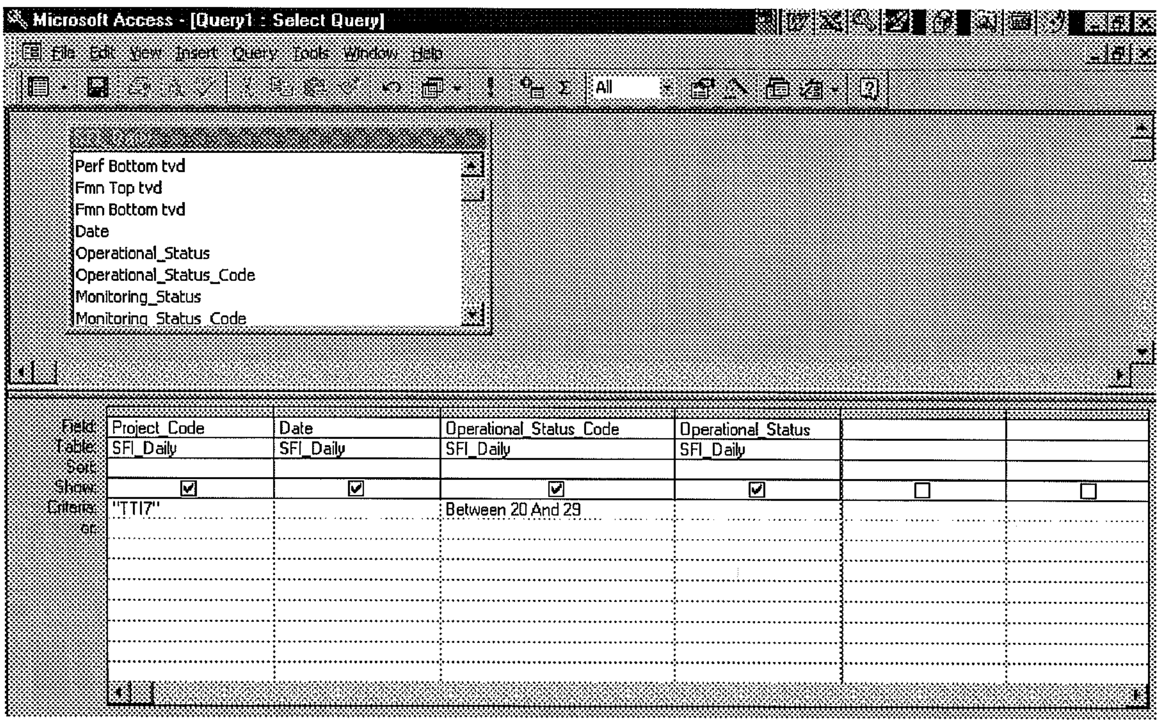


Figure 7: Example of Access Query

Microsoft Access - [Query1 : Select Query]

| Project Code | Date | Operational Status Code | Operational Status |
|---|---|---|---|
| TTI7 | 17/08/97 | 23 | Tracer Log Test |
| TTI7 | 18/08/97 | 21 | Pressure Falloff Test |
| TTI7 | 19/08/97 | 20 | Step Rate Test |
| TTI7 | 02/09/97 | 20 | Step Rate Test |
| TTI7 | 11/09/97 | 23 | Tracer Log Test |
| TTI7 | 15/09/97 | 20 | Step Rate Test |
| TTI7 | 26/09/97 | 24 | Tracer Log and Step Rate Tests |
| TTI7 | 19/10/97 | 23 | Tracer Log Test |
| TTI7 | 31/10/97 | 23 | Tracer Log Test |
| TTI7 | 07/11/97 | 23 | Tracer Log Test |
| TTI7 | 13/11/97 | 20 | Step Rate Test |
| TTI7 | 28/11/97 | 23 | Tracer Log Test |
| TTI7 | 02/12/97 | 20 | Step Rate Test |
| | | 0 | |

Figure 8: Table resulting from query in Figure 7

# DATA CORRELATIONS

The SFI database was constructed to determine which pumping operations and formation parameters are related to each other. The "Terralog Database Plotter" was used to plot individual variables against each other. This section discusses the more significant plots, from which conclusions about relative correlations between parameters can be determined.

When applicable, cross-project correlations, as well as project-specific correlations, use 'normalized' variables (for example pressure gradients instead of absolute pressures or percent materials instead of absolute volume of materials). This will help identify relationships that are independent of the differing formation properties and unique operating conditions of individual projects. An example of a useful cross project correlation is permeability versus injectivity. Project-specific correlations are also important, as they can gauge the effectiveness of various operating strategies, for example, the change of permeability with time as operating strategies change.

## Effect of Cumulative Wastes on Closure Gradient

As waste materials are continuously packed into a disposal formation, it would be expected that pressure required to open the fracture (closure pressure) should increase. Figure 9 shows this trend of slightly rising closure pressures. "Cumulative material" means the total of all wastes including sand, slop, drilling muds, and soil & pit materials.

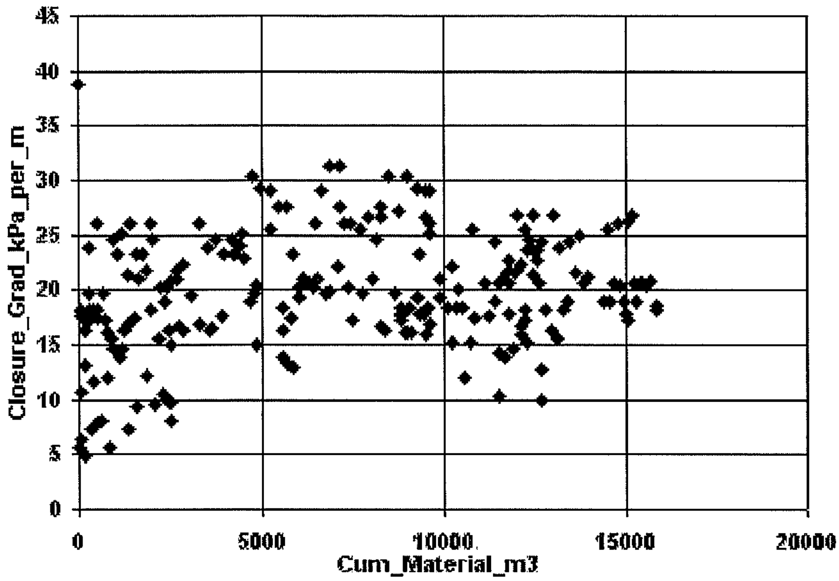


Figure 9: Closure Gradient vs. Cumulative Materials

Figures 10 and 11 show the impacts of individual waste components on closure gradient. The impact of cumulative sand injection in Figure 10 is similar to Figure 9 (combined waste volumes), with a weak rising trend. The effect of cumulative mud injection in Figure 11 does appear to be a slightly increasing closure gradient with time. There is less scatter in this plot than the others since mud was only injected in projects TTI6 and TTI9. The abnormally low closure gradients (below 10 kPa/m) present in Figures 9 and 11 came from project TTI9 which was injecting into a depleted zone at 1250 m depth as opposed to an average depth of 400 to 1000 m for the other projects.

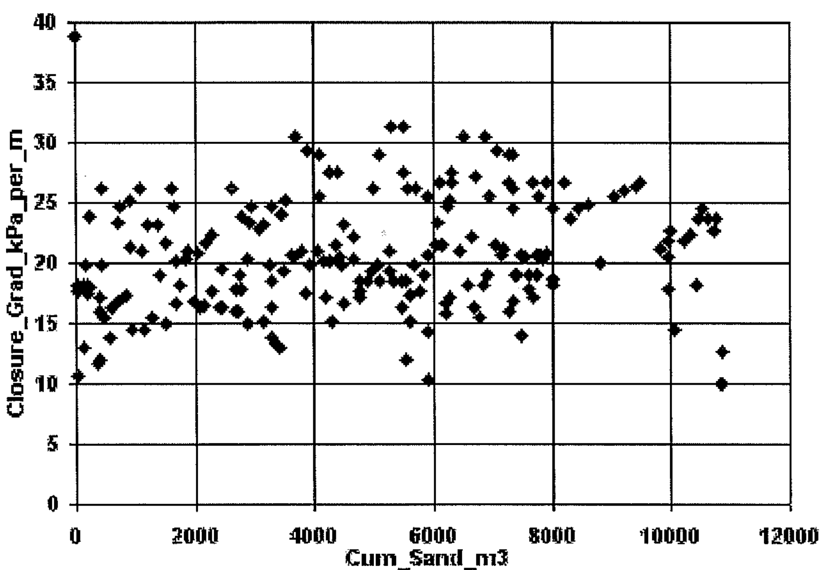


Figure 10: Closure Gradient vs. Cumulative Sand

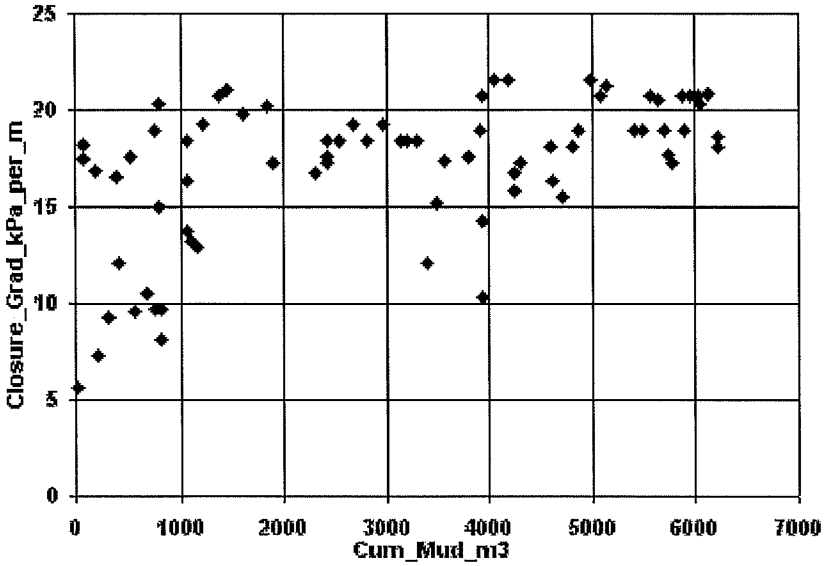


Figure 11: Closure Gradient vs. Cumulative Mud

## Impact of Slurry Component Percentages on Closure Gradient

The waste material percentages refer to the average volume ratio between the waste component and the total slurry volume during an entire day. It appears in Figure 12 that increasing the percentage of waste materials in the slurry causes an increase in the closure pressure gradient. If this were true, it would be advisable to reduce the waste percentage in the injected slurries to minimize stress increase in the target formations.

However, this is not true when you look at the same plot on a project-by-project basis. It can be seen in Figures 13 and 14 that within each project the closure pressure gradient appears to be independent of percentage of waste material. In both cases the trend is horizontal and the scatter is significant, indicating that closure pressures are governed by conditions other than slurry content.

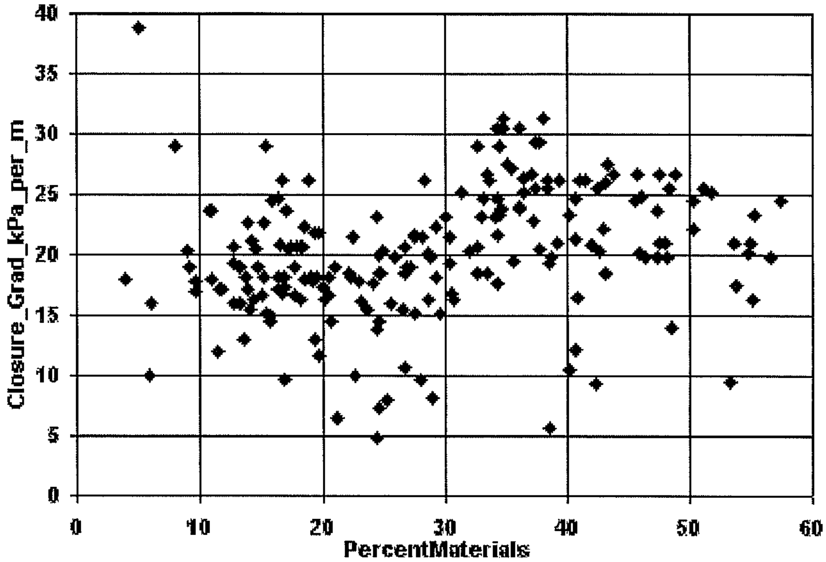


Figure 12: Closure Gradient vs. Percent Materials

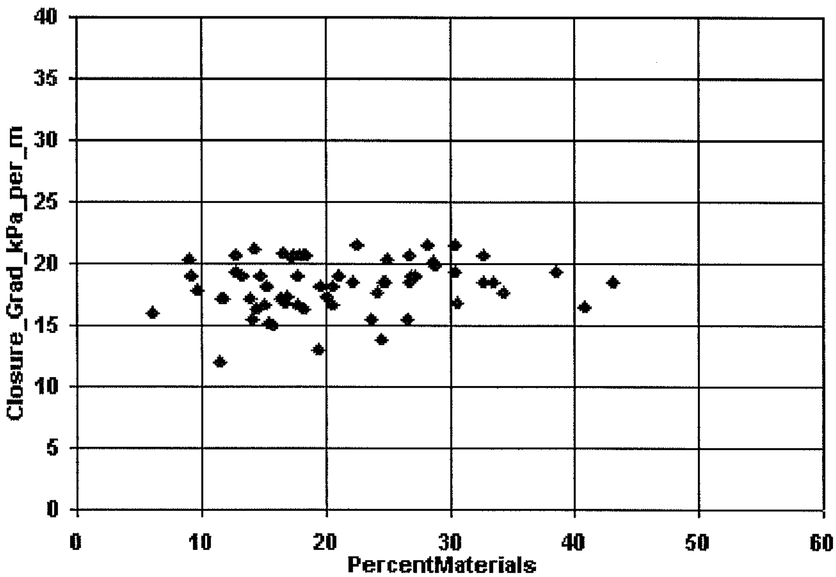


Figure 13: Closure Gradient vs. Percent Materials for Project TTI6

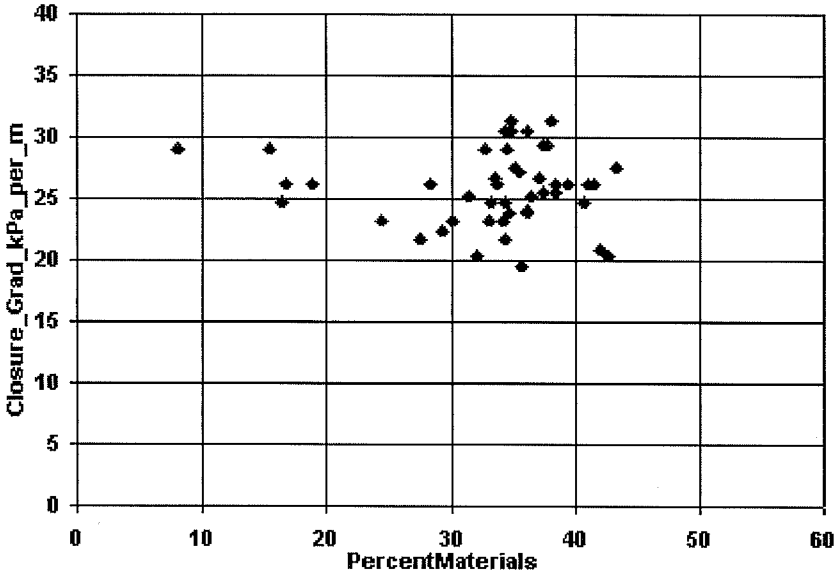


Figure 14: Closure Gradient vs. Percent Material for Project TTI7

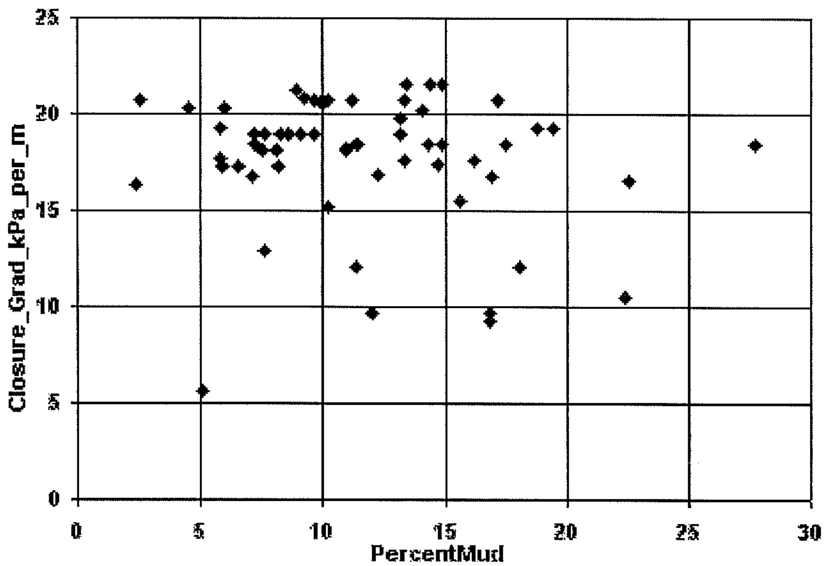


Figure 15: Closure Gradient vs. Percent Mud

Figure 15 presents the effect of an individual slurry component on closure gradient. It can be seen from this plot that the percent mud has no correlatable impact on closure pressures.

## Effect of Cumulative Slurry Volume on Injectivity

Injectivity is equal to the average pumping rate divided by net pressure (average injection pressure – virgin reservoir pressure), and gives an indication of how well the formation is accepting fluid during a given injection episode.

Over the course of an SFI project, it might be expected that as more waste materials are placed within the target formation, the injectivity would tend to reduce over time. Figure 16 shows that this theory is not true, and in fact remained in a consistent band between 0.1 and 0.3 $m^3$/min/MPa. The points above this band typically occurred during water pumping days and points less than 0.1 $m^3$/min/MPa usually occcurred when the injection well was plugged.

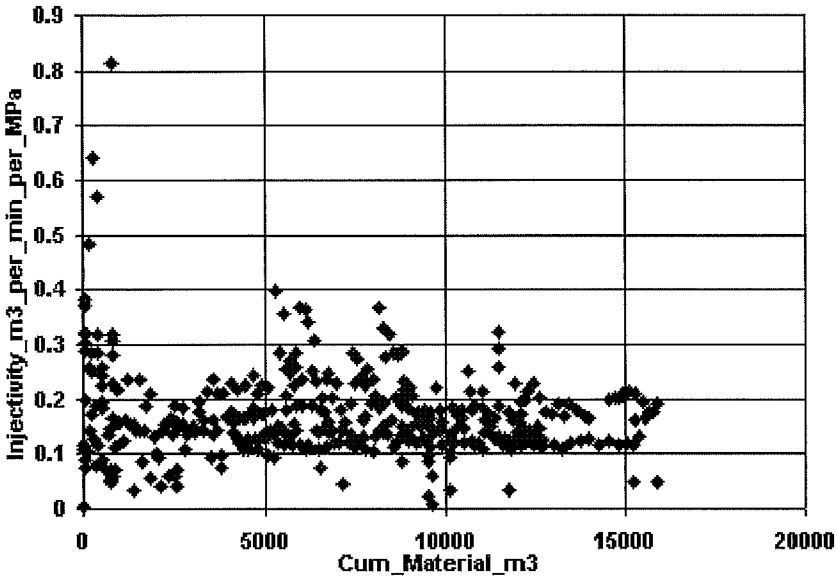


Figure 16: Injectivity vs. Cumulative Material Volume

## Effect of Slurry Components Percentages on Injectivity

It would be expected that slurry containing a relatively high volumetric content of materials should be more difficult to inject into the formation, i.e., result in a low injectivity. Figure 17 shows the relationship between percent materials and injectivity. There appears to be an envelope which causes slurries with higher percent materials to cause lower injectivities. Below this envelope, the correlation is not strong.

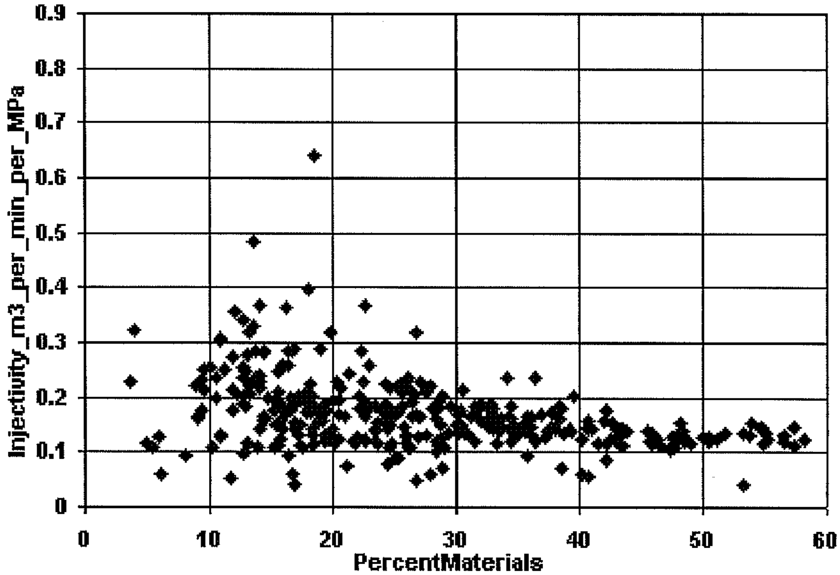


Figure 17: Injectivity vs. Percent Materials

The injection of a viscous material such as mud should result in a lower injectivity, as the slurry would be more difficult to pump. Figure 18 shows the relationship between injectivity and percent mud. There is only a small indication that higher mud content negatively impacts injectivity, independent of other factors.

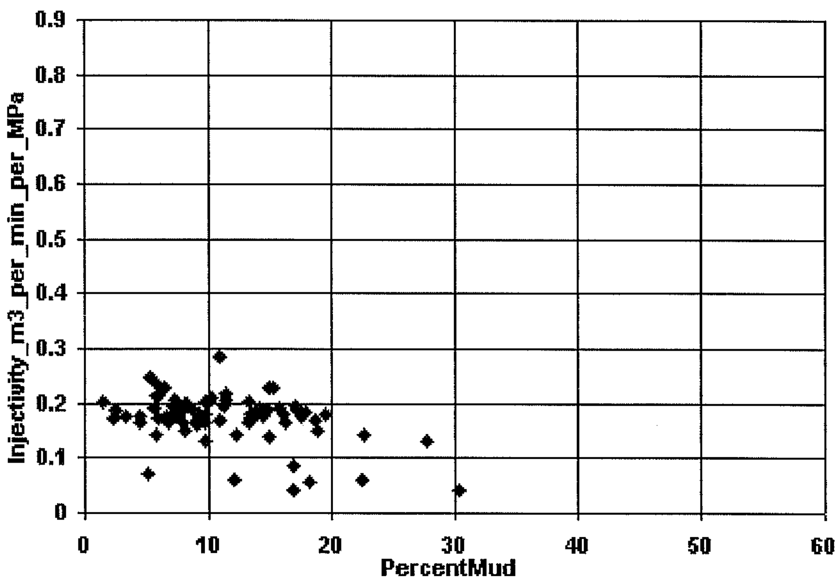


Figure 18: Injectivity vs. Percent Mud in Slurry

Figure 19 appears to show a very strong relationship between the injectivity and the sand percentage in a slurry. It appears that the injectivity is highest when the percent sand is less than 10%, with injectivity as high as 0.40 $m^3$/min/MPa. Above a sand percentage of 20%, the injectivity falls in a band between 0.10 and 0.20 $m^3$/min/MPa. This indicates that injectivity can be improved by using a slurry with a small amount of sand.

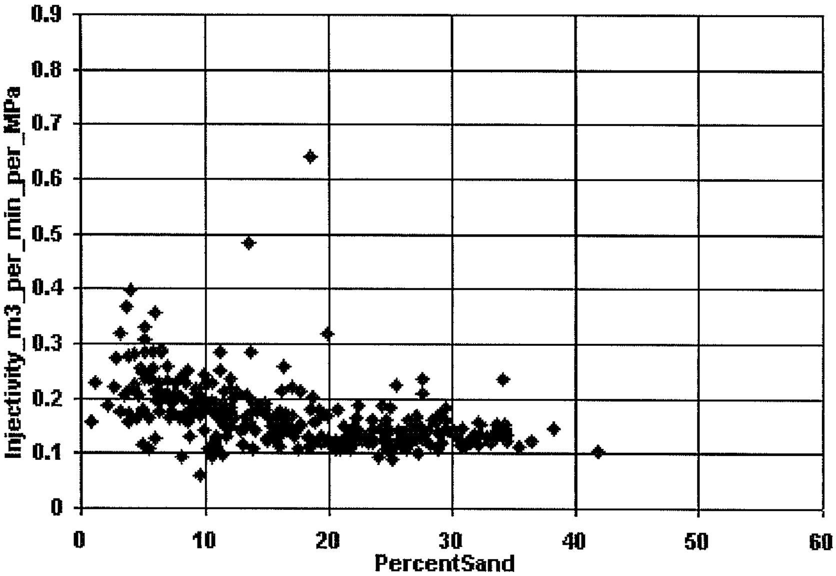


Figure 19: Injectivity vs. Percent Sand in Slurry

It appears in Figure 20 that there is no correlatable behaviour between injectivity and the percent slop contained in the slurry. The broad band of data between 0.10 and 0.40 $m^3$/min/MPa, and the lack of a trend or envelope behaviour indicates that injectivity is governed by factors other than the slop contained in the slurry.

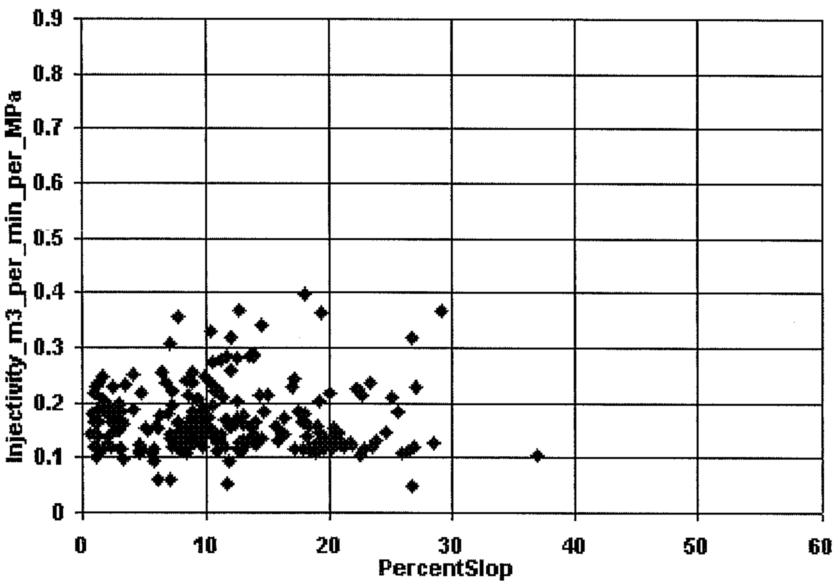


Figure 20: Injectivity vs. Percent Slop in Slurry

## Effect of Viscosity on Injectivity and Permeability

Viscosity has also been correlated against slurry content. The following correlations were performed: viscosity vs. percent mud, viscosity vs. percent sand, viscosity vs. percent slop, and viscosity vs. percent materials. All show the same trend: up to about 20-30%, the viscosity is unaffected specifically by the component in question, but after this, the viscosity increases rapidly. An example correlation is shown in the following plot of viscosity vs. percent material (Figure 21):

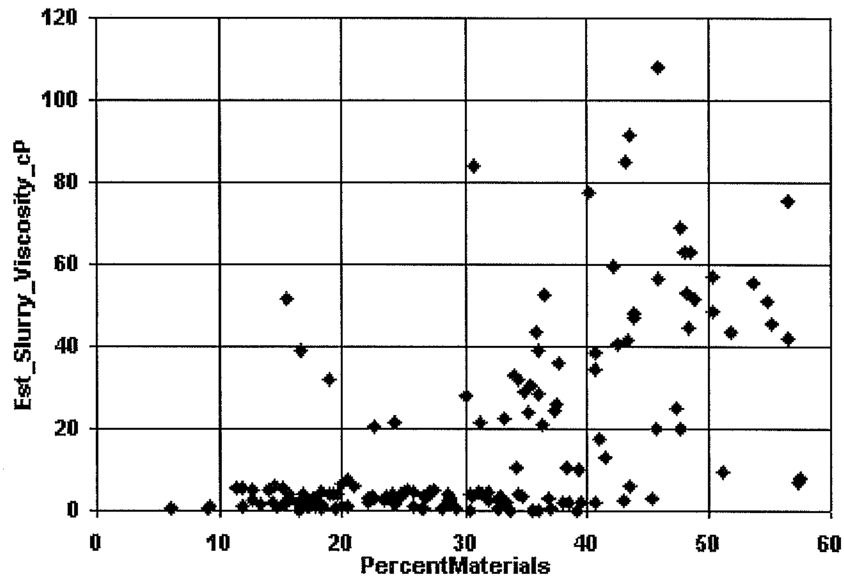


Figure 21: Slurry Viscosity vs. Percent Materials

The viscosities seem to be reasonable. The waste portion of the slurry has little effect on the viscosity until it reaches about 30% by volume; after this, average viscosity increases significantly. Now, it is of interest to see how viscosity affects permeability and injectivity. It is reasonable to expect high viscosity slurry to reduce injectivity. It would also be interesting to see the effect of viscosity on near-well permeability. Figures 22 and 23 show these correlations.

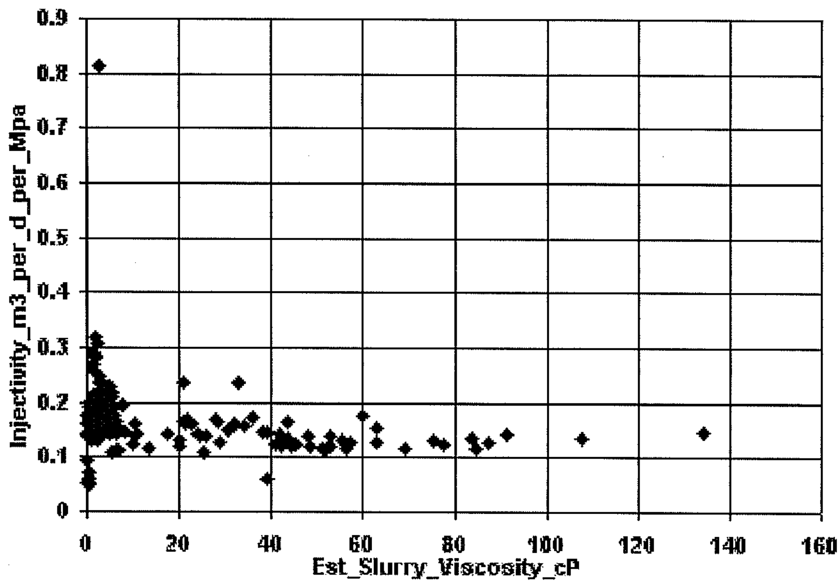


Figure 22: Injectivity vs. Slurry Viscosity

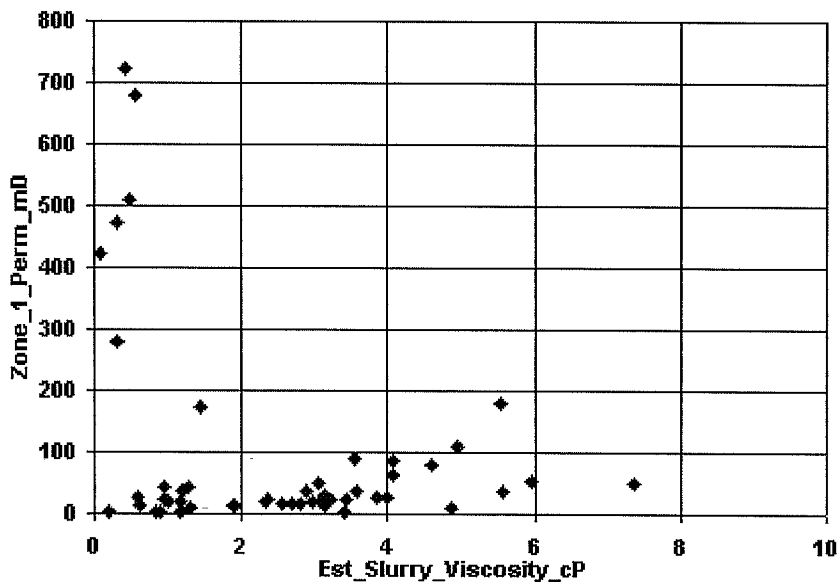


Figure 23: Near-Well Permeability vs. Slurry Viscosity

The expected behaviour is seen in Figure 22; a high viscosity slurry will result in a low injectivity as it is more difficult to inject into the formation, whereas a low viscosity slurry is more easily accepted by the formation. Note that slurries with viscosity greater than 40 cP no longer have the capacity to further reduce the injectivity; it remains relatively constant after this point.

The expected trend is not seen in Figure 23. In fact, the trend seems to be opposite of what is expected. What is likely the case, however, is that on a day to day basis, the two parameters are unrelated, and the above trend is coincidental. Certainly, the continuous addition of slurry into the formation should reduce permeability over time, but on a given day, the slurry viscosity should not radically change formation permeability.

## Effect of SFI Operations on Formation Permeability

At Terralog project TTI6, one of the components of the slurry was a thick, viscous mud-like material, actually a derivative of drilling mud with a small sand and water component. This was an unusual component; normal SFI slurry components are sand, slop (tank bottoms), and water. Mud injection mixed with sand and some slop was the primary make up of the slurry until September 12. Up to this period, there were difficulties in controlling bottom hole pressure, and it was suspected that the mud was starting to plug off the near-well formation. One of the strategies applied to solve the problem was the alternating injection of mud and sand (1-2 hour frequency) in hopes that the sand phase would break up the plugged off zone. The strategy, adopted on September 12 worked, and the bottom hole pressures dropped to acceptable levels. Clearly, the mud was causing a decrease in near-well permeability, and it is of interest to see if the permeabilities obtained from well-test analysis reflect this. Figure 24 shows the change in permeability with time at Terralog project TTI6.

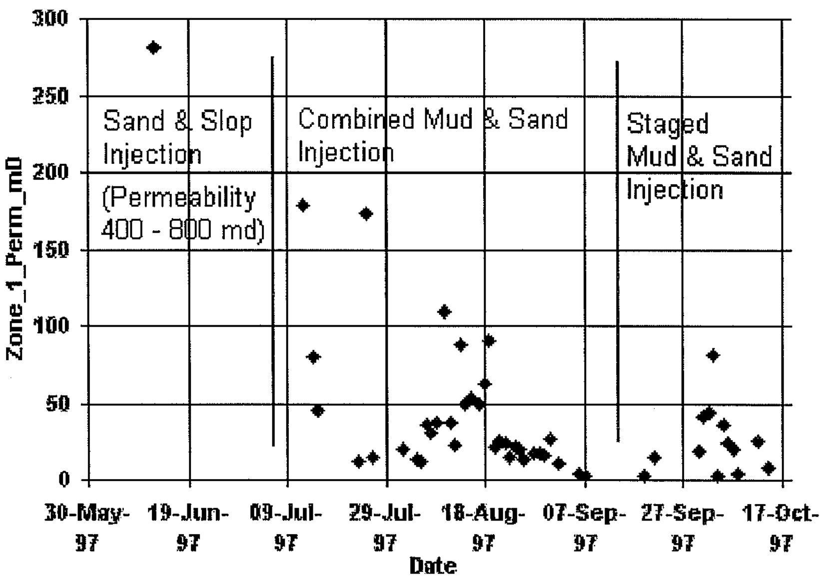


Figure 24: Near-Well Permeability vs. Time for TTI6

Starting on August 20, the permeability dropped significantly, indicating the beginning of plugging problems. The plot shows that the permeability recovered somewhat, shortly after the alternating mud-sand strategy was adopted on September 12. However, the mud apparently did enough damage to limit the permeability to 50 mD or less, whereas nearer to the beginning of the project, it was often 400 mD or more (these points not shown on plot).

## Relationship between Permeability and Waste Material Percentage

Figure 25 is a plot of near wellbore permeability versus waste material percentage in the slurry. It can be seen that permeability occurs in a fairly even band between 1 and 100 md regardless of the waste percentage. Since most of the permeability analyses are from project TTI6, Figures 24 and 25 together tell us that the history of injections has a greater impact on permeability than the composition of slurry on any single day.

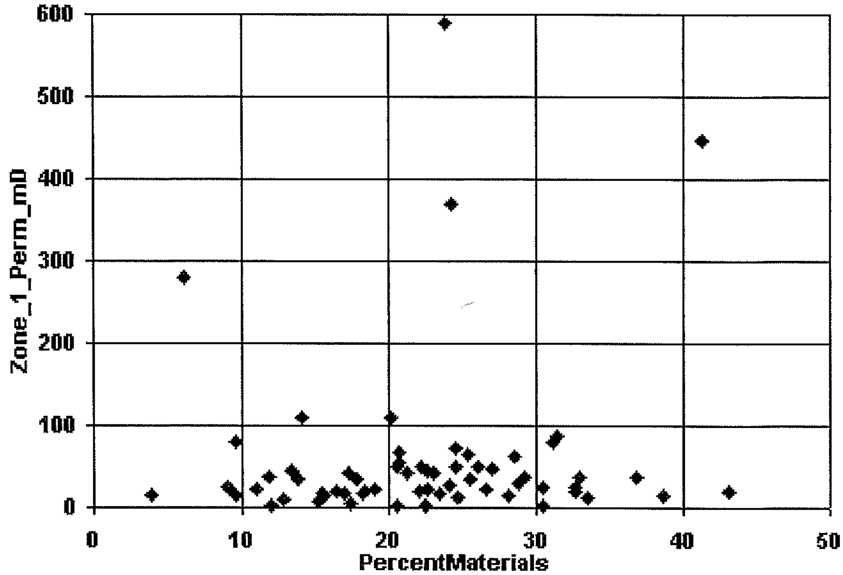


Figure 25: Near Wellbore Permeability vs. Percent Waste Materials

## Relationship between Injectivity and Near Wellbore Permeability

Since injectivity and permeability both measure the ease of fluid flow into a formation, it would be expected that they should correlate well to each other. Unfortunately, when they are plotted against each other the answer is not so clear (Figure 26). Final judgement on this relationship should wait until more permeability data has been entered into the database.

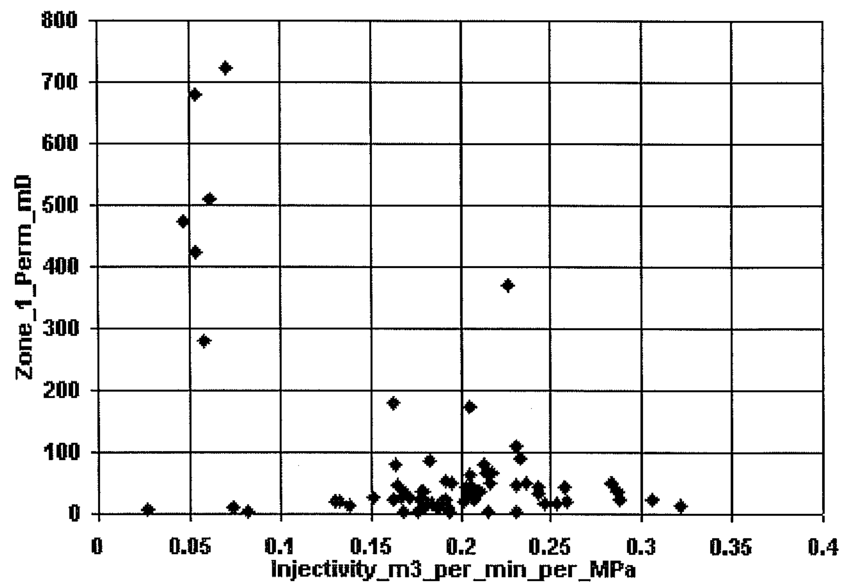


Figure 26: Near Wellbore Permeability vs. Injectivity

## Relationship between Wellbore Storage and Injectivity

It was noted during some preliminary work with TTI1 data that wellbore storage and injectivity had a strong linear relationship (both were low together and high together). If this is true for more projects it may mean that both wellbore storage and injectivity can both be used to indicate whether a hydraulic fracture is open or not. Figure 27 shows that the larger dataset is not so clearly indicative: the large cloud of data makes it difficult to determine if any correlation is present.

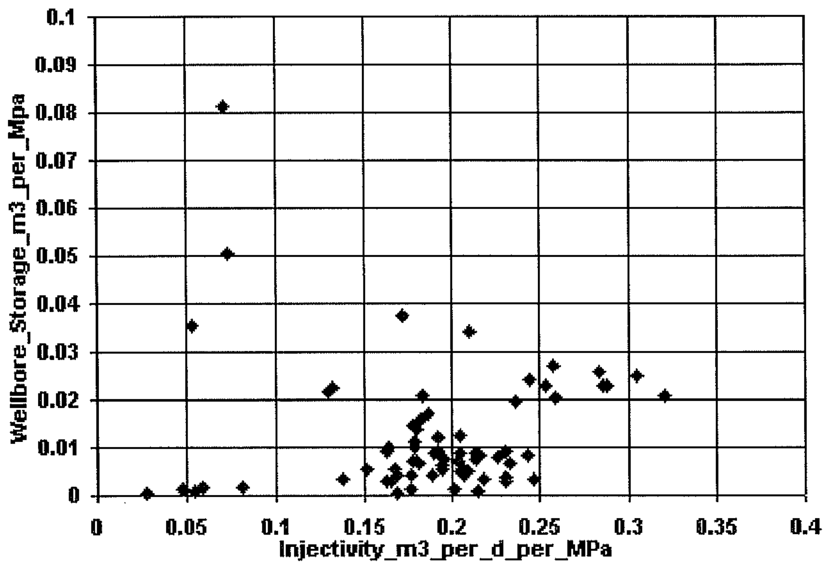


Figure 27: Wellbore Storage vs. Injectivity

## Effect of Injectivity, Viscosity, and Cum. Material on PKNLL Growth Rate

This section deals with PKNLL growth rate and how it is affected by various parameters. It is expected that a high injectivity, which indicates that the formation is accepting fluids well, could result in longer fractures. Also, it is reasonable to suggest that high viscosity fluids will result in longer fractures, because there would be less leak-off of fluid through the fracture walls, and more fluid energy available to extend the fracture. Finally, the growth rate might change over time as material is continuously injected into the formation. These behaviour mechanisms are investigated in Figures 28 through 30.

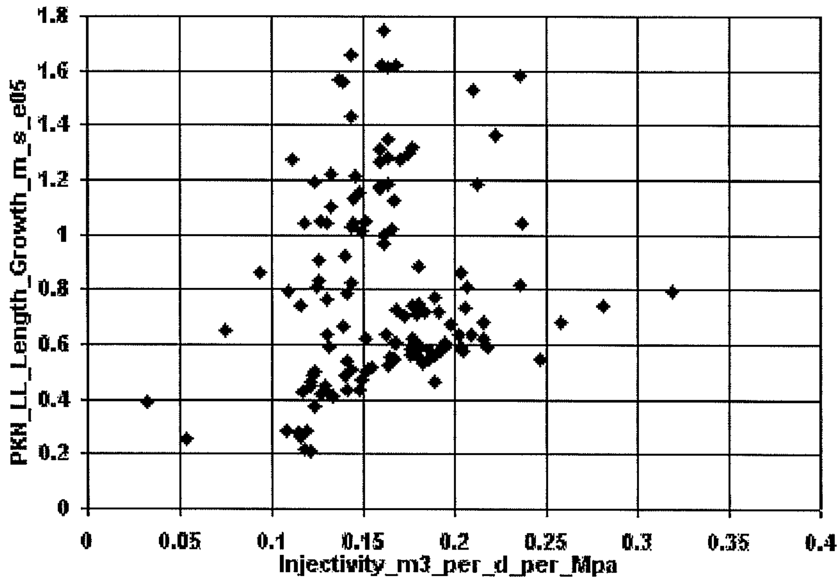


Figure 28: PKN Growth Rate vs. Injectivity

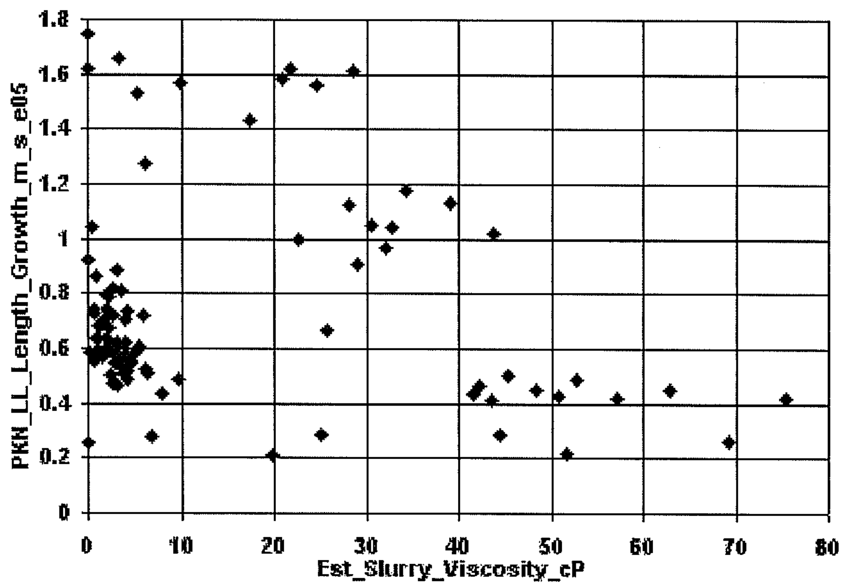


Figure 29: PKN Growth Rate vs. Slurry Viscosity

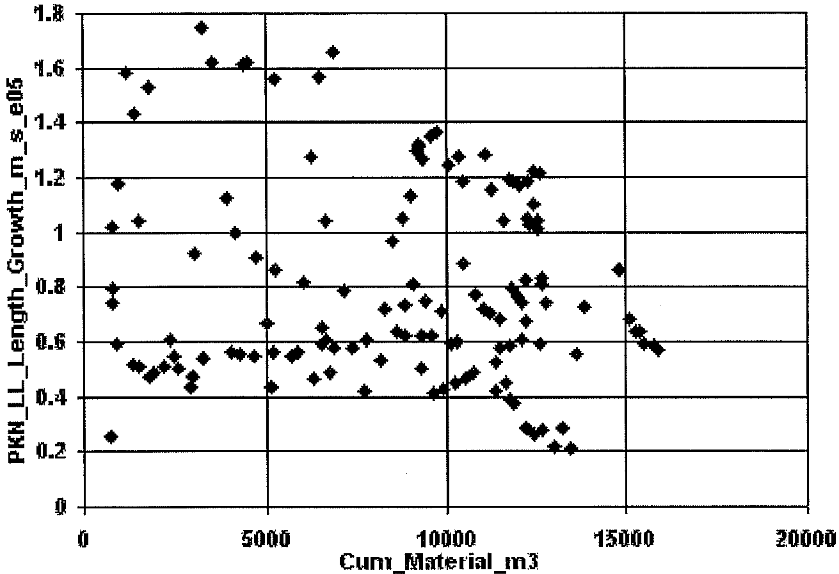


Figure 30: PKN Growth Rate vs. Cumulative Materials Injected

Figure 28 shows that a higher injectivity leads to faster fracture growth. In the case of a high injectivity, the formation is accepting the slurry well, because of the presence of a deeply penetrating fracture. In this sense, it is more prudent to say that a quickly growing fracture results in a high injectivity, rather than the opposite. Figure 29 does not show the anticipated trend. It is evident from the plot that higher viscosity fluids do not generate faster-growing fractures despite the inhibited leak-off. The reason may lie in the effect that viscosity has on injectivity. High viscosity tends to decrease injectivity (as seen previously in Figure 22), and this indirect effect apparently has more influence on fracture development than does restricting fluid leak-off. Figure 30 indicates that fracture growth rate, in general, tends to decrease with the accumulation of slurry material in the formation. The trend is not strong, however, and might not be applicable to every project, as each has associated with them different operating conditions and formation properties.

## Effect of Cum. Material, Growth Rate, and Closure on PKNLL Shear Modulus

The following plots show how PKNLL shear modulus correlates with parameters such as cumulative material, PKNLL growth rate, and closure determined from well test analysis. It is reasonable to suggest that continuously packing waste into the formation would cause the local formation to become stiffer. This would be reflected by a large shear modulus developing over time. Also, it would be interesting to see whether or not a stiff formation results in fractures that are more difficult to extend. Finally, the stiffer the local formation is, the more difficult it should be to open a fracture, i.e., the higher the closure value. These relationships are investigated in Figures 31 through 33.

Figure 31shows that the size (volume) of the waste pod does not influence how stiff the near-well formation becomes. The spike shown in the plot is actually from project TTI3. Wellbore failure was followed shortly after the spike in shear modulus occurred. Whether or not failure was a direct consequence of this is not yet fully understood.

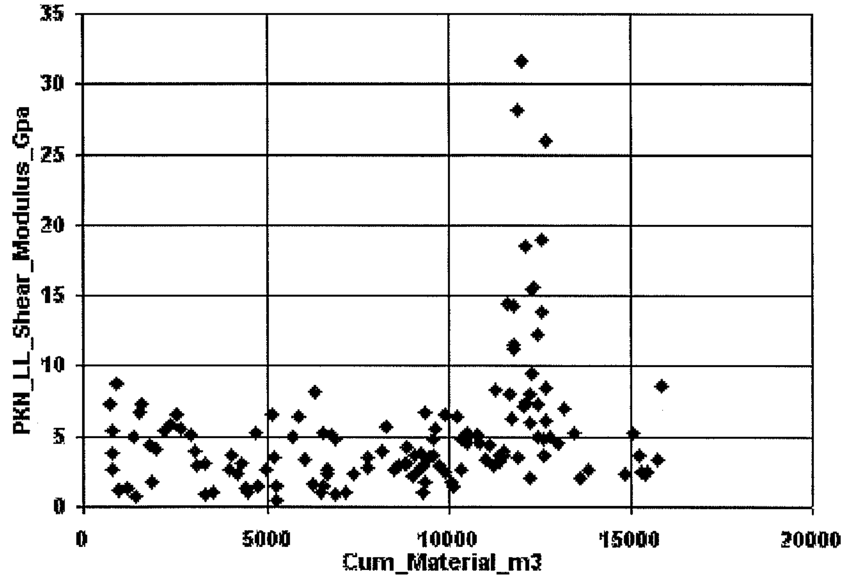


Figure 31: PKN Shear Modulus vs. Cumulative Materials Injected

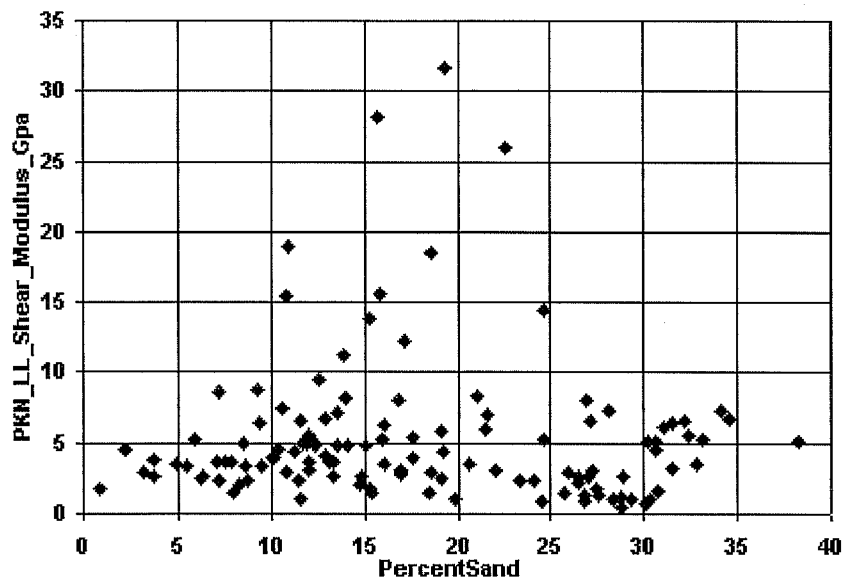


Figure 32: PKN Shear Modulus vs. Percent Sand in Slurry

Figure 32 indicates that formation stiffness is not changed in any particular direction by the sand content of the slurry. Figure 33 does not display the expected trend of increasing shear moduli causing increasing stiffness. Instead, it indicates that an increase in shear modulus results in lower closure values, i.e., fractures that open more easily.

The poor correlations demonstrated in Figures 29 through 33, and the fact that they are somewhat inconsistent with physical expectations, suggests that linear elastic fracture models have only limited usefulness in analyzing high volume injection in soft media. This provides further motivation to investigate alternative modeling and diagnostic techniques in the next phase of this project.

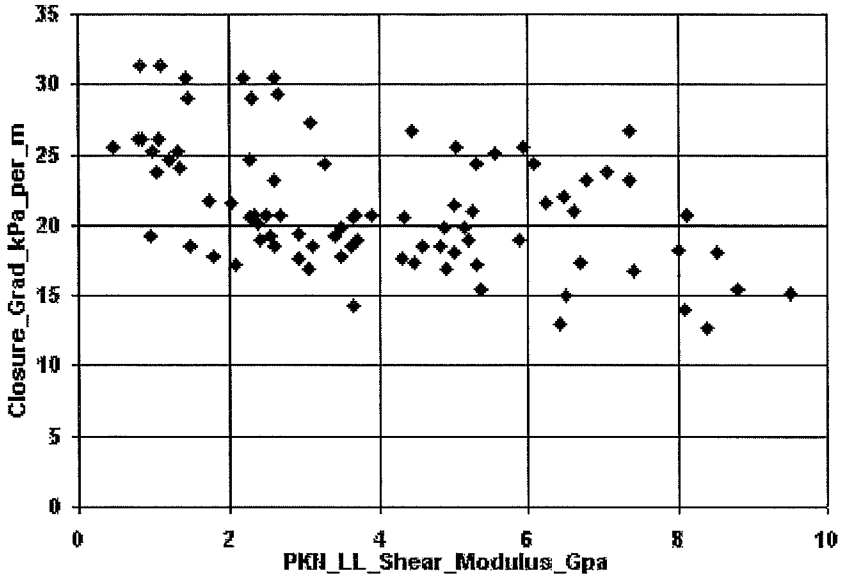


Figure 33: Closure Gradient vs. PKN Shear Modulus

## Summary of Correlations

A summary of the correlations presented in this report is given in Table 7. A "positive" trend indicates a correlation between variables that is increasing, a "negative" trend indicates a correlation between variables that is decreasing, "no trend" indicates that the two variables are independent of each other, and "uncertain" indicates that a judgement cannot be made given the available data at this time.

The following general observations can be made based on the correlations discussed in this report:

- 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.

Figures 9 and 10 show that there is a weak correlation between the cumulative volume of slurry and sand injected into a formation and the closure pressure (formation stress). Figure 18 shows that the mud content of the slurry has no direct impact on injectivity. However, a boundary appears to be present in Figure 17 showing that high waste content in the slurry and high injectivity cannot occur together.

Table 7. Summary of Correlations Investigated

| Figure | Relationship | Observed Trends |
|---|---|---|
| 8 | Closure gradient vs cumulative materials | Slight positive |
| 9 | Closure gradient vs cumulative sand | Slight positive |
| 10 | Closure gradient vs cumulative mud | No trend |
| 11 | Closure gradient vs percent materials | Slight positive |
| 12 | Closure gradient vs percent materials for TTI6 | No trend |
| 13 | Closure gradient vs percent materials for TTI7 | No trend |
| 14 | Closure gradient vs percent mud | Uncertain |
| 15 | Injectivity vs cumulative material volume | No trend |
| 16 | Injectivity vs percent materials | Negative envelope |
| 17 | Injectivity vs percent mud | No trend |
| 18 | Injectivity vs percent sand | Negative envelope |
| 19 | Injectivity vs percent slop | No trend |
| 20 | Slurry viscosity vs percent materials | Uncertain |
| 21 | Injectivity vs slurry viscosity | Negative envelope |
| 22 | Near well permeability vs slurry viscosity | Uncertain |
| 23 | Near well permeability vs time for project TTI6 | Related to sand-mud strategy |
| 24 | Near well permeability vs percent materials | No trend |
| 25 | Near well permeability vs injectivity | Uncertain |
| 26 | Wellbore storage vs injectivity | Positive (?) |
| 27 | PKN growth rate vs injectivity | Positive |
| 28 | PKN growth rate vs slurry viscosity | Slight negative |
| 29 | PKN growth rate vs cumulative materials | Uncertain |
| 30 | PKN shear modulus vs cumulative materials | No trend |
| 31 | PKN shear modulus vs percent sand | No trend |
| 32 | Closure gradient vs PKN shear modulus | Negative |

Figure 21 shows that percent materials increases slurry viscosity significantly, once the slurry is 30% by volume solids or greater. Figure 22 indicates that high viscosity slurry reduces the injectivity, but cannot lower it further after reaching 40 cP and greater. Figure 23 shows that on a given day of injection, the slurry viscosity has no effect on local formation permeability. It is suggested here, however, that the continual injection of high viscosity slurry will degrade the permeability over time. In fact, Figure 24 is consistent with this theory. At Terralog project TTI6, the continuous injection of the high viscosity mud slowly decreased the permeability over time. When the operating strategy was changed to overcome this loss (alternating sand and mud injections), the permeability recovered somewhat as the sand broke up the mud surrounding the borehole. This is seen clearly in the figure.

Figure 28 shows that greater fracture penetration into the formation tends to increase injectivity, while Figure 29 indicates that high slurry viscosity decreases fracture penetration. The latter observation can be explained by proposing that the reduction in injectivity by a viscous fluid will suppress fracture development, more than reduction in leak-off by the viscous fluid will stimulate it. Figure 30 indicates that the fracture growth rate will decline over time as slurry is injected, although the trend is not strong. Changes in growth rate will likely vary from project to project.

Figure 31 shows that calculated PKNLL shear modulus is not affected by cumulative materials injected. Figure 33 shows that, strangely, a stiff formation will have a lower closure pressure than a soft formation.

# CONCLUSIONS

A comprehensive database of waste injection operations has been assembled and evaluated. This database can now be used by operators to evaluate potential influences of operational changes on injection and formation response in order to optimize operations. It also provides some insight into large scale slurry injection in high porosity media. Some of the observed trends are consistent with expectations; however, some are not. For example, closure gradient does increase with cumulative materials over time, but is not particularly sensitive to daily changes in slurry composition. Injectivity appears to be more sensitive to sand concentration then to slop concentration. 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. In the current work, for example, we have modeled fracture propagation with a traditional Perkins-Kern-Nordgren analytic approach. With this model neither fracture growth nor shear modulus appear to correlate well with cumulative waste injection or slurry concentration. Closure gradient seems to actually decrease with shear modulus. These observations are not consistent with physical expectations, suggesting that linear elastic fracture models cannot adequately explain the behavior of large-scale waste injection in very soft, porous media. Improved model and diagnostic techniques are required and will be the focus of the next phase of investigation in this project.

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