IADC/SPE 59119

Environmental Management, Cost Management, and Asset Management for High-Volume Oil Field Waste Injection Projects

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Abstract

Ongoing exploration and production activity, combined with increased regulatory requirements, are increasing the volume and costs associated with disposal of oil field wastes, including produced oily sands and tank bottoms, drilling mud and cuttings, crude contaminated surface soils, and naturally occurring radioactive materials (NORM). A cost-effective and environmentally sound disposal option is to re-inject waste material into the subsurface into non-productive and/or depleted zones under controlled fracture conditions.

High volume injection projects often involve annual injection exceeding several hundred thousand barrels of waste for several years. The critical engineering management goals for such operations are to:

1) Maintain waste containment in the target formation (environmental management);

2) Sustain long-term injectivity with minimum equipment repairs and well workovers (cost management); and

3) Maximize formation storage capacity and well life (asset management).

More than five years experience operating, analyzing, and managing large volume waste injection projects in the US and Canada has enabled Terralog to develop specific design, monitoring, and operating strategies to achieve these goals. Target injection formations must be selected with appropriate overlying barrier and absorption zones. Offset well completions must be carefully examined. The injection well completion should be appropriately designed to take into account high formation stresses and potential movement. Continuous monitoring and analysis must be performed to evaluate varying formation properties, injectivity, stress conditions, and fracture orientation and height growth. Finally, through continuous monitoring and analysis of formation response, injection parameters and properties (such as solids concentration, density, flow rate, shut-in time, etc...) can be adjusted in order to maintain containment, reduce operating costs, and optimize long-term injectivity.

Introduction

Deep well injection of exploration and production wastes provides significant environmental and economic advantages over traditional landfill disposal for oilfield wastes. These include:

1. Improved protection for surface and groundwater;
2. Little impairment of surface land use;
3. Reduced long-term liability risk to waste generator;
4. Reduced transportation and disposal costs.

The use of deep well injection, therefore, has expanded significantly in recent years[1-5]. For example, large-scale E&P waste injection operations have been ongoing in Canada (Srinivasan et al, 1997), Alaska (Schmidt et al, 1998), California (Hainey et al, 1997), and Louisiana (Baker et al, 1999).

Large-volume injection, which may involve several hundred thousand barrels or more of waste material injected annually over several years, must be performed in relatively high porosity sands at fracture conditions. In spite of increased use of this technology, however, the mechanics of massive slurry injection into soft formations remain poorly understood, and there are few guidelines available to industry to optimize and manage this process. In some instances injection zones have filled or pressurized prematurely; well casings have been sheared by excessive formation movement; and in extreme instances waste material has broken out of zone and to the surface.

To help improve industry practices, Terralog Technologies is currently engaged in a two-year research project, supported in part by the Canadian and US Departments of Energy, to develop and test improved fracture injection disposal techniques and diagnostic tools. This effort involves extensive field data assembly and analysis, model development, and field verification.

Our experiences to date indicate that large volume and long term injection projects require optimum strategies tailored to specific waste materials and target formation properties, combined with appropriate and continuous monitoring. In this paper we first present field observaations and data from several large-scale oilfield waste injection operations in the United States and Canada. These have involved injection of varying waste streams into a variety of formations, all with extensive monitoring and diagnostic data. We discuss formation response and operational issues unique to high volume injection, supported by specific field examples. Finally we discuss design and operating strategies to manage high volume oilfield waste injection projects.

Observations From Large-Volume Operations

In typical large-volume waste injection operations, 5000 barrels or more per day of slurry is injected in daily episodes, lasting from 6 to 10 hours, at surface pressures from 1000 to 3000 psi. This requires high capacity pumps (10-20 bbls/min) and high capacity slurrification equipment to maintain process and flow rates. Figure 1 presents a photo of sample injection equipment used by Terralog to process and inject produced sand and water slurries. Figure 2 presents daily injection history for mixtures of various waste streams at another project. About 300,000 bbls (50,000 m^3) of sand, tank bottoms, drilling mud, and water slurry was injected during the 3 month period shown, with continuous monitoring of formation response.

Figure 3 presents formation pressure response during injection of crude contaminated surface soil (Srinivasan et al, 1998), showing excellent pressure decline to initial formation pressure at the end of each daily injection episode. This is the type of ideal pressure response desired to maintain long-term injectivity and well life.

Terralog has compiled and analyzed detailed injection data and formation response from eight projects in the US and Canada, comprising a total of more than 500 carefully monitored injection episodes. The measured data consists of slurry and material volumes, pumping rates, slurry content, concentration, and density, continuous recordings of wellhead and bottom-hole pressures during both injection and shut-in, and other relevant information. Some of these projects were also monitored with surface tiltmeter arrays to investigate fracture orientation changes.

The field observations have been assembled into a Microsoft ACCESS database, and graphical tools have been developed to investigate potential correlations between different operating parameters and formation response, with filtering available on a third parameter. For example, Figure 4 presents a summary of injectivity plotted against percent sand content of the slurry, filtered to display those episodes in which more than 5000 m^3 of waste material had already been injected into the formation.

From reviewing and analyzing such data from our own projects during the past five years, and from reviewing published information on other large-scale injection projects, we can make the following observations regarding high-volume waste injection operations:

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 (see Figure 5 for example);
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.

Design Approach

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 strategies.

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, sand formation which is laterally extensive so as to dissipate pressures quickly after each injection episode (see Figure 3). Multiple shale and sand zones to act as alternating barriers and flow sinks to inhibit upward fracture growth and fluid migration should overlie the injection formation. Experience has shown that for repeated, high-volume injection above fracture pressure, a simple 100ft-shale barrier with an assumed stress contrast will not assure containment. Furthermore, the process must be continuously monitored with tools such as temperature and tracer logs, and analysis of daily shut-in pressures and periodic fracture step-rate tests.

Special care must be taken to evaluate completions in offset wells up to 2000ft away or more, and to select appropriate injection well locations. Nearly all reported containment problems associated with waste injection projects have involved lateral subsurface communication to an adjacent well that was not properly cemented across the injection interval or overlying formations (see for example, Schmidt et al, 1999).

To optimize operations and reduce costs, it is necessary to design/select the surface equipment, well completion, and target formation as a system, recognizing their interaction for the given waste stream and volume. For example, if one has a high permeability target formation and high rate injection equipment available, one can eliminate the need for grinding equipment and time, which often contributes a disproportionate share to the overall process cost. If one is limited by the availability of pumping equipment in a particular part of the world, it may be necessary to select a tighter injection zone to achieve fracture or parting pressure at lower rates. Injection periods and rates can also be designed to reduce other cost factors, such as equipment maintenance costs or labor costs.

Finally, as in any quality management process, performance measures should be continuously evaluated in order to modify and adjust the design operating strategy to achieve the program goals.

Operations Management

Once a system design is in place incorporating the appropriate injection formation, the well and completion, and the surface slurry processing and injection equipment, it is still necessary to actively manage and adjust the operations. The key to operations management for high-volume waste injection projects is appropriate monitoring and analysis.

Monitoring. Monitoring and analysis for high volume injection projects should include the following:

1. Continuous recording of injectate properties (constituents, concentration, density, etc…)
2. Continuous recording of bottom-hole pressure during injection and during extended shut-in periods;
3. Analysis of formation response and fracture behavior during injection and fall-off;
4. Periodic temperature and tracer logs at injection well;
5. Periodic fracture step-rate tests at injection well;
6. Periodic temperature and pressure monitoring at offset observation wells when available; and
7. When practical, fracture growth monitoring with tiltmeter arrays, microseismic arrays, or other techniques.

Detailed monitoring and analysis is necessary to verify containment, to satisfy regulatory requirements, and also to optimize operations.

Data Collection and Review. An ideal way to collect, analyze, and use field observations to optimize operations is to collect and format information with an appropriate database structure and associated query and analysis tools. There are several commercial products available on the market, some of which can be easily customized. For example, waste injection project data collected and analyzed by Terralog is incorporated into a Microsoft ACCESS database which includes a Daily Summary Table and a high sample frequency Pressure and Rate Table.

The Daily Summary Table provides a "snapshot" of information for each waste injection episode, summarizing both directly measured parameters such as volumes of slurry components, average injection rates and pressures, and interpreted or calculated parameters such as injectivity, closure stress, near-wellbore permeability, and far-field permeability. Table 1 presents a summary of measured and interpreted values contained in such a Daily Summary Table, and Table 2 presents a sample portion of the Table for a particular project. Database query and reporting tools can then be used to review this information, such as the correlation plotter illustrated in Figure 4. Information such as this for a specific project, or a compilation of information from multiple past projects, can then be used to anticipate how changes in operating parameters will influence formation response.

The Pressure and Rate Table contains the raw data which is monitored continuously (such as injection rate, pressure, density) and analyzed to provide information for the Daily Summary Table. Query and analysis tools can also be developed and used to facilitate this process. For example, Figure 5 presents a graphical pressure and rate plotting tool that can be used to retrieve and display data from a single injection episode or multiple episodes from the database, and if desired, export this information for well test analysis or fracture stimulation analysis programs.

Data Analysis. Pressure data during injection is analyzed by statistically curve fitting theoretical pressure response with field observations. Parameters obtained with this procedure include estimated fracture length growth and formation closure stress. Pressure data during fall off is analyzed using conventional radial/linear flow well test analysis. Parameters obtained with these tools include near-well permeability, far-field permeability, fracture length, instantaneous shut-in pressure, and closure stress. While it is true that conventional pressure analysis and fracture models[7,8] do not adequately describe non-linear fracture and dilation behavior in soft formations, they are still useful to qualitatively evaluate formation response changes induced by varying operating conditions.

For example, comparison of log-log plots of net pressure and pressure derivative vs. time for multiple injection episodes is useful to distinguish changing flow regimes that occur after shut-in and changes over time in effective permeability and skin. Figure 6 presents an example of a log-log plot of pressure behavior after one waste injection episode, showing the wellbore storage period, the transition phase, and the radial flow period. A large wellbore storage coefficient indicates an effective wellbore system open to the fracture, whereas a small storage coefficient could indicate perforation plugging or other flow restriction. During extended shut-in periods the radius of investigation may extend past a large waste pod and "see" the virgin reservoir. If there is significant contrast in permeability between the virgin reservoir and the waste pod this can sometimes be noted in the pressure derivative behavior.

Well test analysis can also be used to evaluate changes in formation stress and closure pressure over time at injection projects. This occurs when large amounts of solids pack the fracture and dilation zone, increasing the minimum horizontal stress. For example, Figure 7 presents a plot of pressure vs. the square root of time after waste injection shut-in. An intermediate linear flow regime indicates fracture flow, and the end of this behavior indicates closure stress.

By repeating such analyses, it is possible to evaluate changes in formation stress over time. Figure 11 presents a summary of closure stress changes with increasing waste material injection. Increasing formation stress can often be correlated to variations in fracture orientation, and if uncorrected, can also lead to injectivity decline or to potential formation movement and casing damage.

Modifying Operations. With a sound monitoring and analysis system in place to interpret field observations, and with insight gained from past operations, it is then possible to modify operating parameters appropriately to avoid problems or to reduce operational costs. For example, two operational goals often include maintaining high injectivity but avoiding long-term increases in shut-in and closure pressures (i.e., allowing the formation pressure and stress to relax to initial conditions). Total injection costs can be reduced, for example, by increasing waste solids concentration in the injectate, assuming the same rate can be sustained and there is no impairment to the formation and well. Operational data such as that illustrated in Figure 4 or Figure 8 can indicate what impact this might have injectivity or closure stress.

Figure 9 presents one such example in which operating parameters were adjusted in the field to increase injectivity while at the same time avoiding increases in shut-in pressure. Injectivity is shown on the vertical axis; it is highest when only water is injected and lowest when perforations were partially blocked. Intermediate injectivity could be achieved with mud and mixed mud-sand injection, but at the cost of increased shut-in pressure shown on the horizontal axis. Switching to pure sand and water injection interspersed with alternating mud and sand stages, however, allowed equivalent injectivity to be achieved while at the same time reducing shut-in pressure.

Conclusions and Discussion

Extensive field experience and critical review and analysis of field observations provide insight to effectively manage high-volume oil field waste injection projects. The mechanics of massive solids injection into high porosity soft sand is fundamentally different than typical fracture stimulation practice in low permeability, hard rock. It is necessary to apply a systems approach to design and operate such projects, taking into account the surface equipment capabilities and costs, the wellbore and completion, and the formation properties. While past experience provides useful guidelines, it is critically important to continuously monitor and analyze operational data, and to adjust operating parameters accordingly to ensure long-term environmental safety, to reduce operating costs, and to extend formation capacity and well life.

Acknowledgements

Terralog Technologies Inc., The Alberta Oil Sands Research Authority, and the US Department of Energy (contract DE-AC26-99BC15222) have provided funding for some of the research presented in this paper. We gratefully acknowledge important technical contributions by Mr. Chris Flaman and Mr. John Barrera, and valuable oversight by Mr. Bill Good of AOSTRA and Mr. John Ford of the US DOE.

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SI Metric Conversion Factors

cp x1.0*	E–03 = Pa ·s
ft x 3.048*	E–01 = m
ft^2 x 9.290 304*	E–02 = m^2
ft^3 x 2.831 685	E–02 = m^3
in. x 2.54*	E+00 = cm
lbf x 4.448 222	E+00 = N
md x 9.869 233	E–04 + μm^2
psi x 6.894 757	E+00 = kPa

* Conversion factor is exact.

Table 1:Daily Summary Table Parameters

Parameter Description	Parameter Description
General Project Information:	*Dependent Values:*
Project Code	Injectivity
Project Name	Estimated Slurry Viscosity
Well Name	Average Injection BHP Gradient
Formation Name	Minimum Shut-in Pressure Gradient
Perforation Top (tvd)	% Total Materials in Slurry
Perforation Bottom (tvd)	% Sand
Formation Top (tvd)	% Mud
Formation Bottom (tvd)	% Slop
Date	% Soil/Pit Material
Operational Status	
Operational Status Code	*Interpreted Values:*
Monitoring Status	Instantaneous Shut-in Pressure
Monitoring Status Code	Closure Bottomhole Pressure
Shut-in Analysis(type of analysis performed)	Closure Bottomhole Pressure Gradient
Flow Regime	Permeability (Zone 1)
Shut-in Analysis Confidence	Skin (Zone 1)
Injection Behavior	Permeability (Zone 2)
	Skin (Zone 2)
Independent Measurements:	Wellbore Storage
Pumping Time	P* (Estimated Reservoir Pressure)
Shut-in Time	Fracture ½ length
Water Volume	PKN_LL Closure (kPa)
Total Materials Volume	PKN_LL Length Growth
Sand	PKN_LL Shear Modulus
Drilling Mud	PKN_LL r^2 Value
Slop	PKN_LL % Volume Difference
Soil/Pit Material	PKN Injection Time (hrs)
Total Slurry Volume	GDK Closure
Cumulative Water Volume	GDK R^2
Cumulative Materials Volume	GDK Length Growth
Cumulative Sand Volume	GDK Shear Modulus
Cumulative Slop Volume	GDK Injection Time
Cumulative Mud Volume	
Cumulative Soil/Pit Material Volume	
Cumulative Slurry Volume	
Average Injection Rate	
Average Slurry Density	
Average Injection Bottomhole Pressure	
Average Injection Wellhead Pressure	
Minimum Shut-in Pressure	

Table 2: Sample 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

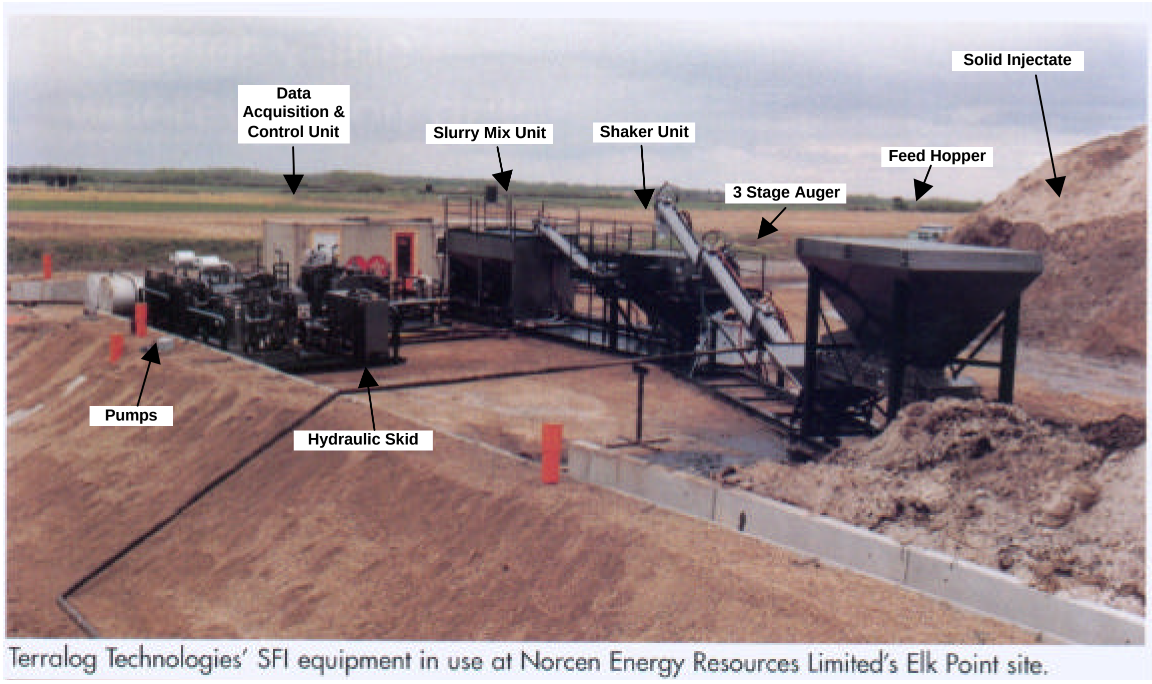


Figure 1. Photo of slurry processing and injection equipment

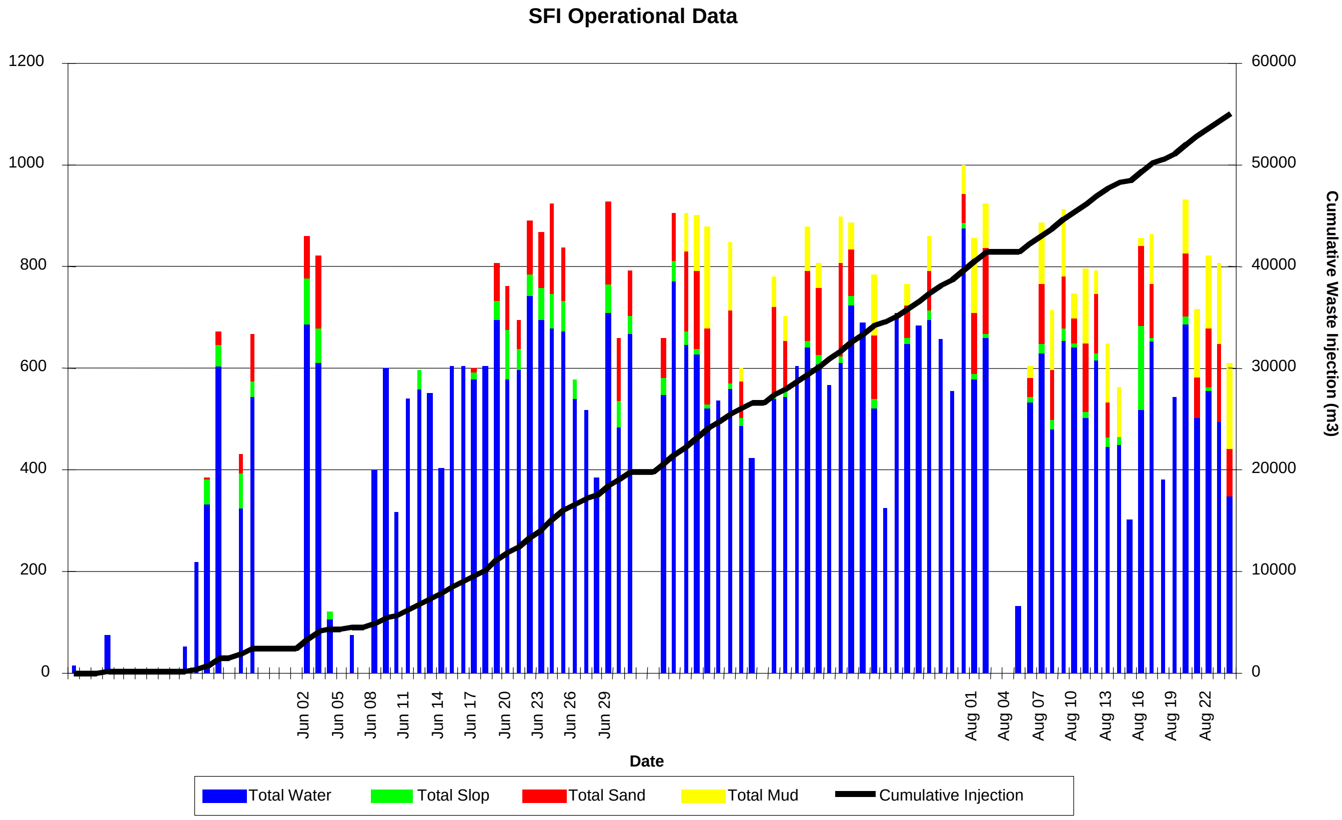


Figure 2. Operations summary for a large volume waste injection project

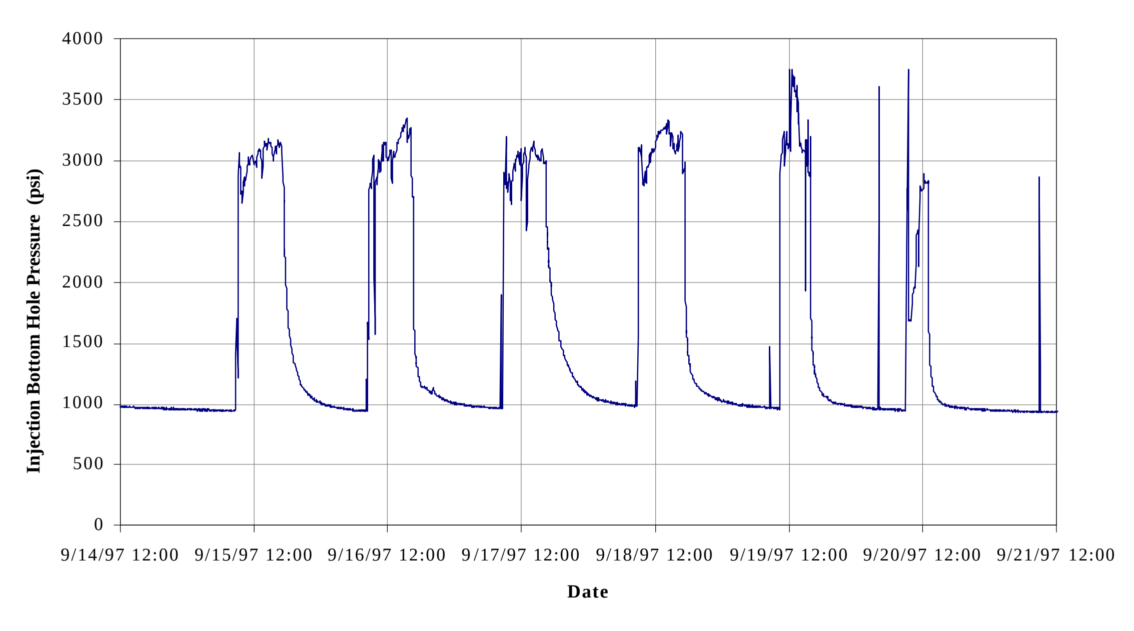


Figure 3. Sample waste injection pressure history over a 1-week period showing excellent formation pressure recovery

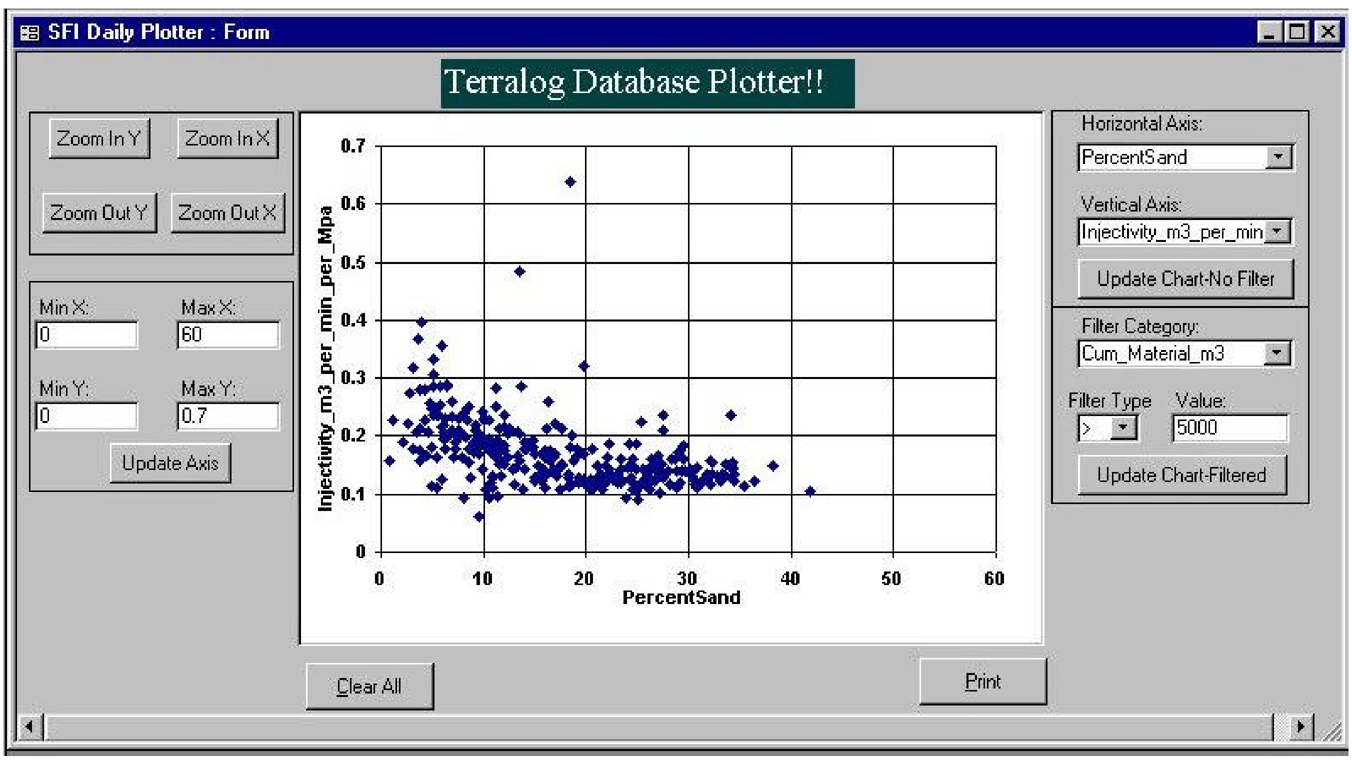
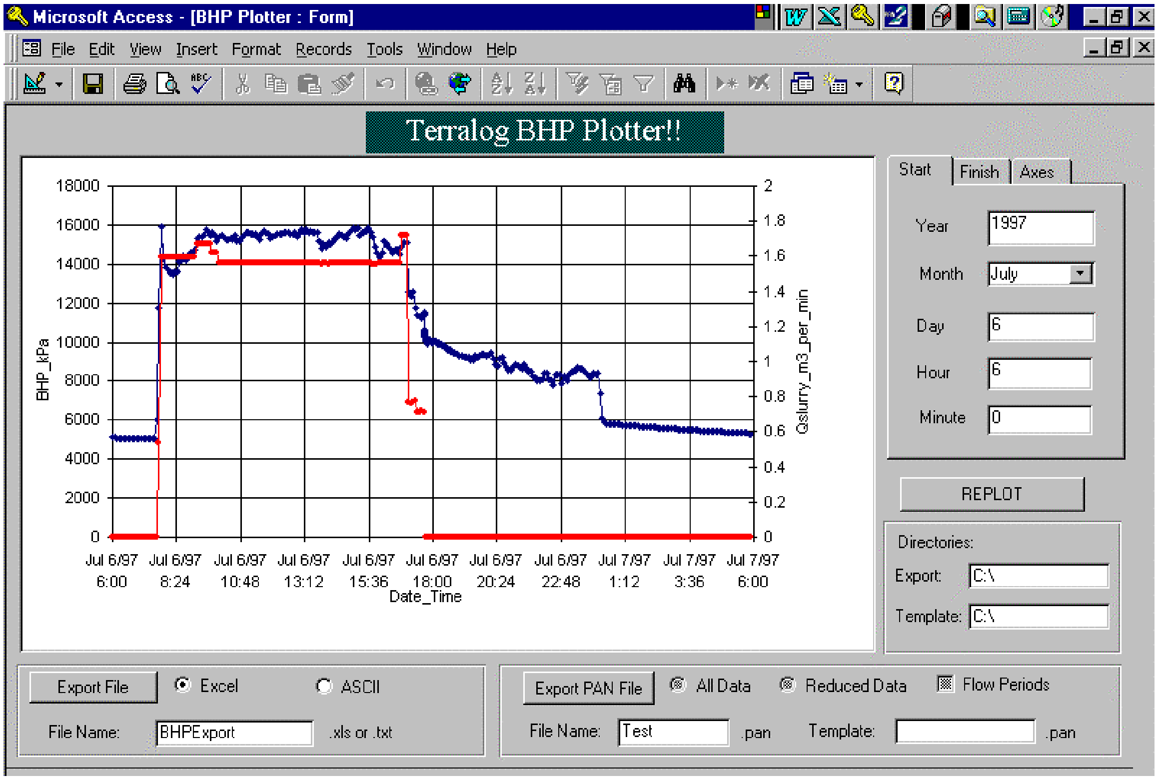


Figure 4. Injectivity vs percent sand content in slurry for projects in which more than 5000m^3 of waste has been injected. Analysis of operating parameters and formation response data from multiple projects can often help optimize new operations.



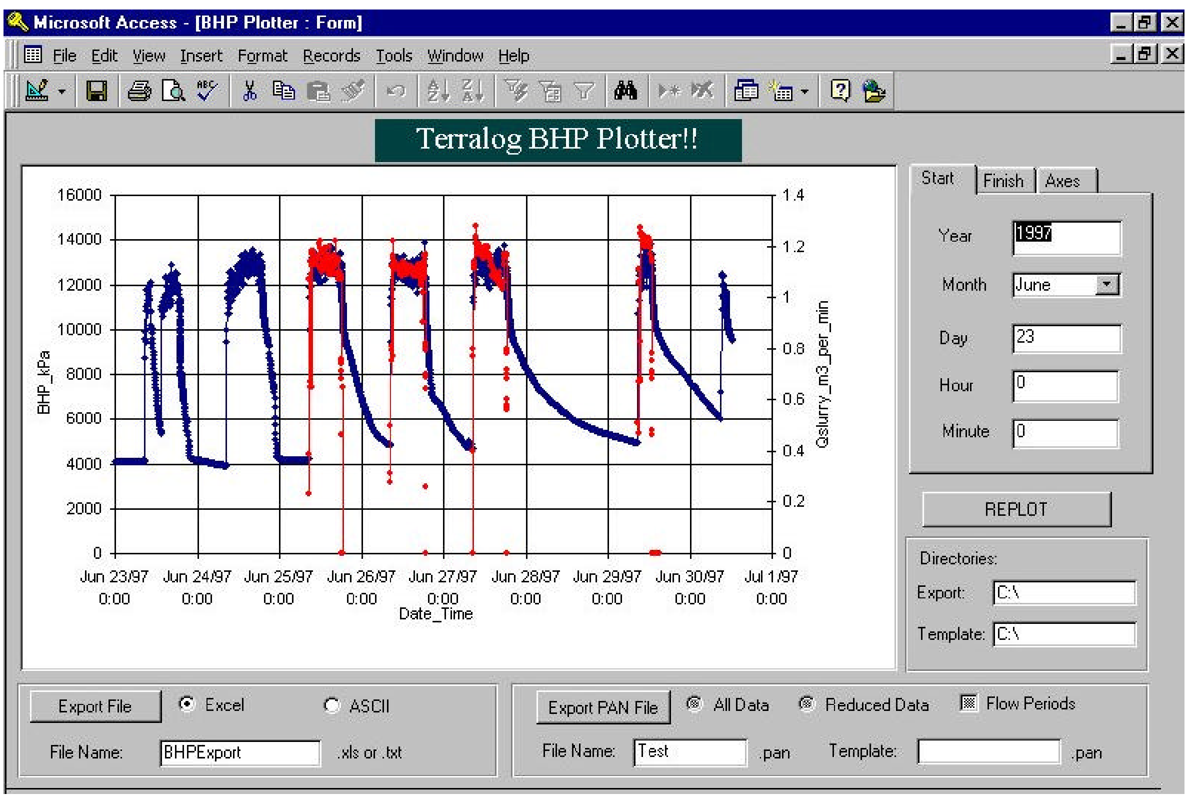


Figure 5. Graphical database query tools allow efficient review and analysis of waste injection operating data for single injection episodes (upper illustration) or multiple injection episodes (lower illustration). Data can then be exported to other analysis packages.

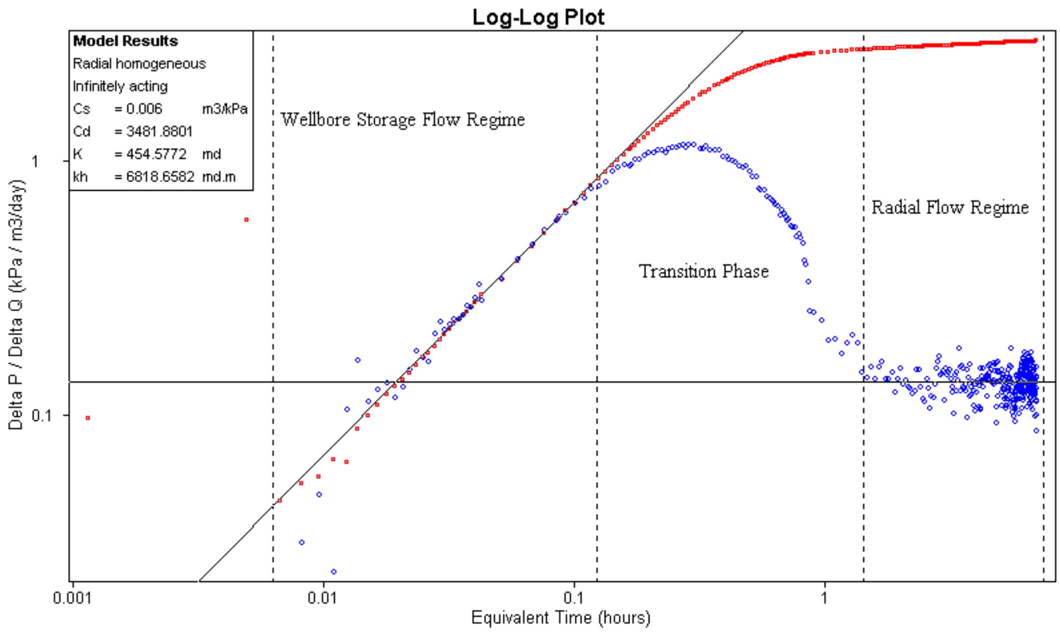


Figure 6: Example of a log-log plot, showing 3 different flow regimes

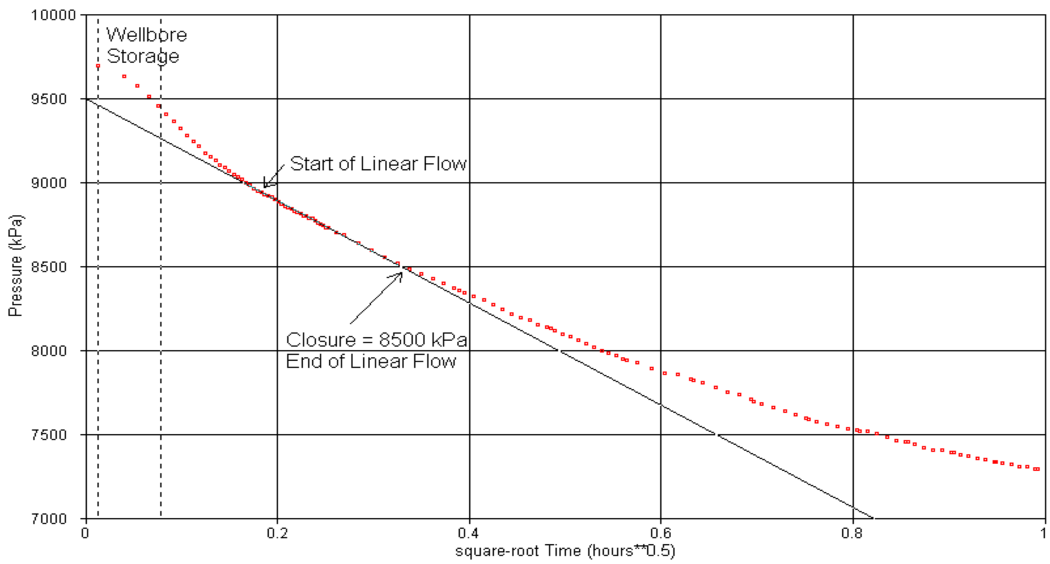


Figure 7: Determining closure stress from well test analysis

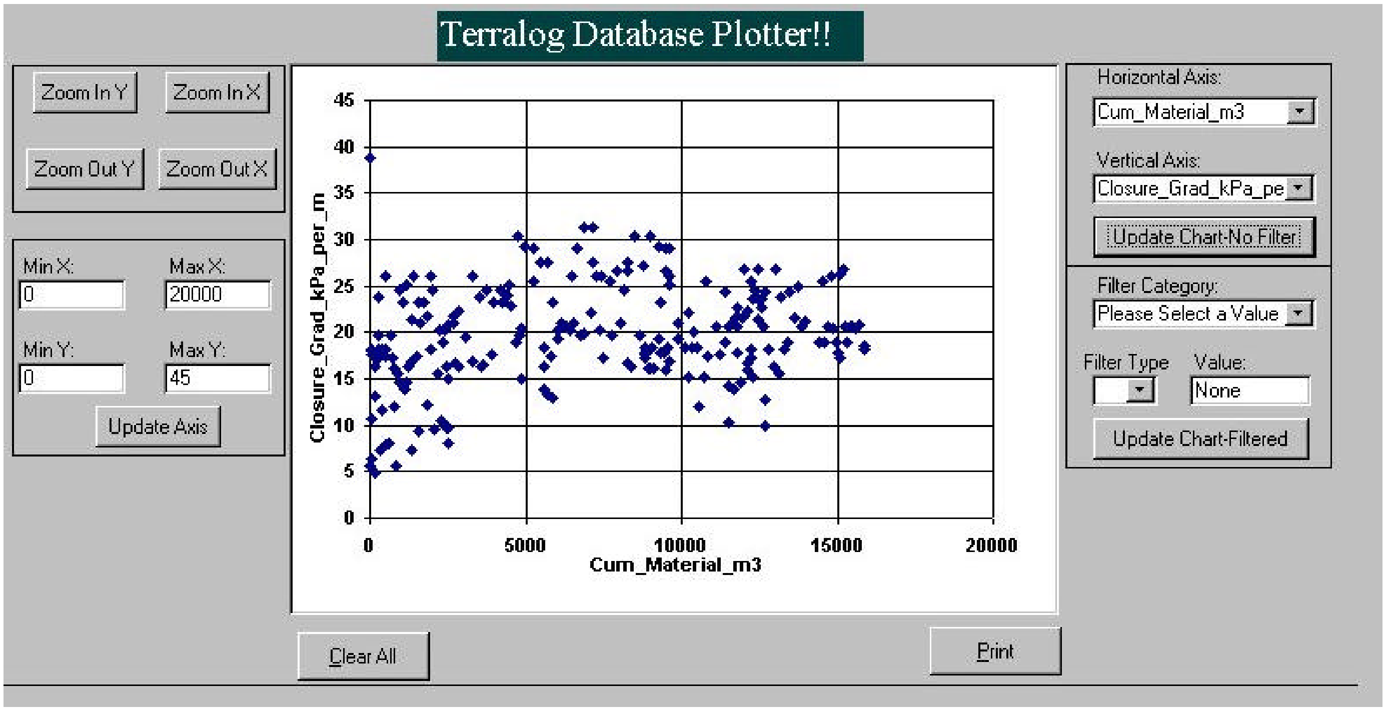


Figure 8: For many formations, closure stress tends to increase with cumulative waste material injection

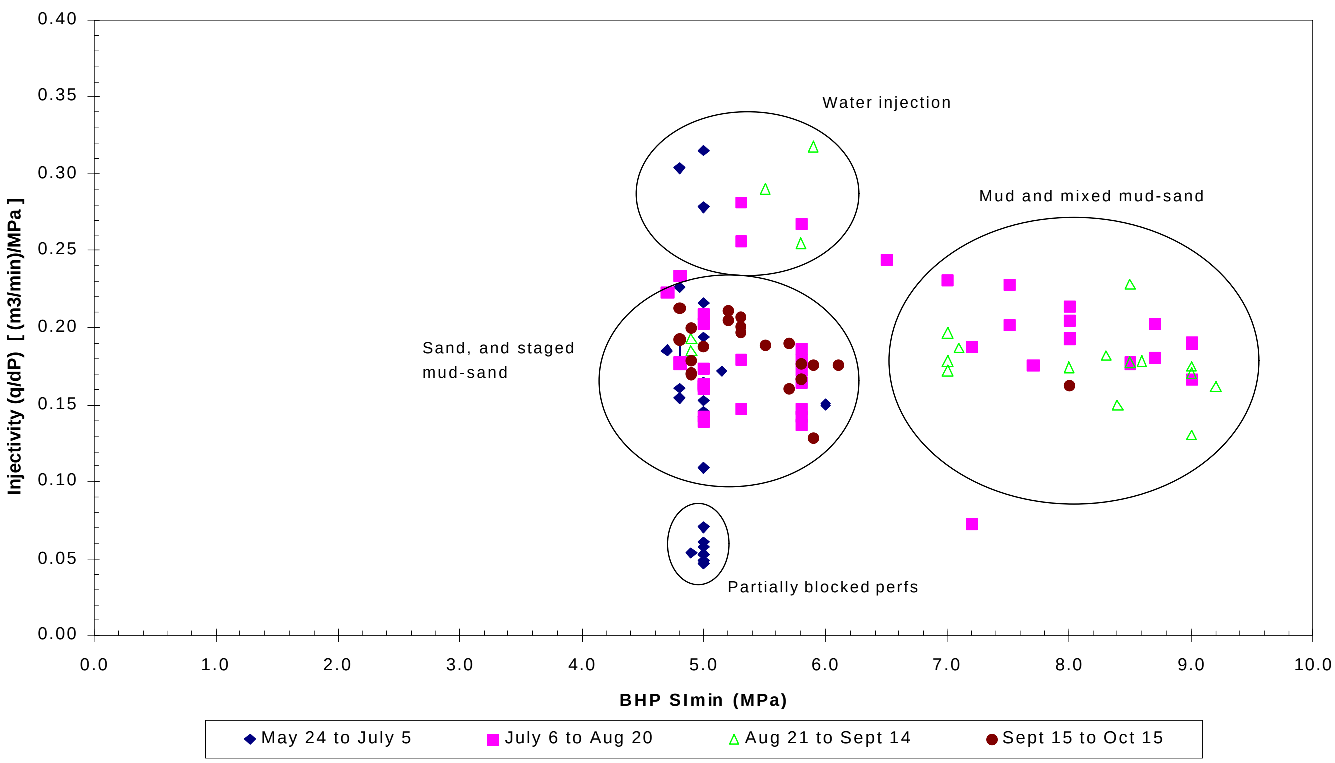


Figure 9: Injection scheme can be modified to maintain injectivity and improve pressure decline after shut-in