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Achieving Zero Discharge E&P Operations using Deep Well Disposal

E. MARIKA
Terralog Technologies Inc.

F. URIANSRUD
StatoilHydro ASA

R. BILAK
Terralog Technologies Inc.

M.B. DUSSEAULT
University of Waterloo

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Abstract

Many innovations in the past five years have significantly improved the applicability, flexibility, and economics of deep well disposal processes for disposal of waste streams from Exploration and Production (E&P) operations. Deep well disposal processes such as Slurry Fracture Injection (SFI^{TM}) and Cuttings Re-Injection (CRI) have proven to be economically viable for heavy oil production operations and offshore drilling operations. When properly implemented, these technologies allow E&P operations to achieve 'zero discharge' for many waste streams that may impact the environment. To maximize zero discharge benefits, the deep well disposal process is fully integrated into the drilling and production operations that generate the waste streams. This integration has operational challenges that can be successfully met by the use of 'best practices' for geological evaluation, well design, injection strategy design, process control and monitoring, data acquisition, risk assessment and technical support.

This paper will discuss the use of deep well disposal processes for 'zero discharge' E&P operations, best practices, integrating the SFI process into E&P operations. Two field cases that have fully integrated the SFI and CRI processes into E&P operations, including a heavy oil project will be reviewed.

Introduction

Zero Discharge-Exploration and Production (ZD-E&P) refers to oilfield upstream operations that generate various waste streams, and managing these waste streams so there is no (or minimal) negative interaction with the biosphere (soil, surface water, ground water, and air quality). In the past few years, the 'greening' of the petroleum industry has started for a variety of reasons, and achieving ZD-E&P operations has become a viable and cost effective goal. The use of deep well disposal processes for disposal of suitable E&P waste streams as a means of achieving this objective has increased. In particular, deep well disposal processes such as Slurry Fracture Injection (SFI^{TM}) and Cuttings Re-Injection (CRI) have proven to be economically viable for heavy oil production operations and offshore drilling operations. When properly implemented, these deep well disposal technologies allow E&P operations to achieve zero discharge for many waste streams that may impact the environment.

To describe the SFI technology in its most basic terms, the waste material is screened (if required) to a specified injection criteria, and then slurried in a stream of water (i.e. mix water). The slurry is made with as high a waste concentration as possible (10-30% by volume); and pumped down a waste disposal well at *in situ* fracturing pressures into a suitable deep formation. Extensive process monitoring is used during SFI operations to ensure effective process control. The SFI process is used in the petroleum industry to dispose of E&P wastes such as produced solids, oily viscous sludge, tank bottoms, pit bottoms, contaminated soils, large volumes of drill cuttings & fluids, and Natural Occurring Radioactive Material (NORM). An advantage of the SFI process is that it also injects very large volumes of produced water and waste water as part of the deep well disposal operation.

The CRI process is specific for the disposal of drilling related wastes, typically using the annulus of a well that is being drilled, or using a temporarily dedicated disposal well on a pad of wells that are being drilled. The slurry typically has a slurrification factor of 2 to 4 (i.e. 2x to 4x the amount of mix-water to drilling waste material). Again, dedicated and continuous monitoring (injection pressure, injection rate, slurry density and slurry viscosity) should be utilized during the CRI operations to ensure effective process control; data should be recorded digitally and properly managed. Figures 1 show schematic diagrams of typical SFI and CRI disposal operations.

Table 1 summarizes the comparison of the SFI and CRI processes. In either case, typical disposal depths can vary 350 to more than 2000 meters (depending on suitable geologic strata). While there are operational and injection strategy differences between SFI and CRI operations, the technical issues and considerations in terms of geological evaluation, well design, injection strategy design, process control and monitoring are the same. Comprehensive geological evaluation includes petrophysical log evaluation, geophysical data interpretation, geomechanic analyses and simulation, and structural analyses.

Best Practices for SFI and CRI operations need to be followed to ensure the environmental, operational and economic objectives of the project are achieved. From an operational standpoint, it is essential to ensure ‘process control’ is maintained at all times during the injection-disposal operations that may last from days to many years. ‘Process control’ requirements for deep well disposal operations can be defined as follows:

- Maintain fracture containment.
- Optimize maintain formation injectivity.
- Maximize formation storage capacity.
- Ensure wellbore integrity (hydraulic and mechanical integrity).

Hence, Best Practices for deep well disposal operations incorporate geological evaluation, well design, injection strategy design, process control and monitoring, and technical support. These factors need to be fully integrated to ensure successful ZD-E&P can be achieved.

Zero Discharge E&P Operations

Figure 2 shows the Zero Discharge Cycle for E& P operations using the SFI process. This conceptual approach shows how SFI is integrated into the oil production process. The waste disposal stage becomes an integral part of the planned upstream activities; all stages in the cycle are interdependent. Field experience with this approach has shown some significant advantages:

- Optimized waste management effort by the oilfield operator.
- Centralized waste disposal for multiple waste streams.
- Reduced waste handling costs.
- Reduced waste disposal costs.
- Reduced land and facilities usage for waste processing at upstream operations.
- Reduction in run-off, odours and emissions from waste streams in pits, ponds, etc.
- Reduction in related contaminated site remediation work.
- Reduced (or zero) long term impact on the environment.
- Reduced logistics related to waste handling (such as lifting operations, skip traffic) and reduced onshore storage requirements.
- Reduced exposure and impact of waste streams on personnel and local communities in rural areas.
- Improved public relations with local communities.

However, there is a risk with this interdependent approach that the oil production process can be affected by another activity (i.e. waste disposal). For example, consider that oil production operations generate a certain volume of waste (i.e. tank bottom sludge), and the SFI process is the ‘backbone’ waste disposal process. There exists the potential that if the SFI operations have an unscheduled shut-down event for an extended period of time, there may be an adverse effect on oil production capabilities to some degree; since the concurrent waste volumes cannot be properly managed by existing upstream facilities. Nonetheless, with proper contingency planning, use of Best Practice for SFI, and responsible operator-ship of the waste management facilities, this risk can be mitigated.

Best Practices for Deep Well Disposal

Figure 3 shows the main elements of a ‘Best Practices’ work flow process. The following specific tasks should be addressed as part of this work flow:

1. Comprehensive data collection effort related to geological evaluation and waste material.
2. Geological Evaluation:

- Provide optimum specifications for a target disposal formation: depth, permeability, porosity, sand thickness, sealing formation, etc.
- Using available geological reports, well logs, well test data, and step-rate tests to identify potential geological formations that are suitable to accept large volumes material during deep well injection operations.
- Assess overall regional geology and stratigraphy with respect to suitability for deep well disposal operations.
- Apply criteria required to determine the correct injection approach for deep well disposal operations (e.g. direct sand injection or bottom shale injection); and properly evaluate the advantages and risks associated with these approaches.
- Design a formation testing program to evaluate formation(s) injectivity, flow behaviour, stress-state, and fracture extension pressures required for deep well disposal operations.

3. Material Audit:
    - Assess significant physical and rheological properties of materials to be injected (drilling wastes, oily sludge, and work over fluids).
    - Review material types, volumes, rates, source locations and current disposal methods.
    - Prioritize various waste streams relative to waste management objectives to be achieved; as well as their suitability for deep well injection operations in the context of regulations, properties and physical condition.
4. Earth Modeling:
    - Suitable models are used to semi-quantitatively represent the formation response to deep well injection operations.
    - Results from this modeling effort are used to assess the suitability of geologic strata as target disposal formations, as per the Geological Review above.
    - Conduct an ‘Area of Review’ assessment to assess impact of injection operations on offset wells.
5. Well design and completion recommendations for deep well disposal operations.
6. Develop optimum injection startup, operating strategies, and emergency shutdown procedures.
7. Design and implement procedures for an injection-disposal process monitoring program that will allow for quantitative assessment of formation containment, injectivity, well integrity, and storage capacity performance during injection operations.
    - Prepare and recommend a monitoring program for process control and evaluation of deep well disposal project performance.
    - Design and implement dedicated instrumentation-monitoring systems for injection-disposal operations on offshore platforms.
    - Training of field crews in the proper usage and purpose of the process monitoring program.
8. Design and implement proper field-based procedures such as:
    - Measure & record slurry design parameters.
    - Implementation of optimized injection strategy and operations.
    - Implement a basic Formation Testing Program based on conducting step rate tests (also called a multi-rate test) and injectivity tests on a regular basis.
    - Establish a regular/daily data recording, data transfer, and archiving process.
    - Integrate these procedures with drilling or production operations.
9. Design and implement Technical Support Program.
    - Technical support during active injection-disposal operations should include:
        - design and implementation of optimum injection strategies;
        - analyses of injection data to optimize the injection strategy;
        - analyses of injection data to ensure process control at all stages of injection-disposal operations; and to mitigate risk of out-of-zone-injection.
        - use of dedicated data management systems for injection-disposal operations.

As will be seen in the subsequent sections, current deep well disposal projects (especially related to SFI) involve the continuous operation and management of large volumes E&P wastes streams. The disposal wells are recognized as an asset of the operator’s Drilling Teams or Production Teams; the value and performance of which needs to be maximized. It is therefore necessary to use SFI and CRI ‘Best Practices' to ensure maximum formation storage capacity and well life.

Field Implementation

Large scale SFI projects are being operated or planned in SE Asia, the GCC region of the Middle East and in China. Most of these projects are related to the disposal of oil production related waste streams. Large scale CRI operations are prevalent in the North Sea on offshore drilling and production platforms.

For such deep well disposal projects, once the initial planning is complete the following main elements of Best Practices need to be implemented for field operations: i) formation evaluation; ii) well design; iii) injection strategy, and iv) monitoring & process control.

Formation Selection.

Planning of a deep well disposal operation always starts with an evaluation of the formation that will be used as main injection zone ('target zone'). A geological assessment model was developed to serve as a screening process to assess suitable formations ('target zone' for deep well waste injection) for slurried waste placement(2). The screening process to select a suitable target zone is composed of two steps: a decision tree and a semi-quantitative ranking system that provides a numerical score for the stratum (Figure 4). Specifically, the geometrical, lithostratigraphical, and physical parameters that characterize a stratum as a suitable target zone for slurried waste placement are addressed. The most important criteria are permeability, porosity, formation thickness, depth, and structural geology of the region. The decision tree is intended to indicate whether a prospective site is geologically and geomechanically suitable for slurry injection operations. Branches represent "go-forward" or "reject" decisions based on the values of the parameters defined in each branch.

Formation Testing.

A Formation Testing Program including tests such as: i) mini-frac; ii) injectivity test; and iii) Step Rate Test (SRT) and iv) Pressure Fall-Off Test (PFOT), needs to be conducted prior to the start of injection–disposal operations to quantify the formation fluid flow and geomechanical properties (Figure 5 – 7). These tests are used to determine the state of injectivity and stress in the formation and to assess the *insitu* waste pod as it develops during injection operations. Decreasing formation stress conditions, for example, can indicate vertical fluid migration out of zone. Significant increasing stress is sometimes a precursor to potential well damage.

i) Mini-frac test (Figure 5) is performed to determine initial fracture pressures (closure pressure) and Instantaneous Shut-in Pressure (ISIP) which is an approximation of minimum principal stress conditions.

ii) Injectivity tests (Figure 6/a) are performed by injecting water into the formation at a rate below the fracture extension rate. This test is intended to determine the radial fluid flow characteristics of the formation. The injection rate must be held constant to obtain good bottom-hole pressure (BHP) data. The BHP data is analyzed using PFOT analyses techniques (as below) for the fall-off period. If the data quality is good, acceptable estimates of formation permeability and skin can be determined.

PFOT (Figure 6/b) are performed by analyzing the bottomhole pressure data recorded during any given shut-in period immediately following slurry or water injection into the well. The duration of such shut-in events typically has to be on the order of 10-24+ hours. The data is analyzed using Horner semi-log and log-log plots, which provides estimates of permeability, skin, and components of fluid flow (such as liner flow, boundary condition effects, etc), if such flow effects are present. Such fluid flow effects typically result from the development of the waste pod *in situ*.

iii) The primary purpose of the SRT tests is to determine the Fracture Extension Pressure (FEP) and Fracture Extension Rate (FER) of the formation. These are the minimum pressure and rates required to initiate and propagate a fracture event within a formation. How the FEP and FER varies/behaves over time is also an indication of the induced changes in the stress state of the formation(s) during deep well disposal operations. SRT should be run at regular intervals, at least once per month, to determine current fracturing pressure and fracture extension rate. Figure 7 shows a typical SRT analyses and how the formation parting pressure, which is a good indicator of the *in situ* stress required to initiate fracture events in the formation, is determined.

Well Design.

Well-design will depend on location of potential target zones in relation to existing wells, future development plans and the distance to installations and/or rigs. When a suitable target zone has been identified, a drilling and completion program is developed that satisfies the following requirements:

- Well monitoring using injection rate sensors and pressure gauges (preferable BHP, WHP and Surface Pressure).
- Easy re-intervention (well work-overs).
- Optimum well angle – different well path or design may be required for an 'underneath sand injection' approach (i.e. bottom shale) vs. a 'direct sand injection' approach.
- Pump capacity (upper and lower limit).
- Fluid flow (tubular selected to ensure turbulent flow during injection operations).
- Well integrity during high pressure cyclic injection operations; ensure mechanical and hydraulic (cement) integrity.
- Optimum perforation strategy – to minimize sand-flow back issue and wellborn plugging; and allow for effective hydraulic communication with the target zone.
- A well profile to avoid any collision or proximity issues related to offset wells.

Drilling and well completion strategy of a deep well disposal (Figure 8) should include the following:

- A larger than normal hole should be drilled so a thicker cement sheath can be achieved.
- A minimum of 75 m (250 ft) rat hole should also be drilled to accommodate any sand influx into the well during disposal operations.
- Cementing practices are used that will give the best possible cement uniformity and bond to the pipe and formation.
- Mud and cement programs for unconsolidated sands that may be encountered during drilling (e.g. careful mud control to avoid wash-outs that could reduce the quality of the cement placement).

- Deep penetration charges must be used to ensure good hydraulic communication between the wellbore and the formation because cement invasion can occur in permeable sands during the cementing of the well.
  - For a loose sand formation, typical perforation strategy is a hole size on the order of 0.5 inches, using 4 spf, and 90° phasing. However, the perforation strategy for a bottom shale approach will be quite different.
- Formation flowback possibilities must be assessed and planned-for:
  - Large injected volumes of waste streams may destabilize and fluidize the formation matrix in the near wellbore area resulting in formation back-flow into the wellbore.
  - Formation back-flow into the well (and resultant wellbore plugging) can be managed/minimized through optimized wellbore completion strategies (e.g. tubing placement, perforation strategy, rat hole depth, etc.).

Injection Strategy.

For deep well disposal operations, ‘injection strategy’ is defined as the integration of:

- Injection rates and pressures.
- Cycle duration (period of time for Injection – Shut-down – Injection stages).
- Pre-flush and Post-flush strategies.
- Stage/batch size (volume).
- Slurry design parameters (density, rheology, particle size).
- Process monitoring data collection and analyses during injection operations. Minimum data collected should be WHP, Pump Pressure, BHP, pump injection rate, volume, slurry density and rheology.

During deep well disposal projects, the injected wastes will be placed around the injection well in a succession of hydraulic fracture events. Waste injection episodes over time will create a ‘waste pod’ of relatively immobile solids (e.g. sands, clays) and low viscosity fluids (e.g. drilling muds, oil emulsions/sludge) around the injection well. The goal (while performing deep well disposal operations) is to maximize the use of the formation space around the injection well and to achieve fracture behavior control. A number of operating guidelines based on field experience and through analysis of a comprehensive database of waste injection operations are established. Main elements that determine what injection strategy will be used are: i) type of waste to be injected; ii) volumes of the waste; and iii) the target-zone geology.

To achieve these goals, daily operation/injection strategies and subsequent continuous operation/injection strategies are implemented during the deep well disposal operations. Daily injection strategy (Figure 9) consists of alternating injection operation between several wells each day; using an 8-10 hour daily operation cycle of injection per well and having 14 or more hours of shut-in time to allow fluid bleed-off and pressure dissipation. Such shut-in time is acceptable for the formation to dissipate the high *insitu* pressure-build from daily injection operations. A continuous operation/injection strategy (Figure 10) may consist, for example, of 3.5 days of disposal operational per well followed by 3 days of shut-in time, alternating injection operation between available deep well disposals. While the waste pod development is in the early stages of development, a suitable injection strategy is a daily operation. When the waste pod development is in the latter stages of development, a suitable injection strategy may be continuous injection operation. Switching to such a continuous injection strategy allows the waste pod ‘growth’ phase to be extended in duration, thereby increasing the overall formation storage capacity. Continuous injection also helps to mitigate formation back-flow into the well.

Monitoring and Process Control.

Since extensive hydraulic fracturing events occur during deep well disposal operations, significant monitoring and process control must be applied to confirm that waste placement is contained within the target zone and that injection behavior and formation response is optimized. Ongoing technical support ensures process control for deep well disposal operations.

A three-fold monitoring program is typically used for deep well disposal project, as follows:

1. The following injection parameters need to be monitored on a continuous basis:
   - Bottom Hole Pressure (BHP) in the injection wells and offset wells.
   - Wellhead Pressure (WHP) in the injection wells.
   - Annulus Pressure in the injection wells.
   - Slurry Composition (grain size, fluid viscosity, fluid density and solid content).
   - Injection Rate & Volumes.

   As well, for an onshore well, a surface deformation monitoring system can be used continuously:
   - Surface movements using a tiltmeter and/or geophone monitoring system.
2. The following formation tests should be conducted at the injection wells on a periodic basis:
   - Mini-frac Test.
   - Step Rate Test.
   - Fall-off Test.
   - Temperature & Oxygen Activation Logs.
3. The BHP data recorded form the injection wells will be analyzed to provide the following key Indicator Pressures (IP). This IP data will be used to assess the daily formation response to the SFI operations.
   - Instant Shut-in Pressure (ISIP).
   - Average Injection Pressure.
   - Minimum Shut-in Pressure.
   - Closure Pressure.
   - Injectivity.

Data collected from the monitoring program is used for typical engineering analyses where formation injectivity behavior along with pressure data response and formation stress state changes due to waste pod development can be assessed and compared (Figures 11 & 12). Formation injectivity is assessed along with other data collected from the monitoring program (slurry concentration, average injection pressure and shut-in pressure). For example, as noted in the data plot in Figure 11, formation injectivity improved when injection strategy changed from daily into continues injection. Changes in the operation strategy also can affect (improve or degrade) injectivity and must be assessed throughout the project so that appropriate strategies are developed and implemented.

As a disposal operation progresses, phases of waste pod development occur from ‘growth’ towards ‘filling’ and ‘packing’ phase; each of these stages represents a progressive movement towards formation pressurization, lower permeability, reduced injectivity, and greater stiffness *in situ*. These changes of the waste pod development are reflected in the injection pressure data analyses. A higher Shut-In pressure can be noted as more waste is injected in the formation (Figure 11). Formation stress changes are determined by the periodic SRT conducted in the formation (Figure 12). Increase of the Fracture Extension Pressure (FEP) with time indicates a higher stress state of the formation as waste pod develops (moving from ‘growth’ to ‘filling’ to ‘packing’ phase) in the formation. This is particularly evident with comparison of the injection-SRT to the baseline data.

Slurry Fracture Injection (SFI) Project Field Case.

The SFI process has been successfully implemented at the PT Chevron Pacific Indonesia Duri oilfield in Indonesia(1). The SFI operation is a multi-well disposal project whereby several injector-disposal wells are drilled and completed using the above techniques. These wells are used for disposal of Oily Viscous Fluids (OVF, a crude oil-water-sand sludge of varying composition and rheology) and waste-water being generated from oil production operations at Duri. The OVF and waste-water are mixed to create a ‘slurry’. The volumes of different waste streams injected in these disposals well are large; varying between 10,000 – 15,000 m^3 (63,000 – 94,000 bbl) of OVF waste per month. This waste needs to be mixed with water (produced water) using a slurrification factor of approximately four (i.e. 1 part waste with 4 parts of water). Therefore, during a month of operation a volume of 40,000 – 60,000 m^3 (250,000 – 377,000 bbl) of slurry can be disposed. Typical monthly injected waste and slurry volumes are presented in Table 2. The SFI wells are approximately 600 m apart and completed into the same target zone (a thick, permeable, unconsolidated sand) at a depth of approximately 425 m. All of these wastes have been injected back into the deep geologic formation sequence from where the waste originated (i.e. returning waste streams to their place of origin).

Data was collected and a comprehensive SFI database developed as follows:

- Well placement with respect to the ‘target zone’ formation.
- Azimuth of the waste pod development (using surface tiltmeter response).
- Results from the daily/weekly/monthly operations data analyses.
- Engineering data analyses (as above).

Accordingly, a comprehensive ‘Conceptual Model’ has been developed with respect to the waste pod development in the target zone. Figure 13 shows the SFI multi-well disposal project where the thickness of the target zone and the azimuth of the waste pod development are indicated. Based on this ‘Conceptual Model’, the future well development of this disposal project can be determined. However the facility/pump capacities also need to be considered in order to properly choose the new well placements (well spacing) and continue with an effective SFI operation.

This project has been on-going for over six years. Surface sludge pits used for surface disposal have either been closed and/or decommissioned. The SFI project has now made the Duri oilfield essentially a 'zero discharge' oilfield in terms of its OVF waste from production operations and a large portion of its waste water.

Cuttings Re- Injection (CRI) Project Field Case (offshore)

Cuttings Re-Injection (CRI) involves injection of waste from drilling operations (slop and drill cuttings) into a suitable deep geologic formation (the ‘target zone’). Injection will typically require pressures that result in hydraulic fracturing in the formation. This process is considered an environmental friendly and cost-effective disposal method during drilling operations, especially with offshore E&P operations.

This offshore project is based on a dedicated injection well for drilling waste disposal in the North Sea. Two different techniques of CRI injection operation have evolved: i) the ‘direct sand’ injection; and ii) ‘bottom shale’ injection approach. Waste generated from drilling operation is classified as Slurry and Slop materials. Slurry is the type of material which typically has a Specific Gravity (SG) greater than 1.20 and FV ~ 45-60; comprised of slurrified drilling cuttings. Slop is the type of material which has a SG between 1.03 – 1.20 and FV<45; comprised of oily or contaminated water (i.e. rig waste water). Volumes of waste (slurry or slop material) using either technique varies on a daily basis and is dependent on the drilling operations needs. The CRI well is completed in a target zone (a deep formation characterized as a thick, permeable, unconsolidated sand unit) at a depth of approximately 1,300 mTVD, thickness greater than 100 m, porosity greater than 25%, and permeability of approximately 500 – 700 md (Figure 14). This well was completed in an unconsolidated sand formation and the ‘direct sand’ injection approach was applied.

Typical monthly volumes injected in a given CRI well are presented in Table 3. A typical period of slurry, slop and water injected volumes for a CRI well are presented in Figures 15/a & 15/b. The associated injection data analyses indicated a relatively thin formation as the injection zone vs. shut-in/ pressure fall-off data analyses indicating a relatively thick permeable formation (an apparent contradiction). Flow back events and well-fill were some of the issues noted during the CRI operations. However these issues were mitigated by using proper injection and shut-down techniques during CRI cycles (as per Best Practices procedures).

Daily/weekly/monthly operations data analyses along with engineering analyses indicate different flow systems developed in the formation. These different flow systems are represented in a wellbore-formation interaction ‘Conceptual Model’ (Figure 16). In this particular CRI operation, due to well design (deviated well), well completion, and the injection strategy, three different flow systems developed during the CRI operation as follows:

- Flow System #01 (FS#01): early stage shut-in; very close to the wellbore and associated with relatively high permeability due to injection related fracture events occurring in a relatively thin part of the formation, resulting in a small ‘kh’ (i.e. permeability x formation thickness) effect (similar to a thin sand zone).
- Flow System #02 (FS#02): early time of leak-off process; characterized by relatively high permeability and more formation area, resulting in a better ‘kh’ effect.
- Flow System #03 (FS#03): late stage of leak-off; which is characterized by high permeability across a large formation thickness, resulting in a higher ‘kh’ effect (typical of the large sand zone that is the target zone).

This conceptual model helped to explain the contradiction that was occurring between injection operations (data analyses indicating a relatively thin formation as the injection zone) vs. shut-in/ pressure fall-off conditions (data analyses indicating a relatively thick permeable formation). Based on this conceptual model, injection strategies were optimized for the ‘direct sand’ injection approach to mitigate sand back-flow into the well and maintain adequate injectivity to meet drilling waste management objectives.

Proper implementation of ‘Best Practices’ for this CRI operation was used to assess/address/resolve injection issues in a timely manner. Accordingly, the technical support work used on this project was able to meet the operational-drilling and zero discharge objectives of the client by ensuring concurrent, controlled, and reliable CRI operations.

Conclusion

Achieving zero discharge with deep well injection is achievable and the technology is maturing. However, proper design and process monitoring, backed by continuous analysis, are necessary to ensure sustained disposal well and formation performance during drilling and/or production operations. Otherwise problems can arise with the disposal operation. Known issues include waste breaching to sea floor, well plugging, breach of injection well integrity, and off-set well communication. These events are all avoidable.

The elements of a deep-well disposal project are now well-understood, as follows: geosciences assessment, waste generation auditing, operational and regulatory criteria assessment, well design and implementation, surface facilities design, integration with drilling and production operations, continuous monitoring and analyses of injection data and formation response to injection operations, and use of necessary HSE procedures. Proper design and implementation of these factors will ensure sustained and safe deep well disposal operations. Projects incorporating these elements into a “Best Practices’ work flow process will help to ensure related risk conditions are identified and subsequent deep well disposal operations can be controlled. Therefore, related risks can be adequately managed to ensure environmental security.

Zero Discharge Exploration and Production operations are now viable and practical for various liquid and solid waste streams; it is achievable through deep well injection. Hence improved environmental management can be fully integrated into upstream activities. Adoption of zero-discharge policies is occurring world-wide, and the project experience discussed in the field-case histories is confirmation that such policies can result in practical economic solutions.

Acknowledgement

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Appendices

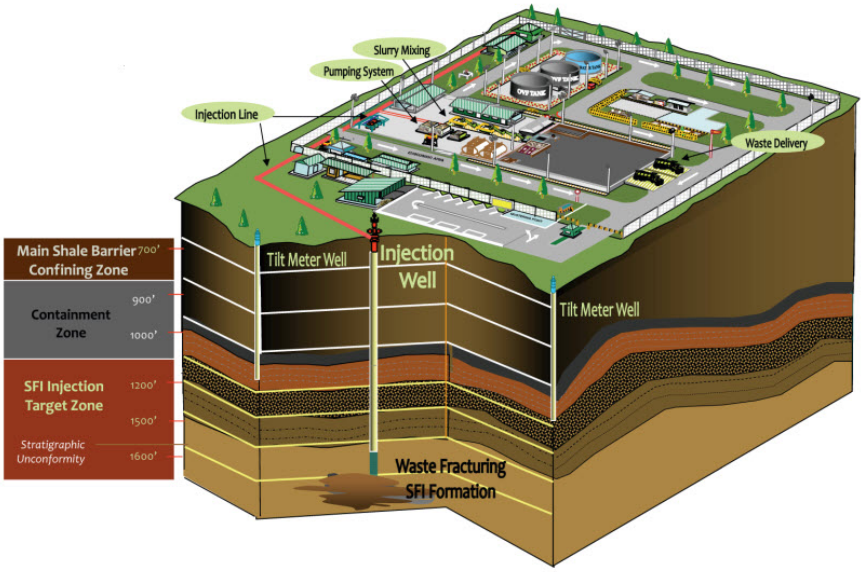


Figure 1a: Schematic diagram for SFI deep well disposal project.

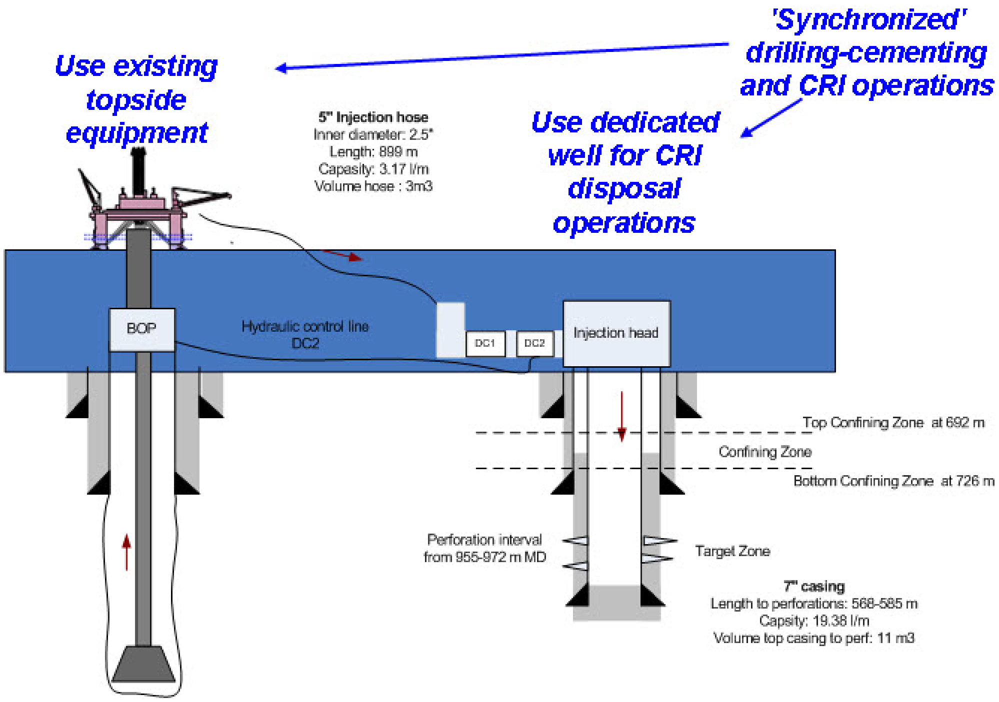


Figure 1b: Schematic diagram for CRI deep well disposal project.

SLURRY FRACTURE INJECTION (SFI)	CUTTINGS RE-INJECTION (CRI)
High pressure injection and rates (fracturing)	Moderate/low injection pressures and rates
Large waste volumes (3,000 – 15,000 m^3/month)	Smaller waste volumes (<100 m^3 batches/cycle)
Continuous injection cycles Multiple waste streams from E&P operations	Injection of drilling wastes while drilling a well (cuttings)
Dedicated disposal wells	Disposal into annulus of drilled well or dedicated disposal well
Dedicated facility - onshore	Rig based operation – onshore or offshore
Direct sand injection/injection strategy	Direct shale or bottom-shale injection/injection strategies

Table 1: Comparison of SFI & CRI processes.

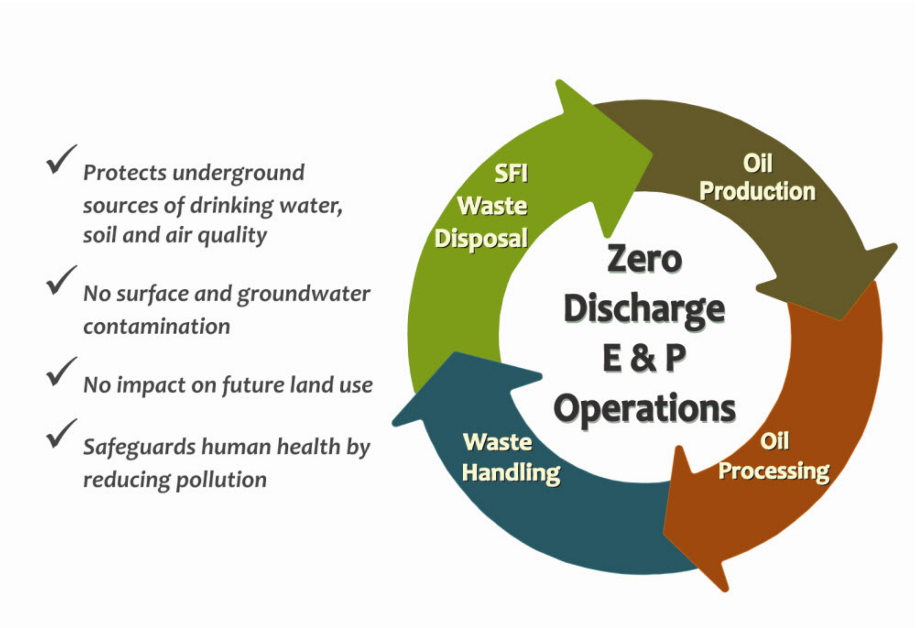


Figure 2: Zero Discharge cycle for E & P operations.

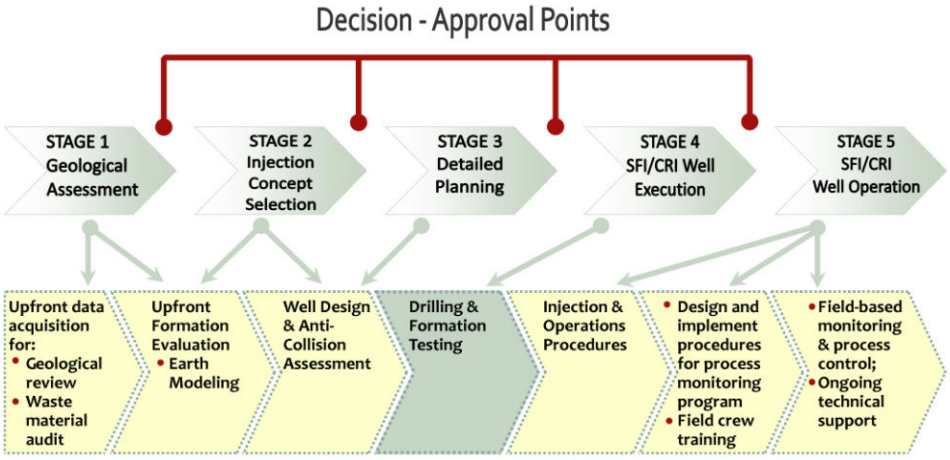


Figure 3: Main elements of 'Best Practice' work flow process.

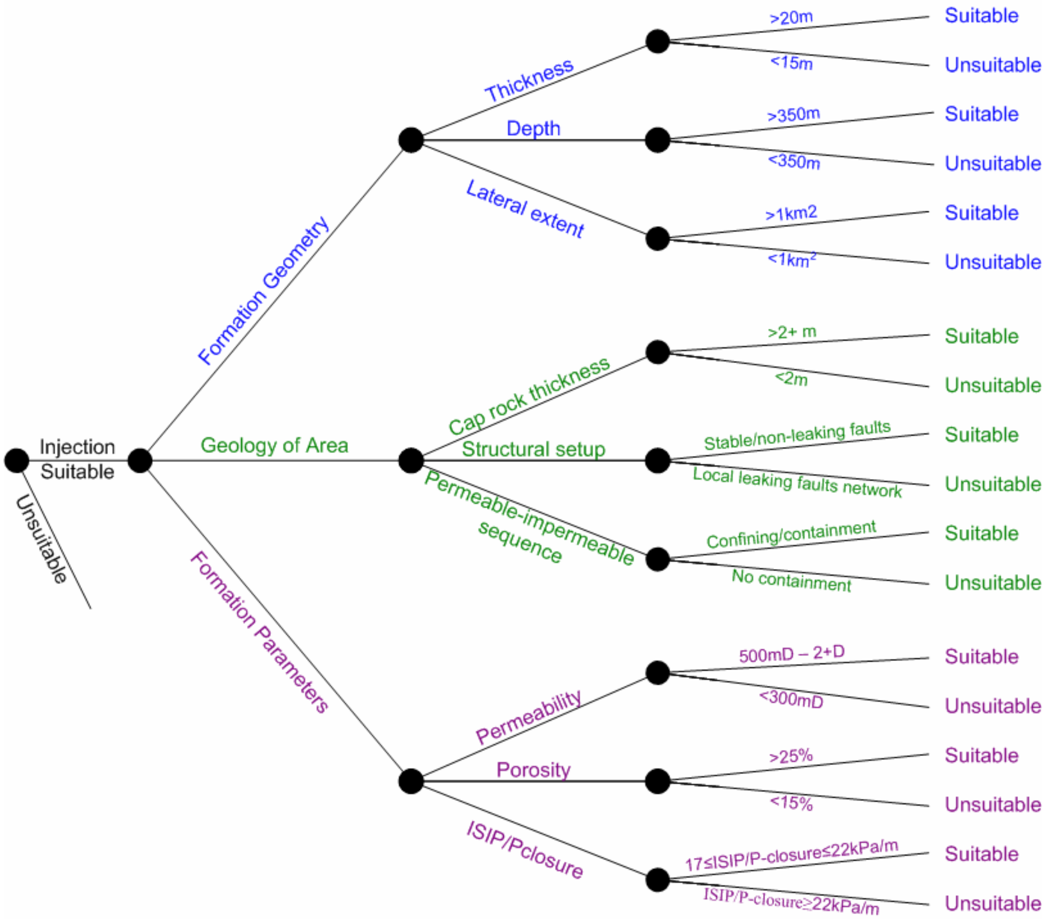


Figure 4: Decision tree assessing geological criteria for a formation.

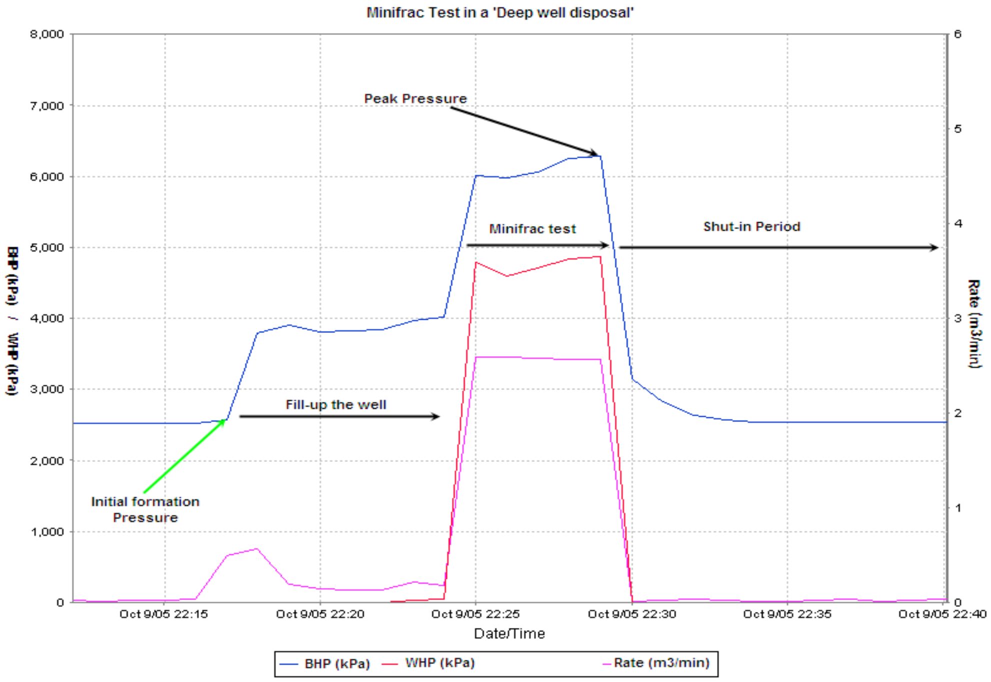


Figure 5: Mini-frac Test

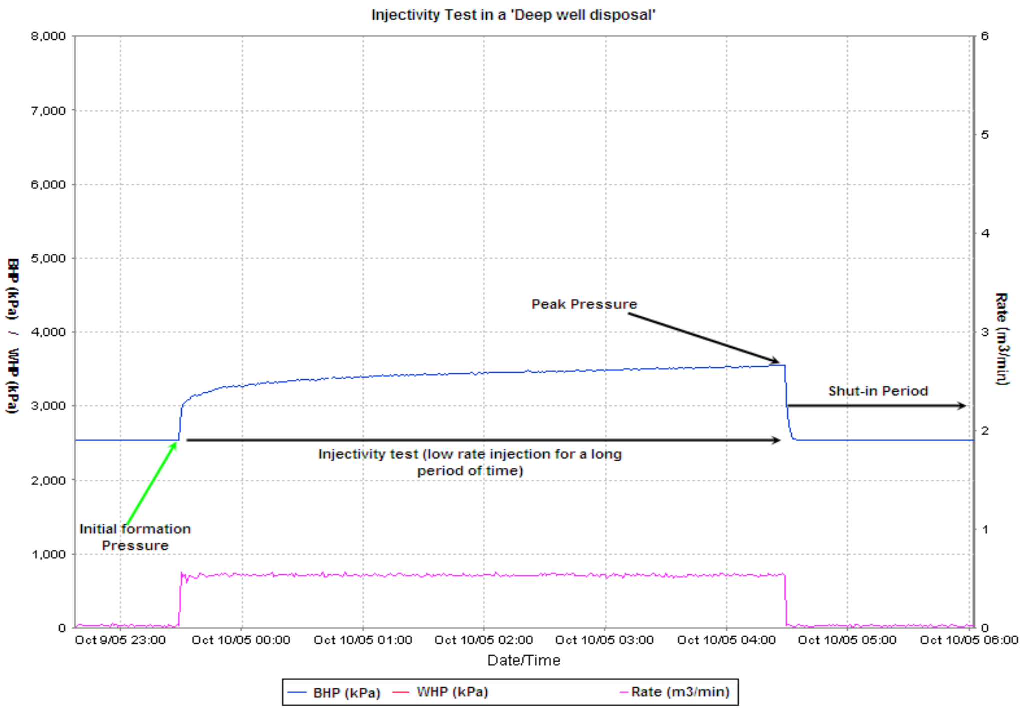


Figure 6/a: Injectivity Test

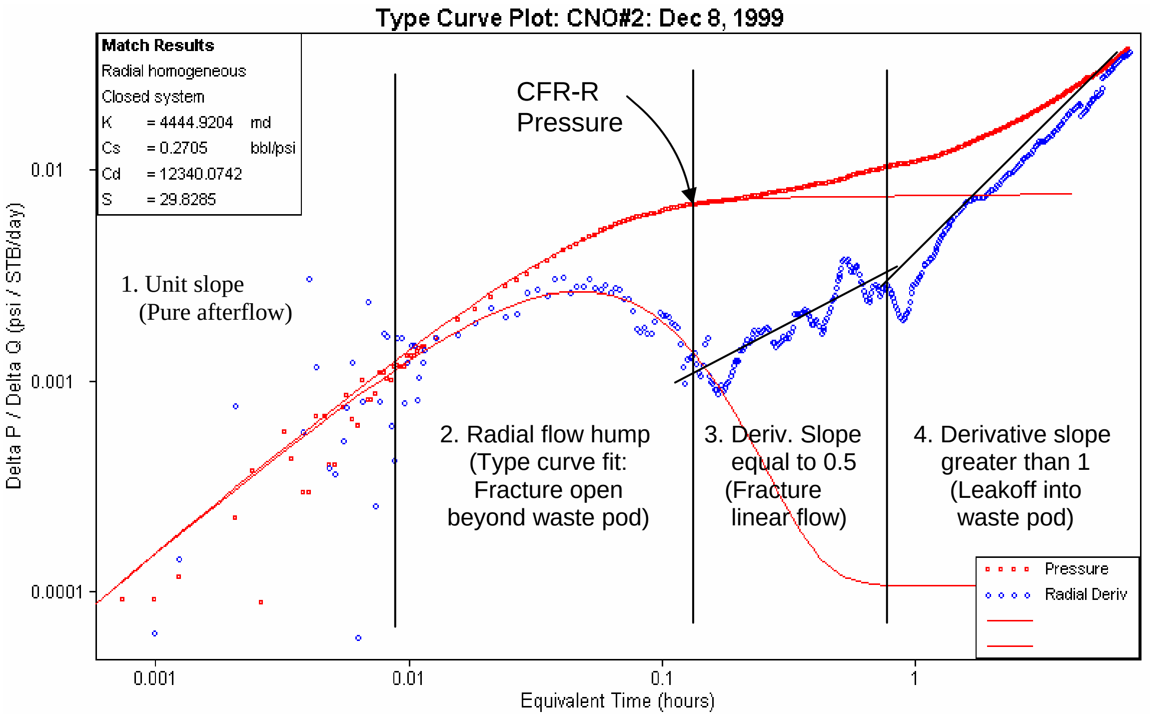


Figure 6/b: Pressure Fall-Off Test (PFOT).

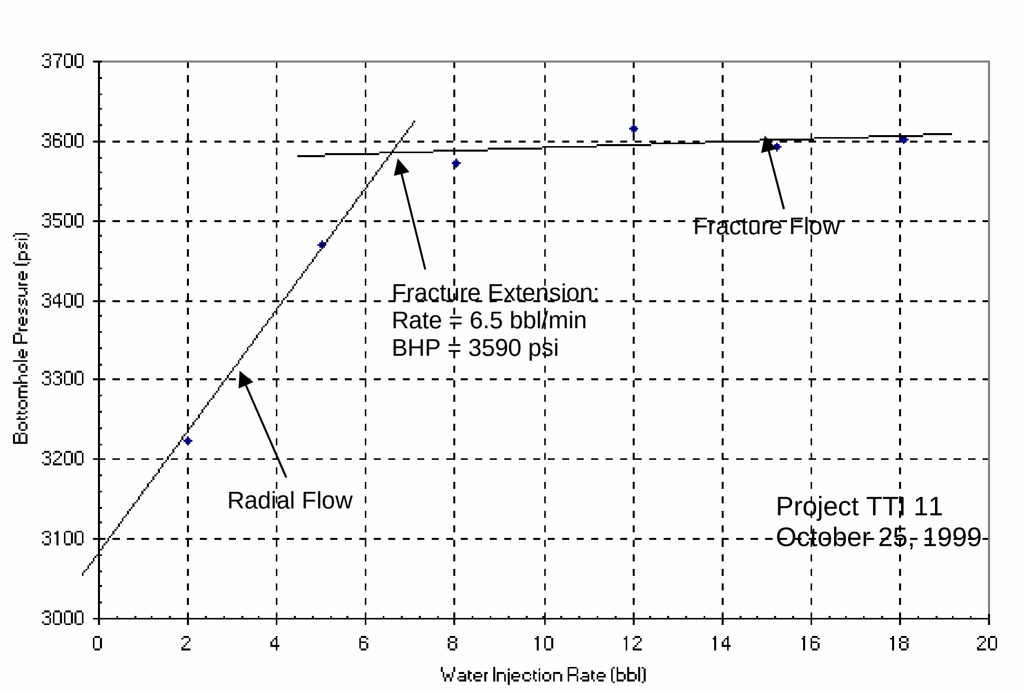


Figure 7: Step Rate Test (known as 'multi rate test').

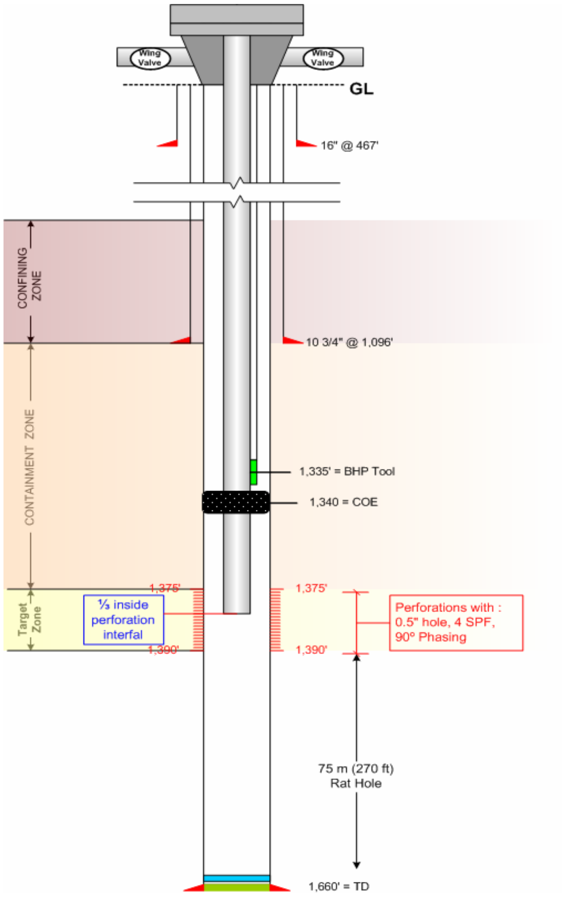


Figure 8: Design of a deep well disposal.

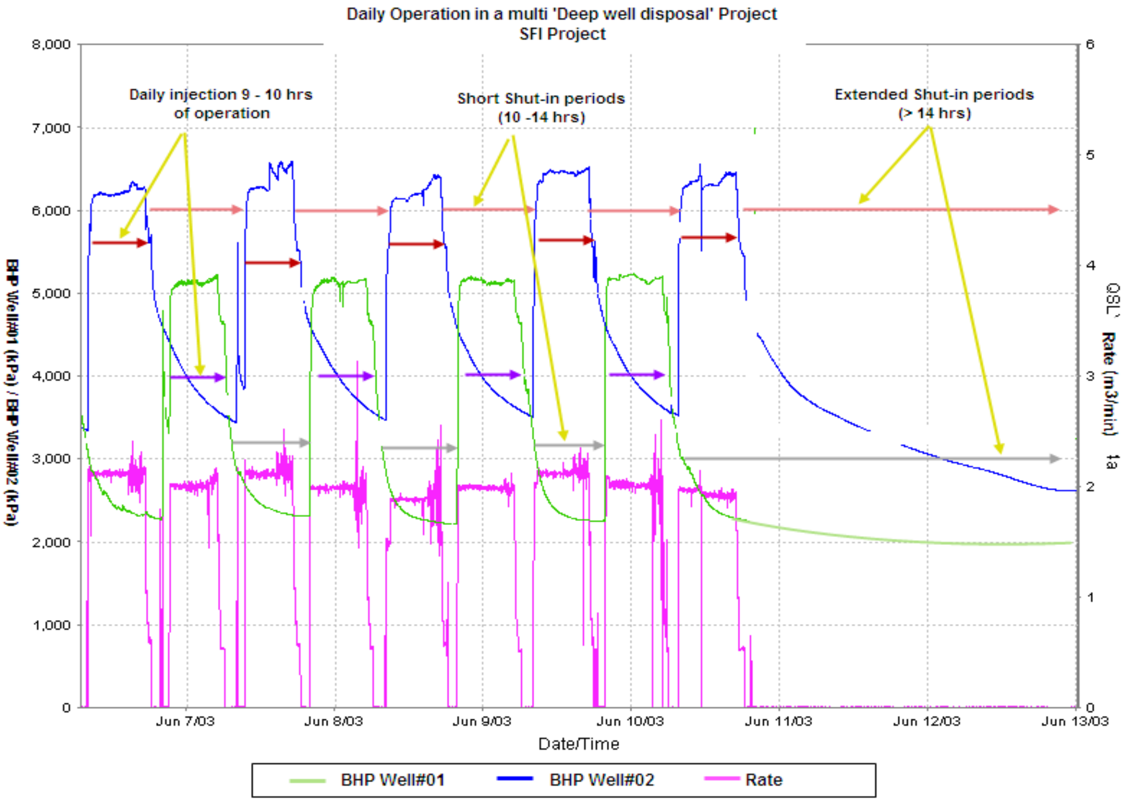


Figure 9: Daily injection operation.

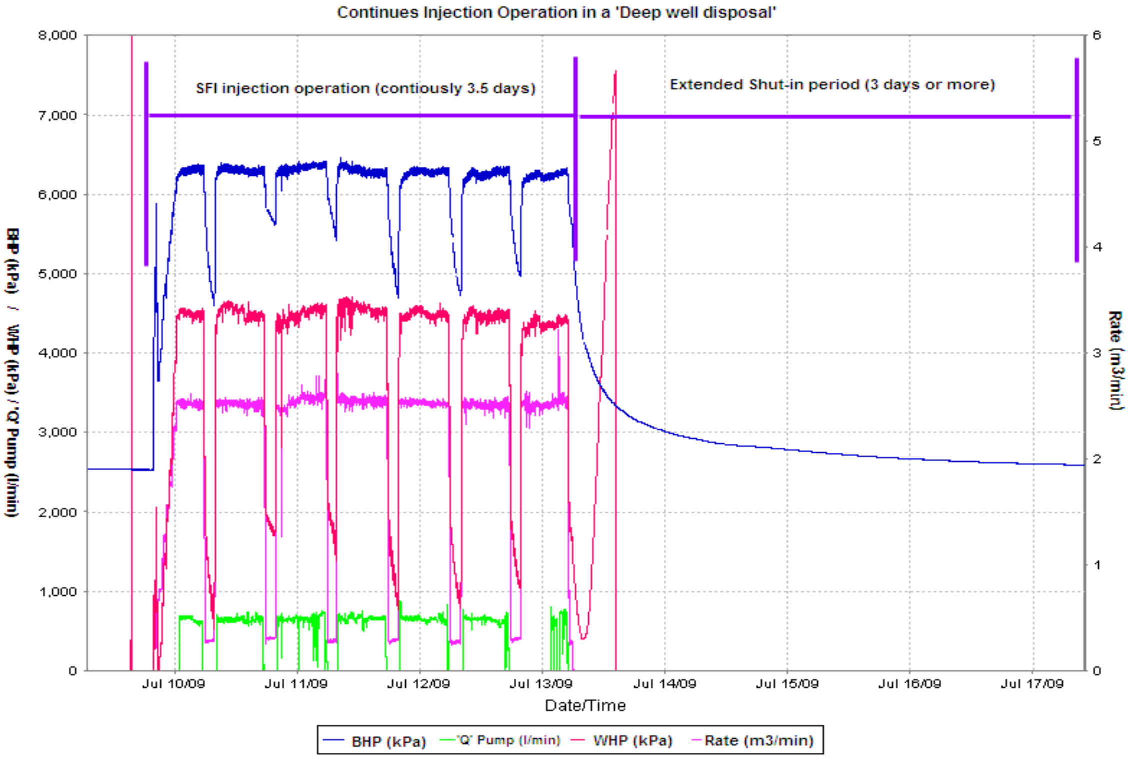


Figure 10: Continuous injection operation.

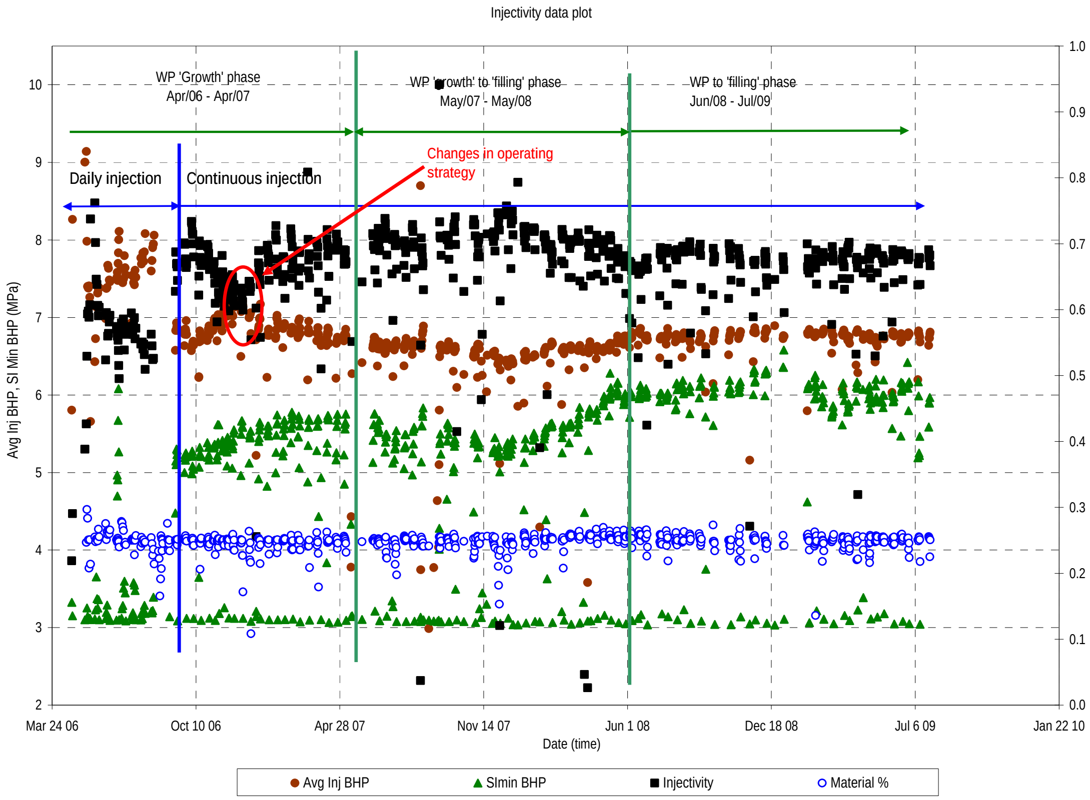


Figure 11: Formation injectivity determination.

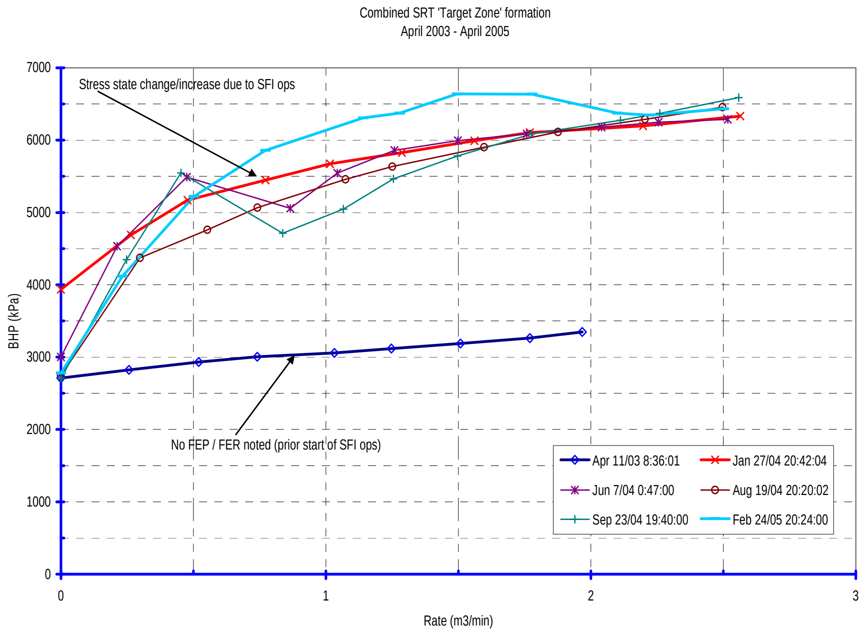
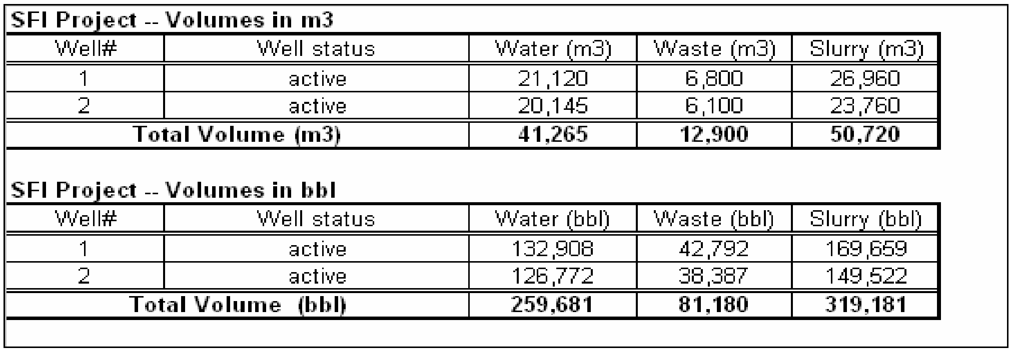


Figure 12: Stress State changes (combined SRT data).



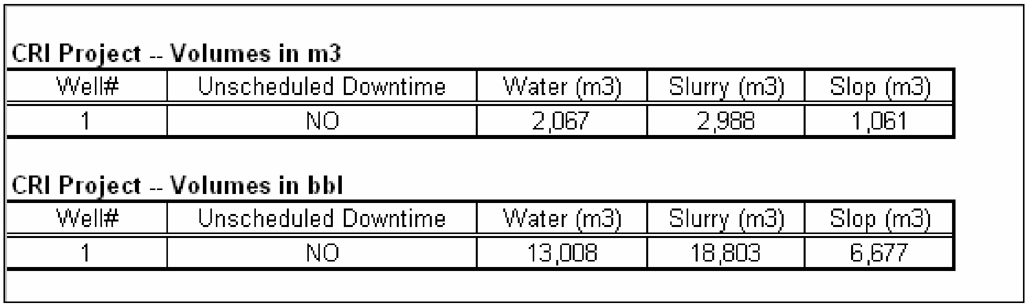
SFI Project -- Volumes in m3

Well#	Well status	Water (m3)	Waste (m3)	Slurry (m3)
1	active	21,120	6,800	26,960
2	active	20,145	6,100	23,760
Total Volume (m3)		**41,265**	**12,900**	**50,720**

SFI Project -- Volumes in bbl

Well#	Well status	Water (bbl)	Waste (bbl)	Slurry (bbl)
1	active	132,908	42,792	169,659
2	active	126,772	38,387	149,522
Total Volume (bbl)		**259,681**	**81,180**	**319,181**

Table 2: Typical Monthly Volumes (SFI Project)



CRI Project -- Volumes in m3

Well#	Unscheduled Downtime	Water (m3)	Slurry (m3)	Slop (m3)
1	NO	2,067	2,988	1,061

CRI Project -- Volumes in bbl

Well#	Unscheduled Downtime	Water (m3)	Slurry (m3)	Slop (m3)
1	NO	13,008	18,803	6,677

Table 3: Typical Monthly Volumes (CRI Project)

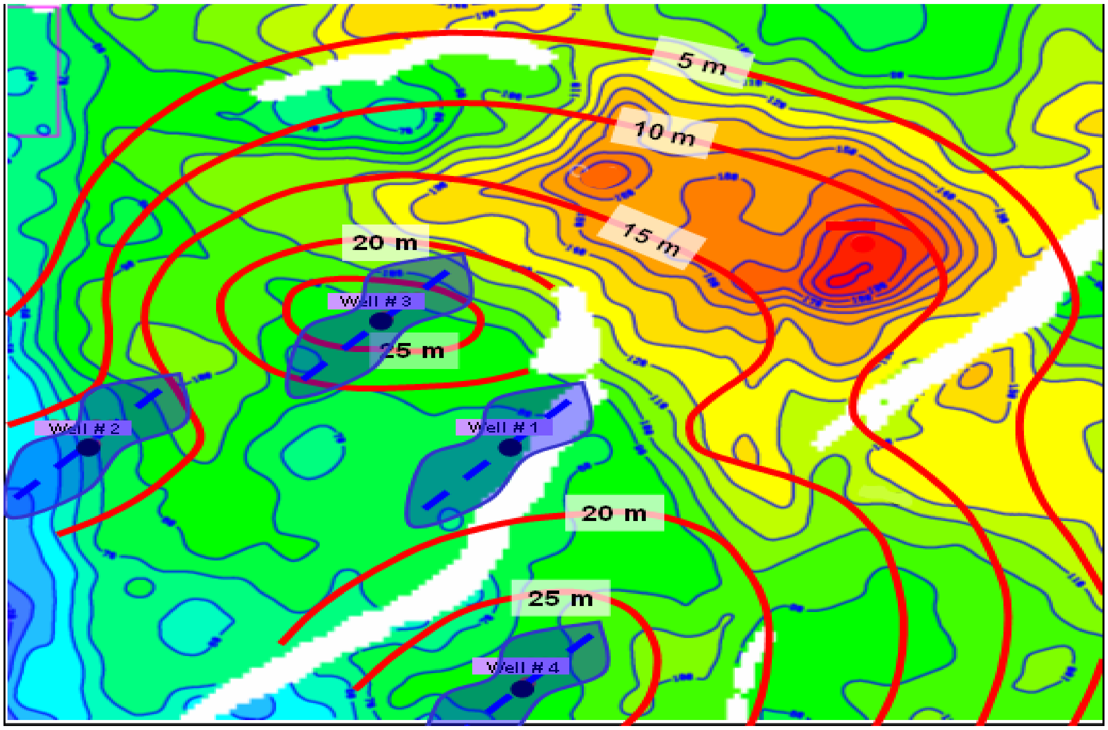


Figure 13: SFI Project ‘Conceptual Model’

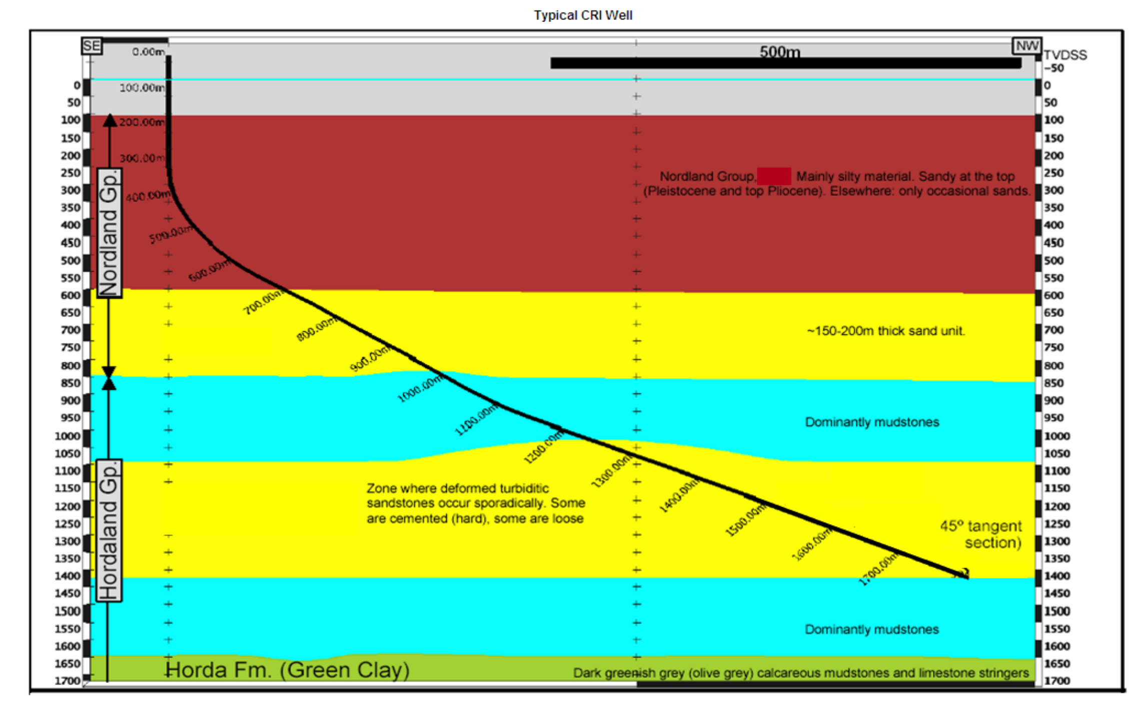


Figure 14: Schematic of an offshore CRI Well.

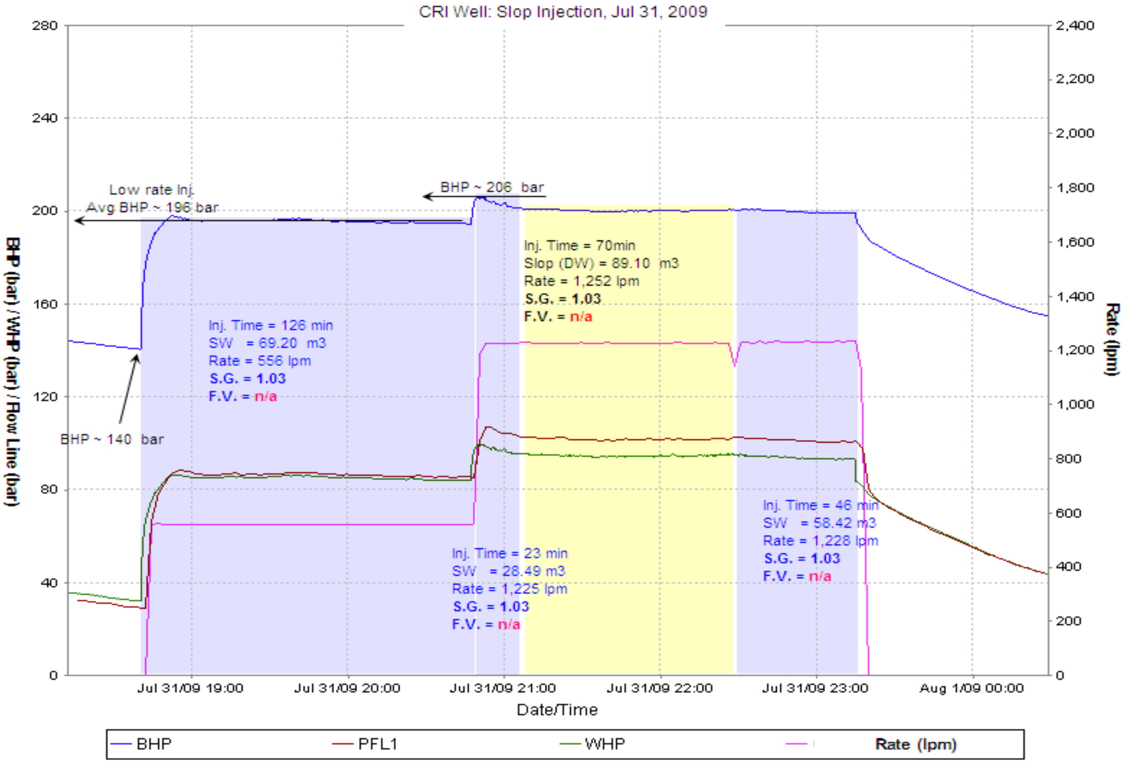


Figure 15/a: Typical period of Sea Water / Slop injection.

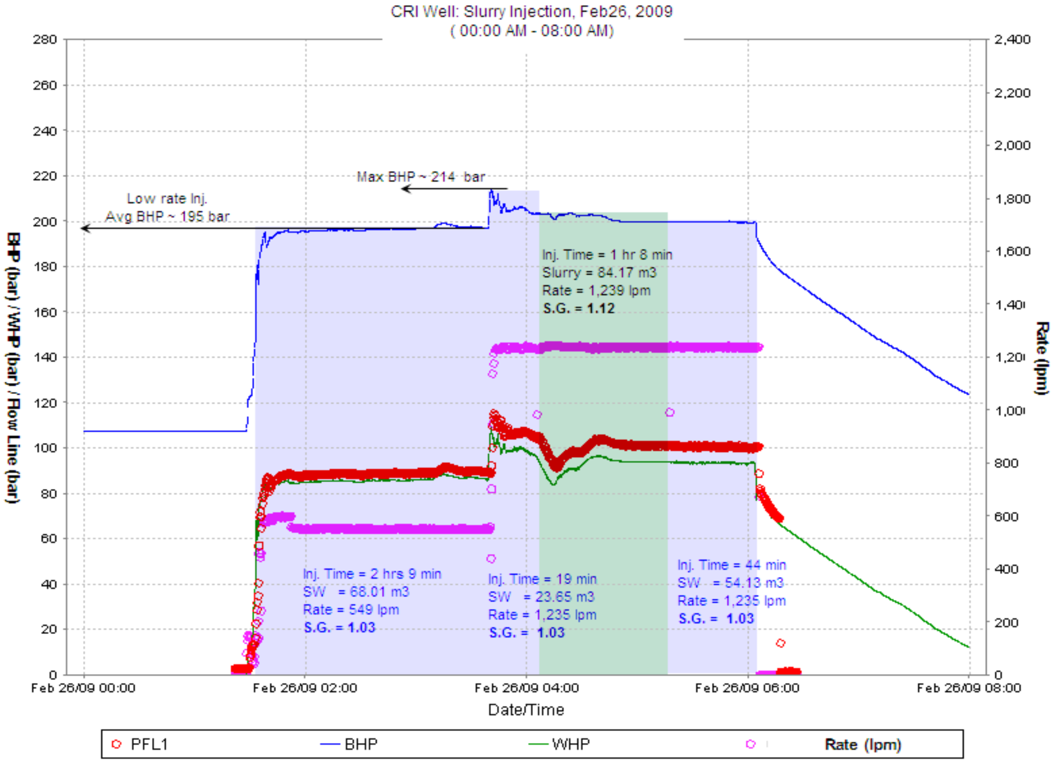


Figure 15/b: Typical period of Sea Water / Slurry injection

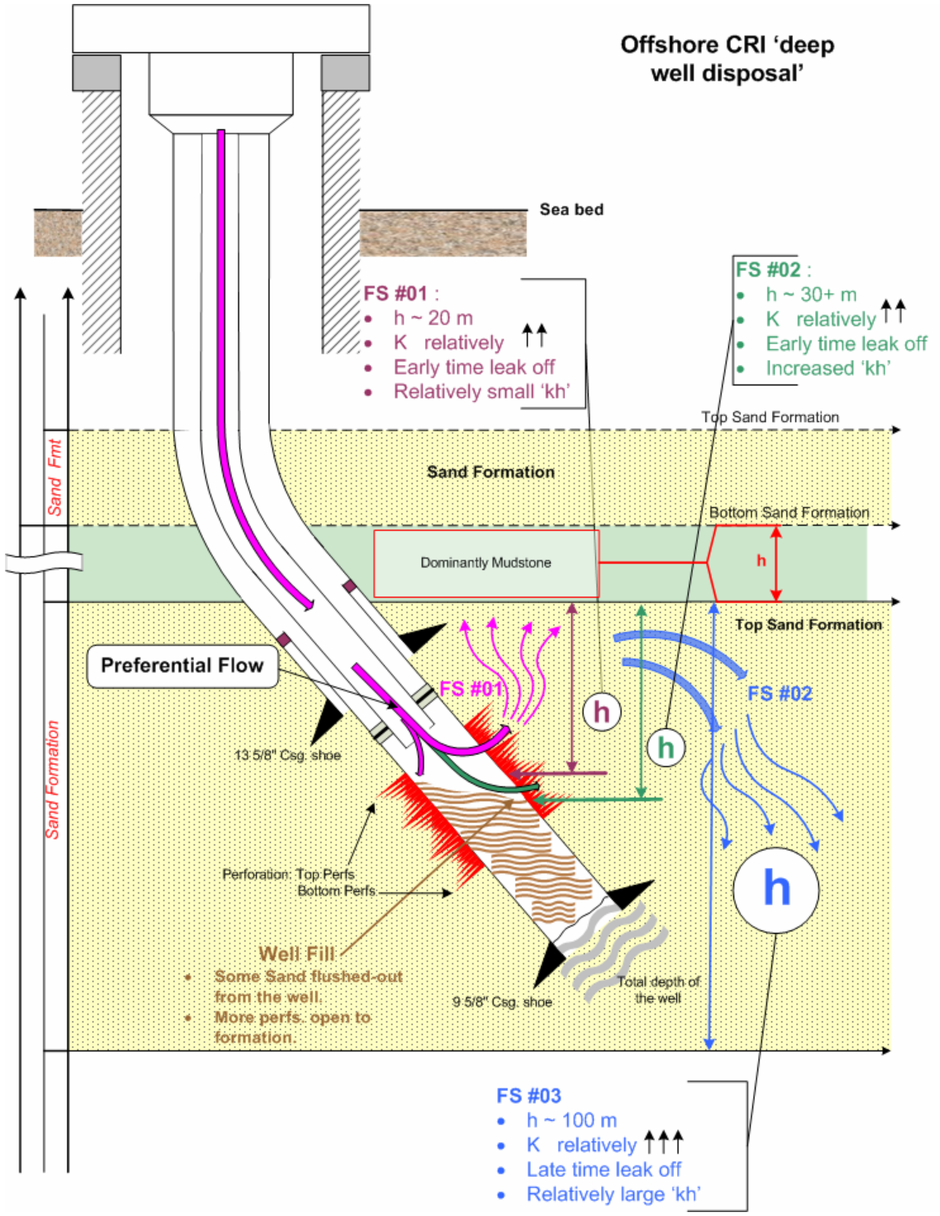


Figure 16: CRI Project 'Conceptual Model'.