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Performance Assessment of Cuttings Re-Injection (CRI) Operations at the Manifa OilField, KSA

Guowei Xia
Terralog Technologies Inc., Calgary, Canada, guoweix@terralog.com

Roman Bilak
Terralog Technologies Inc., Calgary, Canada, bilakr@terralog.com

Eduard Marika
Terralog Technologies Inc., Calgary, Canada, eduardm@terralog.com

Hesham A. Al-Shehri
Saudi Aramco, Dhahran, Saudi Arabia, hisham.shehri@aramco.com

Faisal Y. Al-Qahtani
Saudi Aramco, Dhahran, Saudi Arabia, faisal.qahtani.14@aramco.com

SUMMARY: Deep well disposal of slurried drilling waste using a modified CRI process has been implemented at the Saudi Aramco Manifa Oilfield. Injection of drilling waste into a deep, high porosity, high permeability sandstone (approximately 6500 ft TVD) at Manifa began in 2012, and has continued with up to eleven disposal wells being active during drilling operations. To-date (April 2014), over 238,380 bbls of drilling waste streams have been injected. The modified CRI operations utilize a cyclic 'slurry fracture injection' process at high rates with direct-sand injection via dedicated disposal wells. Extensive process monitoring/analyses is used during CRI operations to ensure process control. The waste streams include drill cuttings, oil based drilling fluids, water based drilling fluids and brine. Deep well disposal provides a secure operation achieving 'zero discharge' by injecting cuttings and associated fluids. Skip and ship is used as secondary waste management method in case of limitations in CRI operations. The Khafji disposal formation was chosen for 'slurry' waste injection at Manifa field since it met or exceeded the desired criteria for permeability, porosity, depth and other properties. Injection takes place on drilling rigs and into dedicated disposal wells. Hydraulic fracturing is necessary to inject the slurry containing drilling wastes. As injection goes on, slurry design, injection strategy and dynamic formation geomechanics/fluid flow response will affect to the performance of the disposal formation. The use of modified CRI operations, using a cyclic, high rate slurry fracture injection process, is essential to ensure process control, maximize the formation storage capacity for these disposal wells/formations; and to ensure that the zero discharge operational-drilling objectives of the Manifa Drilling Team are met. This paper will present a field case assessment of the Manifa CRI operations performance in terms of achieving process control and meeting the zero discharge operational-drilling objectives of the Manifa Drilling Team by ensuring successful, reliable deep well disposal operations.

KEYWORDS: Cuttings Re-injection, Deep Well Disposal, Process Control, Zero Discharge.

1 INTRODUCTION

In 2006, Saudi Aramco embarked on the development of a mega-project at Manifa, an offshore field that would become the world's largest offshore hydrocarbon production increment built in a single phase, and would require the company's technical know-how, economic management and environmental commitment to the limits. Success at Manifa would require an entirely innovative and integrative approach to doing business, from the use of new technologies to minimize the economic and environmental impact on the shallow estuaries of Manifa bay and the local communities that depend on fishing for their livelihoods.

During the planning phase in 2006 of this world's fifth largest oilfield, several options were considered to develop the field in the most economical and environmentally friendly manner, considering the shallow waters and the associated ecology. It was decided to convert over 70% of the field into an onshore field. This conversion required the construction of 27 manmade islands, each the size of ten soccer fields, connected with a 41 km causeway; 15 offshore platforms were also needed for the field's deeper water locations. As a result of carefully placing these manmade islands to ensure minimum environmental footprint, the field became the largest extended reach hydrocarbon producer project in the world. Construction of onshore facilities included: a central oil and gas processing facility, water supply system, water injection facilities, and product transportation pipelines.

Developing a mega project in a coastal and ecologically sensitive area was very challenging. At Manifa that challenge was significant due to the importance of this location as one of the Kingdom of Saudi Arabia's most productive shrimping and fishing zones. Because of the increasing focus on environment protection from oil and gas exploration and production, especially in environmentally sensitive terrestrial and marine location, a 'zero discharge' policy has been adopted by Aramco to dispose of waste streams generated from offshore drilling operations.

Cuttings Re-Injection (CRI) was selected by Aramco as a deep well disposal process that allows for drilling waste management in an environmentally sustainable manner that protects the biosphere, and is in compliant with its zero discharge policy R. Ezell.et al. (2011.). Hence, waste disposed by the modified CRI process ('slurry fracture injection') has been implemented at the Saudi Aramco Manifa Oilfield. Injection of drilling waste into a deep, high porosity, high permeability sandstone at Manifa began in 2012, and has continued with up to eleven disposal wells being active during drilling operations. This paper covers the operational period from February 2012 to April 2014. To-date (April 2014), 238,380 bbls of 'slurry' (multiple streams from cuttings, water based mud, oil based drilling fluid, brine) and 'slop' (dirty water from rig clean-up) have been successfully disposed into the Khafji formation (the 'target zone') using a modified CRI injection technique at these wells (Table 1).

Table 1. Total Volume of Material injected at Manifa Field

	Sea Water (bbls)	Slurry/ Cuttings (bbls)	Viscous Pills (bbls)	Total Volume (bbls)
Feb 2012~ Apr 2014	777,638	238,380	43,329	1,059,347

A geological assessment of the Manifa Field, determined a suitable target zone for disposal and injection to be the Khafji formation; the stratigraphy was also evaluated to ensure the presence of a suitable 'containment' zone and 'confinement' assurance.

The properties of the targeted Khafji formation met or exceeded the desired criteria in terms of porosity and permeability and other properties (Table 2).

Injection is performed on the rig(s) with dedicated equipment and into a dedicated disposal well(s). Most of wells were inclined (less than 20 degrees) across the disposal target zone. The slurrified waste was injected down through the 4.5" (inch) tubing string into target formation. Wells also were completed in a way allowing for easy intervention if a well clean-up was required at any time.

Slurried waste is comprised of single or multiple drilling waste streams (cuttings, water based mud, oil based drilling fluids, and brine) mixed with sea water to reach certain fluid properties and rheology for injection. Proper slurry design is required to successfully carry and deposit these wastes into the target formation by the slurry fracture injection process.

Table 2. Manifa Field Formation Leak-off Properties from Lab Test Alshobailiet al. (2009)

Formation	Porosity	Permeability (md)	Leak-off Coefficient (ft/min^2)
Safaniya	34	9,500	9.06E-4
Khafji(#1)	24	2,240	5.62E-4
Khafji(#2)	24	2,240	8.19E-4
Shuaiba(#1)	16	0.5	3.21E-4
Shuaiba(#2)	16	0.5	5.52E-4

Besides slurry design, appropriate injection strategies are developed and deployed to balance the drilling operational needs and the dynamic formation response to the ongoing waste injection. In this way it is possible to maintain the performance of the disposal well and disposal formation with respect to meeting the waste management needs of the daily drilling program.

'Conventional' CRI injection operations typically employ low rate injection (< 5 bbls/min), annular injection, low volume batches, indirect injection into the target zone (i.e bottom-shale injection approach), and longer shut-in times to dissipate induced pressure and stress gradients *in-situ*. These factors can limit conventional CRI operations ability to meet waste management needs during large volume, continuous drilling operations. Hence, a modified CRI process was implemented for this project, using a cyclic, high rate, high waste concentration, continuous slurry fracture injection process was used to optimize formation response to waste disposal operations and maximize the formation storage capacity for these disposal wells/formations. Thereby ensuring successful zero discharge operations.

CRI operations at Manifa field were conducted in multiple batch injection events followed by 3~4 hours shut-in time, using a cyclic pattern. Under such conditions, as waste material is injected directly into the target formation, an area around the wellbore begins to fill with the injected waste material. The water component of the slurry dissipates (leaks-off) into the formation. The waste injected deposits in the area of invasion and evolves into a 'waste pod' with relatively lower permeability, lower compressibility, and lower porosity than the surrounding formation. Multiple slurry fracturing events and the concurrent mechanics of fracture injection into 'soft rock' (unconsolidated sands) create induced factures that propagate further into the formation and expand the waste pod volume. Thereby maintaining formation injectivity and leak-off, and increasing the overall formation storage capacity. Arfie et al. (2005)

This paper presents a field case assessment of one CRI well out of eleven CRI wells used for Manifa project based on 24/7 monitoring data and data analyses results (i.e. pressure analyses, step-rate test, etc). Given the assessment and performance of Manifa CRI operations, process control for deep well disposal operations will be discussed as essential practice/procedures needed for achieving zero discharge operations.

2 MANIFA GEOLOGY AND WELLS FOR CUTTINGS RE-INJECTION

Geological assessment for long-term deep well disposal needs to meet the following criteria. Arfie et al. (2005)

A suitable '*target'* formation for CRI injection operations should be characterized with features such as poor consolidation, high compressibility and good injectivity, and a high permeability (high leak-off rate) so fluids can drain off quickly during injection.

A '*containment'* zone is typically an interval of alternating sands and shales above the target formation. Injected fluids/slurry from the cuttings re-injection operations may 'leak' up-hole over time due to loss of hydraulic isolation of the disposal well (i.e. loss of cement integrity) or due to vertical growth of the fracturing events during the injection operations.

A '*confinement'* zone is typically a relatively thick (2 to 5+m) of competent shale that 'caps' the 'containment' zone interval. This 'confining' interval provides an effective seal or cap rock to the deep well disposal operations. Injected fluid is not allowed to migrate past this ‘confining’ zone.

The geology of Manifa area contains such suitable lithostratigraphy for cuttings re-injection operations (Figure 1).

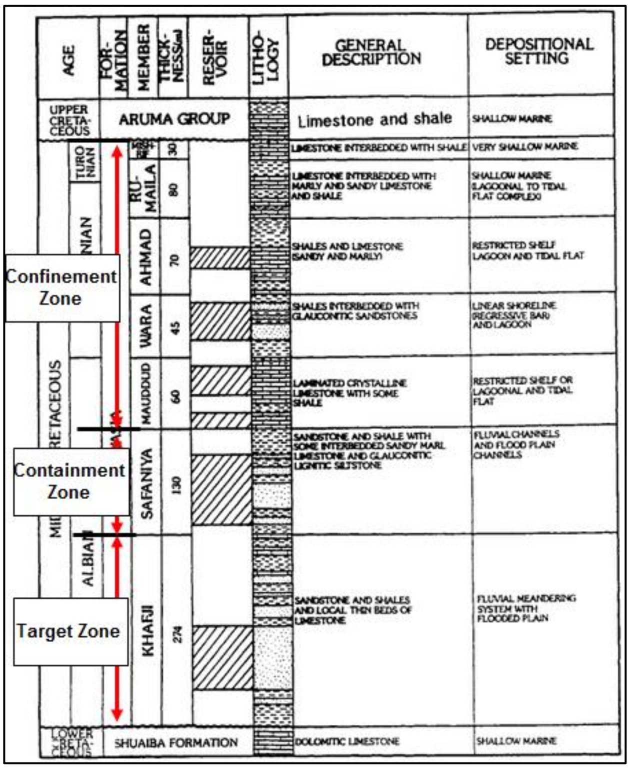

Figure 1. Lithostratigraphy and Deposition Setting of the Wasia Formation in Saudi Arabia Nairn and Alsharhan (1997)

The formations of the upper Wasia group provide an effective ‘cap’ and secure the containment of the slurry injected. In addition, lower Aruma shale acts as the competent confinement layer with high stress contrast with underlying formations of Safaniya and Khafji. Both of these formations are good shaly-sand packages and of low fracture gradient Alshobail et al. (2009). The Safaniya formation lying on top of Khafji formation serves as a ‘containment’ zone. It was determined that the Khafji will be the target zone for CRI operations at Manifa.

The primary characteristics of the Khafji are as follows:

- Clean uniform, unconsolidated sand.
- Thickness ranging from 200 ft to 600 ft.
- Porosity greater than 25%.
- Permeability of approximately 1 ~ 2+ Darcy.

The properties of the targeted Khafji formation as derived from formation testing are listed in Table 3

Table 3. Characteristics of the Khafji Formation from Formation Tests

	Mini-Frac	Injectivity	SRT
Formation thickness, k (ftTVD)	250	250	250
Trasmissivity, kh (ft*D)	252.6	494.5	725.1
Permeability, k (mD)	1010	1977	2900
Formation Pressure (psi)	2982	2981	2983

3 WELL COMPLETION

Dedicated disposal wells were drilled for cuttings re-injection purposes. Wells are either vertical or inclined with an angle (less than 20 degree) across the injection target zone. Slurried waste is preferably injected down through the 4.5” tubing string into the target formation.

Maintaining the mechanical and hydraulic integrity of the injection wells is important during CRI operations. Based on past experience, the critical element in any injection well is the integrity and quality of the cement job, during well completion. During CRI operations, the cement will undergo high pressure injection cycles on a daily basis. The drilling and cementing program should ensure that the injection well has a uniform cement sheath and a good cement bond to the casing and formation along the entire well. Good cement placement along the target zone(s) intervals may be difficult (as these are potentially 'fluid loss' zones); if possible placement of cement above the CRI target zone should be not brittle and have low shrinkage during set-up time. High quality cement placement across the confining zone is essential. The perforation program must ensure good hydraulic communication with the disposal formation and not impair hydraulic isolation around the wellbore Marika et al. (2009).

CRI operations at the Manifa field were performed at eleven CRI injection wells. One CRI well will be discussed in this paper. Well completion for Well #1 is shown in Figure 2.

The cement quality of each well has been reviewed to identify any potential wellbore integrity issues prior to CRI operations. Based on past experience, a CBL value less than 10mV is indicative of a 'good cement interval' that is suitable for the near-well pressure - stress conditions that will be created during deep well disposal operations. Generally, difficulties with respect to achieving good cement placement (i.e. establishing good cement-to-formation and cement-to-casing contact) for these disposal wells were noted (Figure 3).

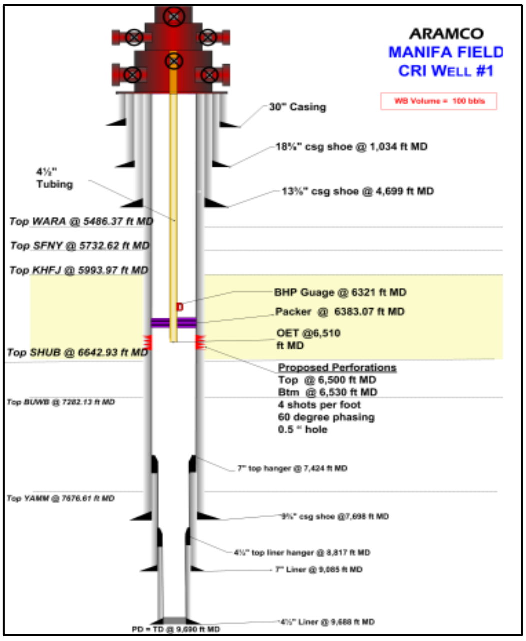

Figure 2. Well #1 Completion Schematic Drawing

This issue is typical of wells that are completed into good porosity and high permeability zones (such as the Khafji formation). During some CRI injection operations at Manifa, a loss of injection pressure was experienced at startup.

Although this loss of pressure is not fully understood, it is likely that degraded wellbore hydraulic integrity due to the relatively poor cement bonding may be an important factor. Injection strategies during CRI operations were deployed to mitigate the risk of wellbore plugging due to the loss of pressure/degraded wellbore integrity, and to ensure adequate injection pressures for the slurry fracture injection process being used at these disposal wells.

The risk of out-of-zone-injection (due to possible degraded wellbore integrity) was deemed to be low. The reason being is the excellent geological conditions (as discussed above) and the deep perforation interval in the Khafji formation.

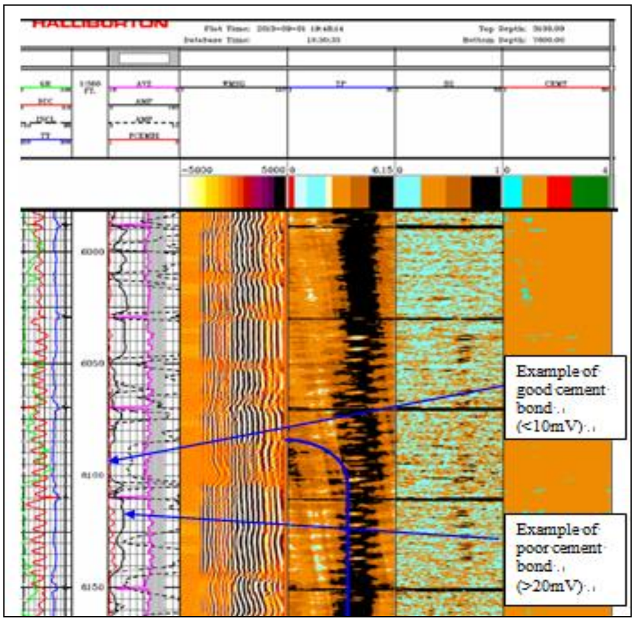

Figure 3. MNIF CRI Well CBL Log

4 MONITORING AND PROCESS CONTROL

Since extensive hydraulic fracturing events occur during CRI injection operations, process monitoring for '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. Fully integrated technical support during CRI operations ensures process control for deep well disposal operations; i.e. data management (of monitoring data), data analyses (i.e. pressure analyses, step-rate test data, etc), and management of field-operating procedures of the modified CRI process need to be integrated in order to maintain process control.

Process control for deep well disposal operations can be defined as follows:

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

A three-fold monitoring program was used for the Manifa CRI operations as follows:

1. The following injection parameters were monitored on a continuous basis:
   a) Bottom Hole Pressure (BHP) in the injection wells.
   b) Wellhead Pressure (WHP) in the injection wells.
   c) Annulus Pressure in the injection wells.
   d) Slurry Composition (grain size, fluid viscosity, fluid density and solid content).
   e) Injection Rate & Volumes.
2. The following formation tests were conducted at the injection wells on a periodic basis:
   a) Mini-frac Test.
   b) Step Rate Test.
   c) Fall-off Test Analyses
3. The BHP data recorded form the injection wells were analyzed to provide the following key Indicator Pressures (IP). The IP data was used to assess the daily formation response to the CRI operations.
   a) Instant Shut-in Pressure (ISIP).
   b) Average Injection Pressure.
   c) Minimum Shut-in Pressure.
   d) Closure Pressure.
   e) Injectivity.

Data collected from the monitoring program were used for typical engineering analyses to assess the formation response to the deep well disposal operations (i.e. formation injectivity behavior along with pressure response data and formation stress state changes due to waste pod development were assessed and compared). This formation response evaluation was then integrated with operational data collected from the monitoring program (slurry concentration, average injection pressure and shut-in pressure, volumes injected, etc) in order to optimize/refine injection to ensure process control.

5 SLURRY DESIGN

Integrating slurry design with the type of waste material being disposed and the geology of the target formation is essential for successful CRI operations. The CRI operations at Manifa field have established slurry design criteria as follows:

- Waste generated from drilling operation is classified as ‘cuttings’ (water based mud, oil based drilling fluids) and slop materials (dirty water from rig clean-up and brine).
- Slurry is comprised of single or multiple waste streams from cuttings, water based mud, oil based drilling fluids that is mixed with sea water to reach certain fluid properties and rheology for injection.
- Typically slurry material has a Specific Gravity (SG) of approximately 1.20 and a fluid viscosity of FV ~ 45 – 70 sec per quart.
- Typically slop material and brine has a Specific Gravity (SG) of approximately 1.05 and a fluid viscosity of FV < 35 sec per quart.
- Volumes and properties of waste (slurry or slop material) vary on a daily basis and are dependent on the drilling operations (Table 4).
- The waste material composition and rheology have been highly variable, requiring ‘on-the-fly’ adjustments to continually optimize the injection strategies and slurry design to maintain formation injectivity.

Certain slurry design criteria have to be followed to maintain the optimal formation response and maximize formation storage capacity. Proper waste auditing is conducted and reported in the daily operations report to allow for effective slurry design and injection strategy development. As well, there are limits to the properties of the slurry that can be achieved due to constraints related to top-side CRI equipment and operational drilling factors. Table 4 shows the typical slurry parameters under CRI operating conditions used at this project.

Table 4. Manifa CRI Project Slurry Parameters

	Parameters
Maximum Density (SG):	1.30
Average Density (SG):	1.20-1.25
Viscosity Sand Slurries:	45 – 70 seconds/qt Marsh Funnel
Waste Content in Slurry:	10%-25% by volume

Solids Particle size:	<300 micron

6 FORMATION RESPONSE TO CUTTINGS RE-INJECTION

The formation response performance at one CRI disposal well is presented with regards to the respective CRI operations.

CRI operations take place at injection pressure higher than the formation fracturing pressure. Hence, extensive hydraulic fracturing events occur in the target zone. Continuous process monitoring and ongoing data analyses are required to make sure no out-of-zone-injection occurs and to maintain process control throughout the CRI operations.

Therefore, as part of the technical support for this project, a 'portfolio' of injection strategies is prepared for each well. Different injection strategies are developed for different waste streams, and the specific well completion and geological conditions at the disposal well. A typical CRI injection strategy consists of the following:

- Pre-flush Stage: Sea water pre-flush at two different injection rates (low injection rate and high injection rate),
    - A viscous polymer pill (if required) at maximum sustainable injection rate,
- Slurry Stage: Waste-slurry injection stage at a sustainable injection rate and pressure (above *in-situ* fracturing conditions).
- Post-flush Stage: Completing the CRI injection operation with sea water post-flush at maximum sustainable injection rate.
    - This volume should be greater than wellbore volume.
- Shut-In Stage: CRI operation is following by a 3~4 hours of shut in time.
    - Pressure is continually monitored during shut-in.

CRI operations can restart and repeat the above injection period. Hence these injection periods are carried out on a cyclic basis – up to five injection periods per day (Figure 4). For this project, due to the high quality target zone characteristics (fluid flow and geomechanic) of the Khafji formation, there is no limit (to-date) on the number of CRI periods that can be used, so long as the recommended shut-in stages are implemented. On other deep well disposal projects, an 'injection cycle' may be defined as a number of 'injection periods' followed by an extended pressure falloff period of 24 – 72 hours Marika et al. (2009).

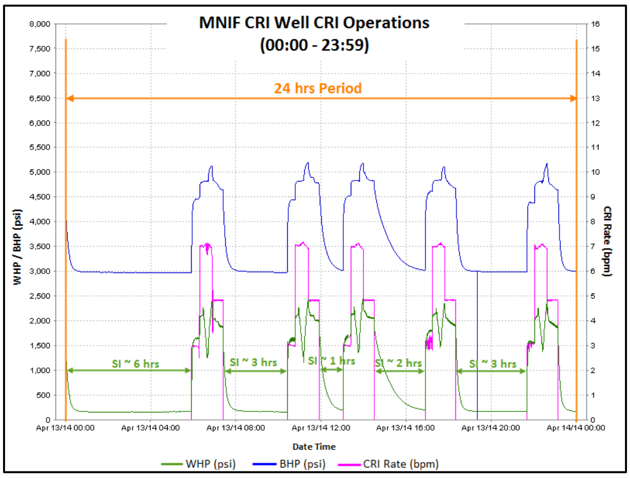

Figure 4. Typical Daily Injection Cycle

A typical injection strategy for these Manifa CRI well is shown in Table 5. A resultant CRI injection period(s) (of injected slurry and water volumes) for the respective CRI wells are shown in Figures 5.

Table 5. Typical Injection Strategy

Injection strategy	
SW Pre-flush at Low Rate	65 bbls @ 3 bpm
SW Pre-flush at High Rate	65 bbls @ 7 bpm
Slurry	100 bbls @ 7 bpm
SW Post-flush	200 bbls @ 7bpm

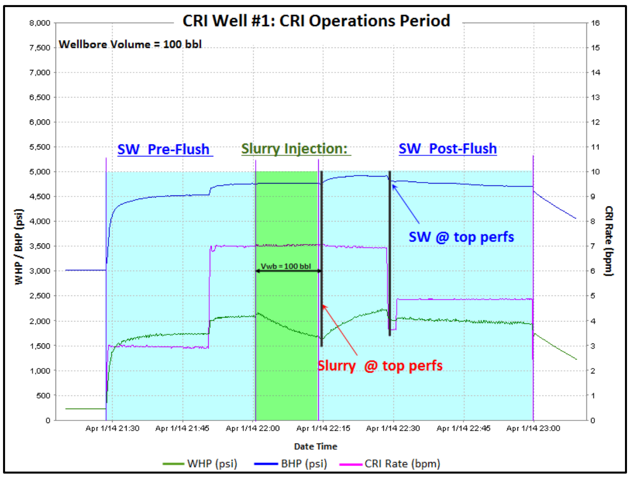

Figure 5. Typical Injection Period for Well#1

The formation response for Well #1 is shown in Figures 6 & 7. Figure 6 shown the Bottom

Hole Pressure (BHP) response during daily injection periods with volumes injected (stage volumes as well as cumulative total volume). The data shows a strong trend related to the various injection strategies used and the total volume of fluid injected.

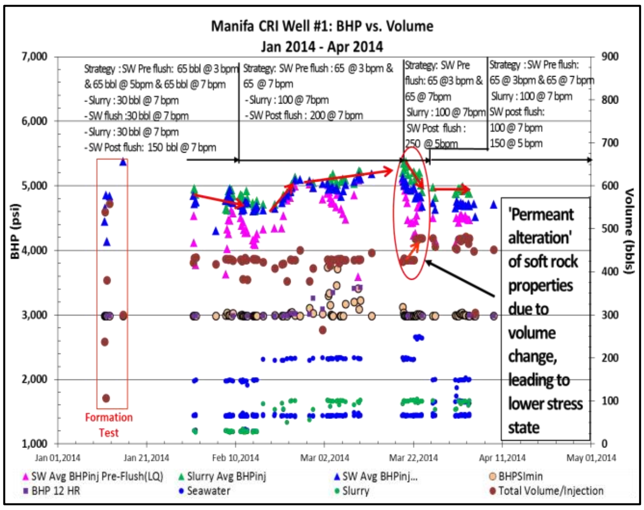

Figure 6. Well#1 Pressure Response vs. Volume

The data starts with very good formation injectivity/injection pressures (BHP_{inj}), when CRI operations are applied with alternating stages of slurry and SW (multi-batches of 30 bbl slurry). Reduced injectivity (higher BHP_{inj} at a given injection rate) is noted when strategy is changed to a single batch of larger volume of slurry (100 bbls) to meet drilling operational needs; during which a large amount of cuttings is generated over a relatively short period of time. Referring to Figure 11, the elevated stress state is noted from the increase of the Fracture Extension Pressure (FEP) up to March 12; likely indicative of a higher stress state in the (near-well) formation as the waste pod develops. This initial development of the waste pod is expected with more slurry injected, which is represented by the formation pressurization, reduced injectivity, and slower leak-off due to lower permeability.

With the large total volume injection periods (approximately 475 bbls) that commence on March 22, there appears to be a permanent alteration in the formation properties that result in lower BHP during injection (BHP_{inj}), corresponding improved injectivity (injection rates are uniform), and lower pressures during the shut-in stage (BHP_{SImin}) (Figures 6).

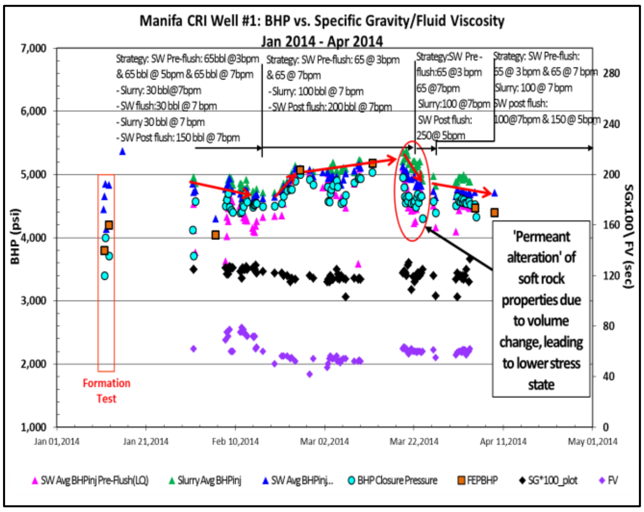

Figure 7. Well#1 Pressure Response and FEP Trend

Figure 7 shows the *in-situ* stress-state response to the CRI operations, in terms of daily closure stress/pressure (BHP Closure Pressure) determined from the Shut-in periods (Pressure Fall-Off analyses - PFOT), and Fracture Extension Pressure (FEP) determined from intermittent Step Rate Tests (SRT) (as per Figure 8). The data profile has a very good correlation between the BHP Closure Pressure and the FEP data. The data is indicative of a 'softening' of the formation stress state when the large total volume injection periods (approximately 475 bbls) are implemented during CRI operations in late March.

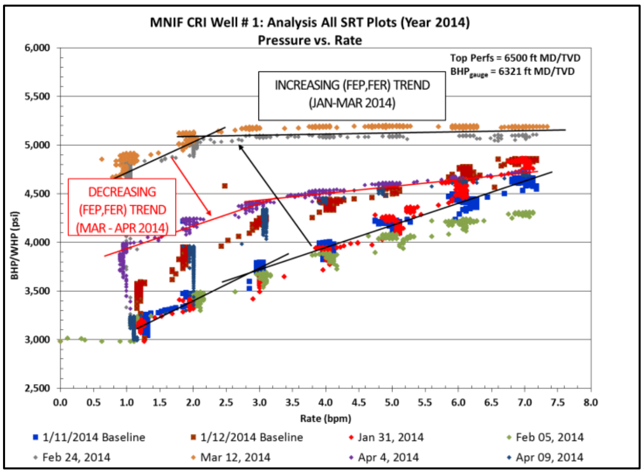

Figure 8. Well#1 Overview Step Rate Test Analyses

The Step Rate Test results for Well #1 are shown in Figure 8. The data again is consistent the with the waste pod development and injection strategies used at this well. From January – March, the data is indicative of a stiffening stress state in the formation (increasing FEP trend), followed by a 'softening' stress condition in April (decreasing FEP trend).

The analyses also indicate different flow systems (from PFO analyses) associated with fracture events and waste pod development. There is very good correlation between the type of 'kh' flow system dominating the formation and the formation pressure/stress response during CRI operations. An enhanced 'kh' flow system is seen to be occurring *in-situ* after March, and corresponds to the reduced stress state and higher injectivity.

For Well #1, the observed alteration of stress state and pressure/injectivity conditions in the target formation are typical of the fracture mechanics that are known to occur with large volume slurry fracture injection of waste materials into a sand-type target formation with very good 'kh' (permeability x thickness) (Reed et al., 2001). Such slurry fracture mechanics include shear dilation, fracture rotations and waste pod development with localized change in permeability. The monitoring data and analyses support the likely occurrence of these mechanisms during the modified CRI operations at this project.

The analyses presented demonstrate that the Khafji formation is sensitive to the slurry properties, injection strategy, and volumes injected. A suitable injection strategy is required to maintain optimal formation response, even though a thick and permeable formation is used as the target disposal zone.

Based on the monitoring program and data analyses for this project, the waste pod development in the Khafji formation can be characterized initially as near-wellbore development. This is followed by a period of fracture expansion within the formation as the fracture events propagate further into the far-field to 'grow the waste pod'. Overall transient pressures and stress conditions indicate that process control is being maintained during the CRI operations and development of the waste pod. Figure 9 shows the Conceptual Model for the CRI Well#1.

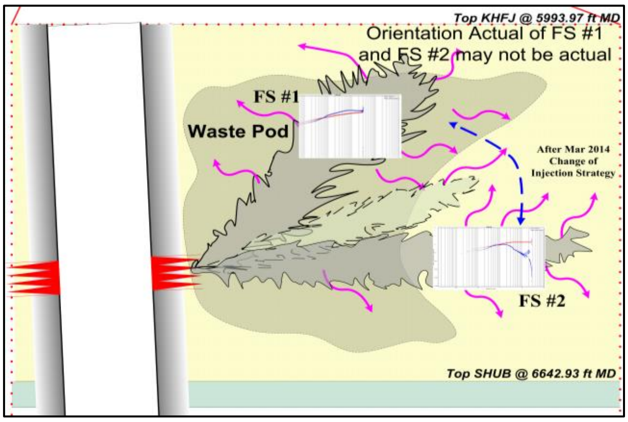

Figure 9. Well#1 Conceptual Model

7 CONCLUSION

1. The zero discharge drilling objectives of the Manifa Drilling Team are being achieved by implementing a modified CRI operation with process control. The drilling waste disposal operations at the Manifa field demonstrate the suitability of the Khafji sand formation for deep well disposal. Appropriate process control is followed throughout the entire operation ensuring both operational success and environmental safety.

2. The Khafji formation is suitable for deep well disposal operations, in terms of its high porosity, bulk compressibility, high permeability, large thickness and suitable depth. This good 'kh' system provides a large storage capacity, good injectivity and relatively quick pressure dissipation for deep well disposal operations. Such characterization offers advantages for the CRI project at Manifa in terms of the disposal operations being able to meet the waste disposal needs of the active drilling operations. On the other hand, it also imposes challenges and risks for the operations; i.e. pressure loss, wellbore plugging, maintenance of wellbore integrity, and out-of-zone-injection; all of which need to be effectively managed.

3. Close process monitoring of the CRI operations at Manifa, made feasible the semi-quantitative assessment of formation containment, injectivity, well integrity and storage capacity; which allowed for the optimization of the injection strategy. Through

the implementation of a properly designed injection strategy, CRI operations at the Manifa field were well managed and met the process control requirements.

4. The key elements required to ensure process control during a modified CRI operation involve geology assessment, waste stream auditing, well design, top-side equipment design, continuous process monitoring, and analyses of injection data to assess formation response. At Manifa, field-disposal operations, CRI technical support (to assess formation response), and drilling operations were fully integrated to manage risks, and to ensure successful and environmentally secure CRI operations.

5. The modified CRI operation (using slurry fracture injection) is a reliable technology providing a safe and environmentally sound drilling waste management strategy for the development of the Manifa field.

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GLOSSARY

BHP	Bottom Hole Pressure
CBL	Cement Bond Log
FEP	Fracture Extension Pressure
FER	Fracture Extension Rate
FS	Flow System
Injectivity	Injection rate / ΔP (injection pressure – formation pressure)
Injection period	Injection event + shut-in time
'kh'	permeability x thickness
PFO	Pressure Fall-Off
SG	Specific Gravity
SRT	Step Rate Test
WHP	Well Head Pressure

CONVERSION

1 m^3 = 6.293 barrel
1 kPa = 0.145 psi

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